

PHYSISCHGE GEOGRAPHIE

PHYSICAL GEOGRAPHY

MAPPING AND DOCUMENTATION OF GULLY EROSION IN SELECTED AREAS OF LOWER AUSTRIA

Sarah DIEM and Ronald PÖPPL, Vienna [Wien]*

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Summary

Gully erosion is a special form of water-induced soil erosion and is often accompanied by devastating geomorphological effects on the landscape. It is characterised not only by

* Sarah DIEM, M.Sc. M.Ed., Teacher, c/o Department of Geography and Regional Research, University of Vienna, Universitätsstraße 7, A-1010 Vienna, Austria; – Mag. Dr. Ronald PÖPPL, B.A., Senior Researcher, Institute of Hydrobiology and Aquatic Ecosystem Management, University of Natural Resources and Science (BOKU University), Gregor-Mendel-Straße 33, A-1180 Vienna, Austria. – Emails: sarah.diem16@gmail.com; ronald.poeppel@boku.ac.at.

high rates of soil loss, but also by lasting changes in the landscape as well as its degradation.

Extensive research on gully erosion has increased in the last two decades. Although studies on this topic had been conducted previously too, they were rather scarce. In Austria, only few studies have dealt with this specific form of soil erosion to date. Accordingly, one of the main objectives of this study was to issue an inventory of gully erosion in a selected study area in Lower Austria. To this end, identified erosion sites were mapped and displayed on a hotspot map to provide an overview of where accumulations of gully erosion can be found. In addition, a geomorphometric analysis was carried out to provide information about soil and sediment loss induced by gully erosion, as well as other specific characteristics of selected erosion phenomena.

As the results reveal, 2,065 permanent gullies and 289 sunken lanes could be detected in the study area, concentrated in regions characterised by thick loess layers and intensive land use. Moreover, it has been shown that the gullies contribute to considerable soil loss rates. In three representative catchment areas, detailed examinations of the geomorphometric characteristics showed that gully erosion is responsible for more than 1,000,000 m³ of sediment loss. Not only does this lead to the emergence of 'scars' in the affected landscapes, but it also leaves agricultural land unusable.

Since heavy rainfall events are expected to become more frequent in Austria due to the advance of climate change, soil erosion may likewise increase in the future. Therefore, there is an urgent need to intensify research on soil erosion in order to take corresponding measures and protect the soil from devastating erosion events.

Keywords: Soil erosion, gully erosion, gullies, sunken lanes, linear erosion, loess landscape, geomorphometric analysis, digital elevation model (DEM), Lower Austria

Zusammenfassung

KARTIERUNG UND DOKUMENTATION DER GULLY-EROSION IN AUSGEWÄHLTEN GEBIETEN NIEDERÖSTERREICHS

Gully-Erosion (auch: Grabenerosion) ist eine spezielle Form der wasserinduzierten Bodenerosion und geht oftmals mit massiven geomorphologischen Landschaftsveränderungen einher. Zum einen ist sie durch hohe Verlustraten an Boden gekennzeichnet, zum anderen aber auch durch nachhaltige Veränderungen des Landschaftsbildes und seine Degradation.

Intensive Forschungen zum Thema Gully-Erosionen haben sich in den letzten beiden Jahrzehnten gehäuft. Davor gab es zwar auch Studien zu dieser Thematik, allerdings nicht im selben Ausmaß. In Österreich haben sich bislang nur wenige Studien mit dieser speziellen Form der Bodenerosion beschäftigt. Dementsprechend war das Ziel dieser Arbeit, eine Inventarisierung von Gully-Erosionen in einem ausgewählten Untersuchungsgebiet in Niederösterreich zu erstellen. Dafür wurden identifizierte Erosionen kartiert und in einer Hotspot-Karte dargestellt, um einen Überblick darüber zu geben, wo Akkumulationen

dieses Erosionstyps gefunden werden können. Eine geomorphometrische Analyse sollte zudem Aufschluss über den verursachten Bodenverlust sowie über weitere Charakteristika ausgewählter Gullies geben.

Neben insgesamt 2065 detektierten permanenten Gullies wurden im Untersuchungsgebiet auch 289 Hohlwege gefunden. Häufungen dieser Erosionsformen konzentrieren sich auf Regionen mit mächtigen Lössschichten und intensiver Landnutzung. Darüber hinaus tragen die Gully-Erosionen zu beachtlichen Bodenverlusten bei. In drei repräsentativen Einzugsgebieten des Untersuchungsgebiets wurde eine detaillierte Untersuchung der geomorphometrischen Charakteristika durchgeführt. Dabei stellte sich heraus, dass die Erosionsphänomene für mehr als eine Million Kubikmeter an Bodenverlust verantwortlich sind. Dies führt nicht nur zur Entstehung von „Narben“ in den betroffenen Landschaften, sondern beeinträchtigt auch die Nutzung für die Landwirtschaft oder macht Flächen für diese völlig unbrauchbar.

Da die Annahme besteht, dass sich aufgrund des fortschreitenden Klimawandels Starkregenereignisse in Österreich künftig häufen werden, kann es zu einer Verstärkung der Bodenerosion kommen. Daher braucht es dringend auch weiterhin Forschung zum Thema Bodenerosion, um Gegenmaßnahmen zu setzen und die Böden bestmöglich vor verheerenden Erosionsereignissen zu schützen.

Schlagwörter: Bodenerosion, Grabenerosion, Gullies, Gully-Erosion, Hohlwege, lineare Erosion, Lösslandschaft, geomorphometrische Analyse, Digitales Höhenmodell (DEM), Niederösterreich

1 Introduction

Soil erosion is a serious problem across the world as it is associated with different forms of land degradation (incl. loss of soils). Not only does this threaten ecosystems, but it also has significant impacts on food security and human health (FAO 2019; COLLINS and OWENS 2006). Erosion processes can be triggered by both water and wind, although anthropogenic activities, especially in agriculture, are becoming increasingly important in this respect (STRAUSS and SCHMALTZ 2020; POESEN 2018; DURÁN ZUAZO et al. 2011).

Gully erosion is a special form of water-induced soil erosion. It constitutes a linear flow process in which surface runoff accumulates in rills and increasingly incises them (VANMAERCKE et al. 2021; FRANKL et al. 2020; MORGAN 2005; TOY et al. 2002). This form of soil erosion is accompanied by high rates of soil loss, with deeply incised permanent gullies often leaving landscapes irreversibly damaged. Gully erosion is particularly disastrous not only due to these high soil loss rates, but also since erosion gullies usually develop within very short timescales (FRANKL et al. 2020; CHAPLOT 2013; POESEN et al. 2003). Moreover, they lead to soil drainage, which is a major problem if it occurs on arable land (ZGŁOBICKI et al. 2017; VALENTIN et al. 2005).

The formation of gullies is strongly influenced by climatic conditions, especially precipitation events, but also by soil properties, the underlying lithology and their erodibility (VANMAERCKE et al. 2021). Other driving factors include the topography, specifically slope

gradient and length (XU et al. 2017), as well as anthropogenic influences, e.g. due to different types of land use and management (CASTILLO and GÓMEZ 2016; DOTTERWEICH et al. 2012; POESEN et al. 2003).

Although gully erosion causes large amounts of soil to be lost, there were barely any studies on the issue until the beginning of the 21st century. This is partly due to the fact that both the *formation* and the *progressive expansion* of gully erosion are relatively complex and not always fully understood (VALENTIN et al. 2005). The complexity of the research is, for instance, reflected in the fact that gullies can be assigned to different types, strongly differing depending on their local occurrence and the impact they cause (CASTILLO and GÓMEZ 2016).

Despite the fact that research on gully erosion has steadily increased in recent years, various gaps in knowledge still remain (CASTILLO and GÓMEZ 2016; VALENTIN et al. 2005). In Europe, there is a lack of research on the existence, characteristics and development of gully erosion. Most research has been limited to studying individual erosion phenomena on a local scale, with a lack of surveys on a larger scale.

There is also a methodological and geographical imbalance. Methodically, the focus so far has been on field studies, emphasising a limited number of gullies or individual systems. The geographical imbalance, meanwhile, prevails due to the fact that research on gully erosion has been carried out only in a few European countries. In addition, there is a very limited number of countries that can provide an inventory of gully erosion, mostly concentrating on specific areas, and with only few including an entire state. As a result, there exists no accurate overview of where gully erosion occurs in Europe (ESDAC 2024).

In Austria, a small number of studies was dedicated to the topic of gully erosion in the past (cf. PETSCHKO et al. 2022; VANMAERCKE et al. 2021; WIESBAUER 2020; WIESBAUER and ZETTEL 2014; KRISSEL 1982). However, these studies focussed mainly on one specific gully type, namely sunken lanes, which are a typical feature of the Lower Austrian loess regions. In some areas, these phenomena were mapped, while in others, the investigations highlighted their (historical) formation or possible influencing factors (cf. PETSCHKO et al. 2022; WIESBAUER 2020; WIESBAUER and ZETTEL 2014).

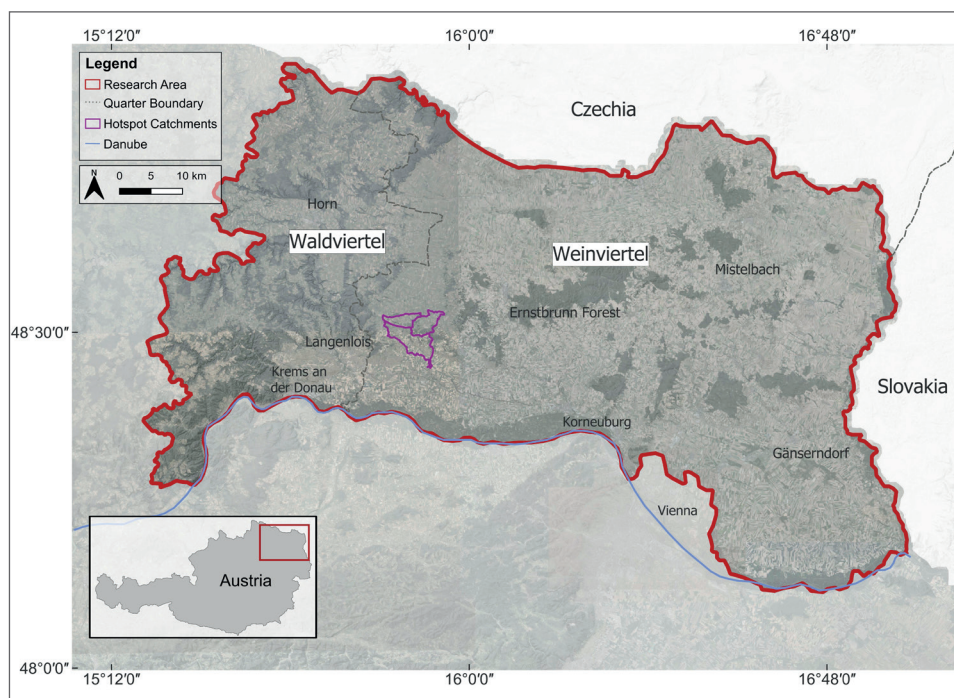
Based on the research gaps as identified above, the main objective of this research was to compile an inventory of gully erosion in a selected study area. The focus was set on the loess regions of Lower Austria, situated north of the Danube. Due to their high fertility, loess soils are often used for intense agricultural cultivation, as is the case in the investigated regions (ZGŁOBICKI et al. 2017; cf. SCHUSTER et al. 2015). However, this particular parent material is highly susceptible to water-induced erosion, especially in combination with intensive agricultural usage (ZGŁOBICKI et al. 2017; CASTILLO and GÓMEZ 2016; WIESBAUER and ZETTEL 2014). Since the study area expands over a large territory, the mapping of gully erosion was not based on a field approach, but on the use of a remote sensing-derived digital elevation model (DEM). DEMs support the analysis of larger areas, especially with regard to the overall occurrence of gullies as well as the spatial distribution and density of erosion processes (VANMAERCKE et al. 2021). The chosen methodolog-

ical approach is therefore well suited for the purpose of compiling an inventory of specific erosion types and is also efficient for studying a larger area.

The study objectives were therefore pursued by 1.) mapping gully erosion using a DEM and presenting the results cartographically in a hotspot map; 2.) distinguishing between permanent gullies and sunken lanes in order to draw attention to the occurrence of different types; and 3.) performing a geomorphometric analysis in three catchment areas to gain an overview of the extent of gully erosion (especially regarding the eroded volumes).

2 Research Area

This research was conducted in the Austrian province Lower Austria, in selected regions north of the Danube (Figure 1). In total, the study area covers more than 6,700 km² (Statistics Austria 2021). The entire region of the *Weinviertel* and the eastern parts of the *Waldviertel* (the districts of Horn and Krems-Land) are located within the analysed area. The investigated parts are characterised by a rather dry climate, which is an important prerequisite for soil erosion (BAW 2020). In addition, the region is used intensively for



Source: Digital elevation model (DEM): Provincial Government of Lower Austria; Orthophoto: geoland.at. Own design.

Figure 1: Research area in Lower Austria

agricultural purposes, which results in a low vegetation cover during periods of sowing and early growth stages. These periods, however, correlate with those of intense rainfall, which significantly increases soil erosion potential (BAW 2020; KLIK and EITZINGER 2010).

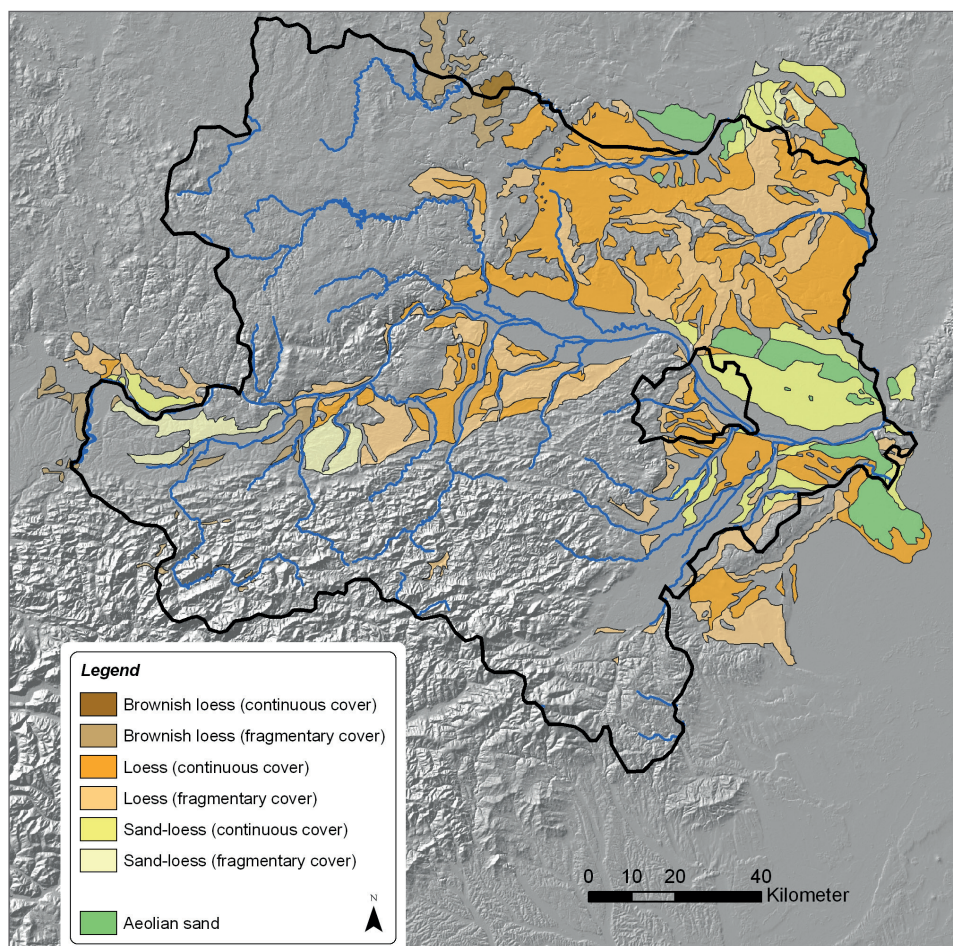
In terms of its geological characteristics, the *Waldviertel* can be determined as part of the Bohemian Massif. Low mountain ranges and hilly landscapes define the area, which is dominated by granite and gneiss and, in the south, is also overlain by sedimentary deposits (e.g. loess, alluvial material) (SCHUSTER et al. 2015; HOFMANN 2003). The *Weinviertel*, by contrast, belongs to the Molasse Belt and, to some extent, to the Vienna Basin. Both marine and freshwater deposits (gravels, sands and clays) characterise the landscape (WAGREICH et al. 2008).

Since large parts of Lower Austria belong to the Austrian loess belt, this specific parent material can be found in almost the entire study area (Figure 2). In the dry loess landscape, which includes the areas east of the city of Krems, loess layers of several metres in thickness occur (PETSCHKO et al. 2022). Around Krems itself, layers with an average thickness of more than 8 metres can be located (MEYER-HEINTZE et al. 2018), which strongly increase further to the east towards the municipality of Langenlois, where layers of up to 20 metres can be identified (THIEL et al. 2011). Such thick loess layers can be found across large parts of the study area (HAESAERTS et al. 2016); nevertheless, their extent decreases towards the south-eastern border of the research area. In those regions, the parent material is only present in thin, partially fragmented layers (BRANDTNER 1954).

Due to the prevalence of loess as parent material, Lower Austria is characterised by productive and fertile soils. Cambisol and chernozem are the predominant soil types in the investigated area, with smaller amounts of humid black chernozem and colluvium also occurring (NÖ Agrarbezirksbehörde n.d.).

Because of the high fertility of Lower Austrian soils, intensive agricultural use has been carried out for centuries. During Roman times, the cultivation of wine intensified, for which large areas were terraced (WIESBAUER and ZETTEL 2014). Agriculture also became increasingly important in the High Middle Ages. Large forest areas were cleared to initiate the cultivation of arable fields. In addition, viticulture continued to flourish, due to which even more settlements emerged, and the population grew steadily. From the 18th century onwards, the cultivation of other crops became important as well. Arable land was dedicated not only to viticulture but also to the cultivation of potatoes and different types of cereals (KRAWARIK 2006; ÖBIG 1985). Today, around 46 percent of the *Waldviertel* and 65 percent of the *Weinviertel* are designated as agricultural land (AMA 2024; Statistics Austria 2021). Viticulture continues to play a prominent role, but overall cultivation has diversified. As a result, various types of cereals, potatoes, sugar beets, rape and pumpkins are raised on Lower Austria's agricultural fields (Provincial Government of Lower Austria 2022; LAMM 2010).

In terms of climate, the *Waldviertel*, the westernmost part of the study area, is generally defined by Atlantic-Oceanic influences. However, these impacts are rather minor, as this part can be designated as a transition zone to the *Weinviertel*, which is dominated by Continental-Pannonian influences (PETSCHKO et al. 2022). Accordingly, a rather dry climate prevails in the investigated area. The Pannonian influences result in dry and cold



Source: TERHORST et al. 2009, p. 69; LOISHANDL and PETICZKA 2005.

Figure 2: Loess map of Lower Austria

winters as well as dry and hot summers. Average precipitation in the study area ranges from 500 to just over 600 mm per year (Provincial Government of Lower Austria 2025a, 2016b). The highest monthly precipitation values occur between May and September, whereas the winter months tend to have low rainfall rates (Provincial Government of Lower Austria 2025b). This is also consistent with studies on erosive precipitation. In the studied regions, erosive precipitation falls mainly during the summer months, especially in conjunction with thunderstorms, while erosive rainfall events are also frequent in late spring and early autumn (May–September) (VÁSQUEZ et al. 2024). The accumulation of erosive precipitation in late spring, while the vegetation cover in agricultural areas is still low, poses a particular risk for soil erosion (JOHANNSEN et al. 2022).

3 Data and Methods

Within ArcGIS Pro (version 2.7), a Digital Elevation Model (DEM) with a resolution of 1 x 1 m was used to achieve the objective of creating an inventory of gully erosion in Lower Austria. The DEM was provided by the General Building Services Department of the Provincial Government of Lower Austria. It consists of aerial laser scanning data, with the photographs taken in 2011/2012 for small parts in the south of the Weinviertel. For the rest of the study area, however, the recordings date from 2018 and, for the most parts, from 2020. The data acquisition of the present study took place in 2021 and 2022 (see DIEM 2022).

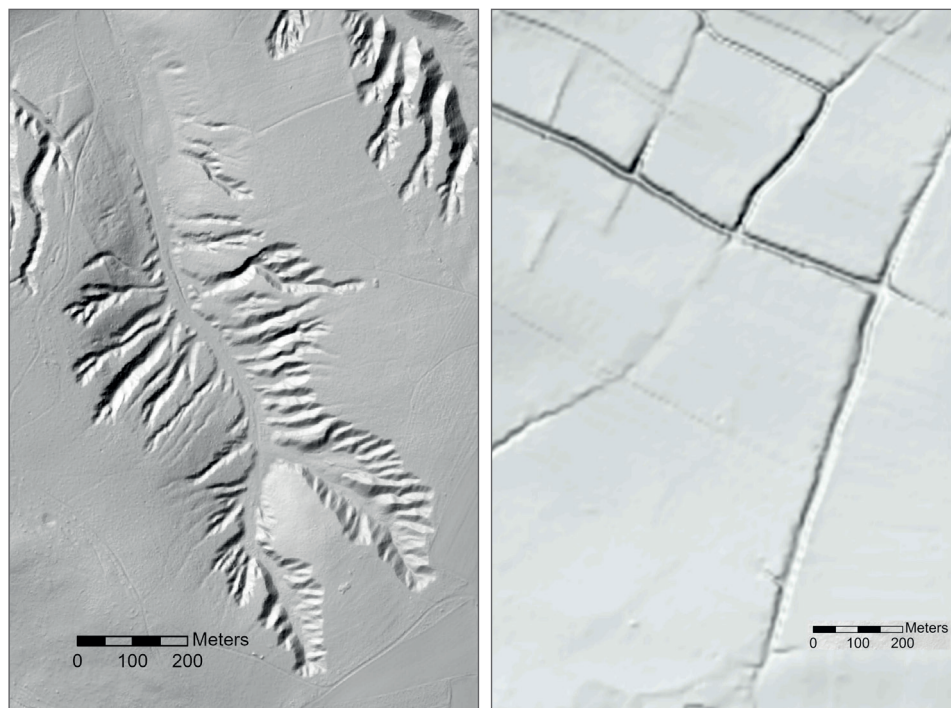
DEMs have increasingly been applied for gully mapping in recent years as they enable a detailed geomorphological and hydrological analysis due to their high resolution. In addition, they offer the advantage that erosion phenomena can be identified easily and swiftly on a larger spatial scale, while also providing an overview of erosion density (VANMAERCKE et al. 2021). Based on the DEM, a hillshade was generated in ArcGIS, which was overlaid with a grid measuring 2 x 2 km. The grid was used for the subsequent search of the gullies, whereby each column was scanned manually.

Eventually, two different types of gullies were mapped: permanent gullies and sunken lanes (see Figure 3). A gully is described as permanent if it covers a depth between 0.5 and 20–30 m, which means it cannot be removed by common tillage practices (BORRELLI et al. 2022; ZGŁOBICKI et al. 2017). Sunken lanes are also a form of permanent gully erosion, but their formation occurs exclusively due to anthropogenic influences. Sunken lanes mainly developed in the past when the soil of unpaved paths was loosened by carriages and livestock and entrained during precipitation events. Consequently, deep incisions characterised by particularly high walls have formed (ZGŁOBICKI et al. 2021; WIESBAUER and ZETTEL 2014; BOARDMAN 2013).

Although there are other types of gully erosion, the selected methodological approach only allowed the search for permanent gullies and sunken lanes. For the identification of ephemeral gullies, which are quite small in their extent – max. 0.5 m in depth – (cf. THWAITES et al. 2021; POESEN et al. 2003), the spatio-temporal resolution of the DEM was too low. Moreover, ephemeral gullies tend to appear only for a short time span as they can be obliterated by common tillage practices. It is therefore rather unlikely for ephemeral gullies to be recorded in a time-limited survey such as a DEM (VANMAERCKE et al. 2021). Another type of gully that could not be mapped using this methodology is the bank gully. Bank gullies are characterised by a significant drop in elevation (THWAITES et al. 2021; VANDEKERCKHOVE et al. 2000; POESEN et al. 1996). As many regions of the study area are used for the cultivation of wine, there existed a great risk of confusing terraced vineyards with bank gullies.

The decisive factor in distinguishing between the two selected types of gullies, while mapping them, was their planform shape (see Figure 3). Permanent gullies are usually strongly branched, with several gullies often forming an entire system. Mostly, they consist of a wide main channel and many smaller and larger branches (see also THWAITES et al. 2021). Sunken lanes, by contrast, are characterised by much more pronounced lateral boundaries, are often longer than permanent gullies and extend more linearly. In addition, no branches are visible. For verification purposes, an orthophoto and a basemap of the study area were

attributed to the DEM to additionally examine the general landscape appearance. Since sunken lanes are mostly used as (agricultural) tracks or roads, their usage differs greatly from the one of permanent gullies, which occur both on agricultural land and in forests and are mostly left fallow.



Source: DEM: Provincial Government of Lower Austria. Own design.

Figure 3: Analysed gully types: permanent gully (*left*); sunken lane (*right*)

Identified erosion features were mapped using the Image Mensuration Tool integrated in ArcGIS. The measurement type 'line' served for the mapping of the gullies. A line can be drawn by splitting it up into several sections, so that each individual gully could be accurately represented. The erosion features were mapped from their head to their drainage area and automatically saved by the programme as polygon feature classes. In addition, the length of each section as well as the total length of a gully were likewise automatically calculated by the programme (ESRI n.d.a).

Once all the gully erosion identified in the study area had been mapped, a hotspot map was created using the 'Kernel Density'. The Kernel Density requires point or polyline features and a radius for its calculations, with the latter being set either manually or automatically. For this study, the radius was set to 5 km, as this yielded the best results. Eventually, hotspots occur at those points where an accumulation of the input feature class is detected

within the set radius. Hotspots of gully erosion are therefore located where the Kernel Density shows a particularly high density of point features, which were derived from the mapping (ESRI n.d.b).

As a next step, three streams were determined within the calculated hotspot areas, into which as many gullies as possible drained. In the vicinity of these three selected streams, high numbers of gullies were mapped in general, but also in terms of the two distinguished types. Since significantly fewer sunken lanes than permanent gullies were identified, they exist only in two of the three catchments, but also in strong accumulations. Based on the large number of phenomena located in the catchment areas, it was assumed that the results of the geomorphometric analysis could be considered representative of the entire study area.

As with the mapping of the gullies, the '*Image Mensuration Tool*' was likewise applied for the following geomorphometric analysis:

- *Length and width:* The gullies were measured from their head to their drainage area using the Distance Calculation Tool. The shape of the main channel was precisely replicated, while ArcGIS automatically calculated the length of the drawn features in the background (ESRI n.d.a). The same procedure was used to calculate the width.
- *Depth:* The depth was calculated using the 3D Point Calculation Tool. A point was set in the terrain outside the gully, as well as one within the erosion (ESRI n.d.a). The calculated Z values were then subtracted from each other to calculate the differences in height.
- *Volume:* The Volume Calculation Tool was applied to determine the entrained material of each erosion. The tool calculates the cut and fill volume of an object, subsequently generating the total volume. The calculations are based on the elevation data set (ESRI n.d.a). For each erosion phenomenon, the planform shape was explicitly traced.

4 Results

A total of 2,065 permanent gullies and 289 sunken lanes were mapped within the surveyed area, with most of them identified in the southern part of the study area. Although the two types of erosion often occur alongside each other, the hotspots are clearly distinguishable.

4.1 Permanent Gullies

Permanent gullies are the predominant type of gully erosion identified in the study area (Figure 4). They are distributed across the entire region, occurring both on agricultural land and in forests. The accumulations of permanent gullies in the west (around the area Wagram) developed in a rather flat terrain (average slope gradient smaller than 10 percent). Nevertheless, most gullies are concentrated where the slope gradient increases significantly. Locally, the slope around clusters of permanent gullies exhibits a gradient around 10–20 percent, often even 35 percent upwards. In general, the slope increases towards the eastern clusters. In the Ernstbrunn Forest, the inclination averages out at 10–30 percent, although even steeper slopes can be discovered, too (Figure 5).

Regarding the lithology, loess constitutes the main parent material underlying the accumulations of permanent gullies. The western clusters around the Wagram are characterised by relatively thick loess layers of up to 8 metres, in some cases even thicker (MEYER-HEINTZE et al. 2018; THIEL et al. 2011). Towards the east, however, the thickness decreases. Around the Ernstbrunn Forest, only a fragmented cover exists in some places (cf. Figure 2).

The regions in which the erosion phenomena accumulate exhibit a history of intensive agricultural usage. Historical maps reveal that, centuries ago, orchards, vineyards and arable land dominated the landscape (FUHRMANN 2007). Even the Ernstbrunn Forest was used



Source: DEM: Provincial Government of Lower Austria; Orthophoto: Geoland.at. Own design.
Figure 6: Permanent gully as represented in the DEM hillshade (*above*) and orthophoto (*below*)

for such purposes. Especially in the Middle Ages, deforestation increased to create fields for crops as well as livestock (BIDNER n.d.). Viticulture remained an important economic branch throughout the centuries; nevertheless, since the mid-19th century, cultivation has diversified. Since then, various types of cereals and vegetables have also been harvested (LANGTHALER 2012). The hotspot regions have largely remained agricultural land to these days. Viticulture continues to predominate in the western part (Wagram), while at other hotspots of permanent gullies the fields are also used for other forms of cultivation (Provincial Government of Lower Austria n.d.).

The orthophotos highlight that the occurrence of permanent gullies has a lasting impact on the landscape. If erosion occurs on agricultural fields, this part is left fallow, and vegetation often covers the erosion features (see Figure 6). The permanent gullies that were detected in the Ernstbrunn Forest are equally identifiable on orthophotos as they appear as a clear cut through the otherwise dense canopy and leave a gap in the closed vegetation cover.

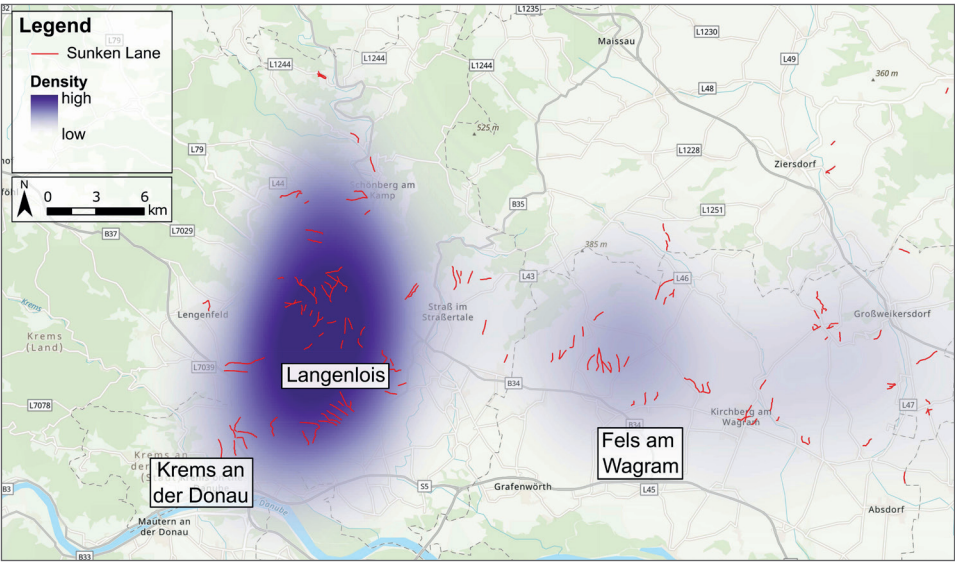
4.2 Sunken Lanes

Sunken lanes account for a much smaller proportion of the mapped gully erosion. The area around the locality Langenlois has been identified as the main hotspot for this type, although smaller accumulations also occur in the Wagram region (Figure 7). While sunken lanes clearly dominate in Langenlois, and permanent gullies are hardly detectable, the two types of erosion occur side by side in the Wagram area. While Langenlois itself is very flat (slope gradient <10 percent), the surrounding vineyards have much steeper slopes. Locally scattered, the slopes often exceed inclinations of 35 percent, and in some places even 50 percent. A few sunken lanes were identified within such steep slopes, but most of them emerged on gentler hillslopes (Figure 8).

Like the permanent gullies, the accumulations of sunken lanes are geologically dominated by loess as parent material. In Langenlois, very thick layers of loess prevail, some of which are at least 20 metres in their extent (THIEL et al. 2011).

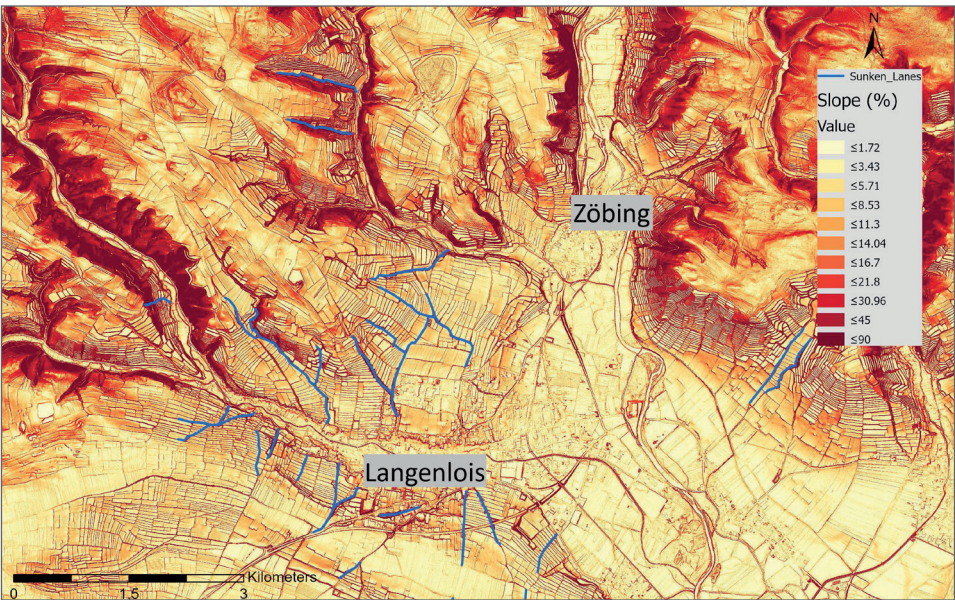
Settlements were established very early in the areas where sunken lanes cluster. During the Roman Age, viticulture was established and brought great prosperity to the settlements. The cultivation of vineyards continued in the Middle Ages, but by that time, fields were also used for the harvest of crops (WIESBAUER and ZETTEL 2014). Intensive land use continued, and by the 18th century, around 75 percent of the population was involved in viticulture. After the Second World War, industrialisation took hold, but viticulture remained the most important branch of agricultural use for the regions where clusters of sunken lanes are found (ÖBIG 1985). Even today, viticulture continues to dominate the landscape (Provincial Government of Lower Austria n.d.).

Many sunken lanes have been destroyed in recent decades, either through waste disposal, land consolidation, levelling, or intensive agricultural use. Those sunken lanes that still exist today continue to be used as paths, although most of them have been paved to prevent further erosion. Some of them are also used as cellar lanes (*“Kellergasse”*) to store wine in cellars built into the thick layers of loess (PETSCHKO et al. 2022; WIESBAUER 2020).



Source: Basemap: ESRI 2024. Own design.

Figure 7: Hotspot map of sunken lanes in the study area



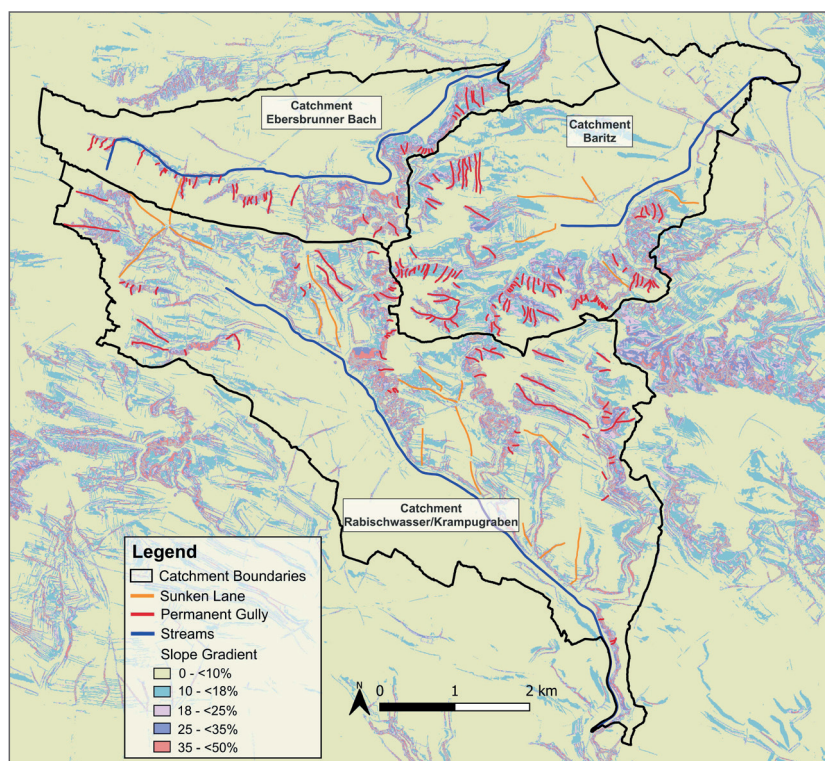
Source: DEM: Provincial Government of Lower Austria. Own design.

Figure 8: Slope gradient in Langenlois, hotspot of sunken lanes

4.3 Geomorphometric Analysis

To highlight the dimensions of the mapped erosion phenomena, which varied greatly in some cases, exemplary gullies were selected both in the catchments and in the rest of the study area; these were examined in more detail in terms of their length, width and depth. The examination of these exemplary gullies was intended to illustrate the range of the occurring geomorphometric characteristics. The smallest erosions that could be identified with the chosen methodological approach were around 20 metres in length, whereby all of these smaller examples could be designated as permanent gullies. Sunken lanes, by contrast, exhibit the smallest widths as they often only occupy the width of a single lane. Considering the depth, the smallest values are around 0.5 metres, which applies to both permanent gullies and sunken lanes. In contrast, the maximum values of the exemplary gullies amount to 1.5 km in length (both permanent gullies and sunken lanes), slightly more than 100 metres in width (permanent gullies) and over 20 metres in depth (permanent gullies).

Every erosion identified within the selected catchments (Figure 9) was likewise analysed in terms of length, width and depth, but the main focus was the eroded volume.



Source: Basemap: Geoland.at. Own design.

Figure 9: Catchments and gully erosions included in the geomorphometric analysis

Permanent gullies were found in all three catchment areas, with the highest values of all parameters examined as follows: approximately 1.2 km in length, slightly more than 100 metres in width, around 2 metres in depth and a material loss of 147,389 m³.

The dimensions of the permanent gullies vary greatly, as do the eroded volumes. However, considering the overall soil loss due to permanent gullies in the catchment areas, results revealed that more than 1.3 million m³ of material were entrained. Converted to linear metres, the material loss per permanent gully is slightly more than 40 m³/m (Table 1). Despite the general differences in the geomorphometric characteristics mentioned above, this last value applies to permanent gullies in all three catchment areas without exception.

Catchment	Cumulative volume loss (m ³)	Volume loss (m ³ /ha)	Volume loss (m ³ /m)
Rabischwasser/ Krampugraben	464,334	91.7	47.1
Baritz	594,613	252.3	42.5
Ebersbrunner Bach	257,924	127.1	42.6

Source: Own calculations

Table 1: Volume loss caused by permanent gullies in the selected hotspot catchments

Catchment	Cumulative volume loss (m ³)	Volume loss (m ³ /ha)	Volume loss (m ³ /m)
Rabischwasser/ Krampugraben	94,655.7	18.7	17.1
Baritz	6,996.8	3	4.3

Source: Own calculations

Table 2: Volume loss caused by sunken lanes in the selected hotspot catchments

Since, in general, fewer sunken lanes than permanent gullies were detected, this second type of erosion only occurs in two of the three selected catchment areas. Considering the geomorphometric parameters examined, the highest values for sunken lanes can be stated as follows: over 600 metres in length, 73 metres in width, approximately 4.5 metres in depth and around 30,000 m³ of material loss. As with permanent gullies, the geomorphometric characteristics of this erosion type vary greatly. In contrast to the permanent gullies, however, the sunken lanes eroded significantly less material. While the soil loss for permanent gullies accumulated to 1.3 million m³, it was just over 101,000 m³ for the sunken lanes. Even when converted to linear metres, no similarities between the sunken lanes in the two catchment areas are detectable. While the volume loss per linear metre in one catchment area is around 17 m³/m, in the other it is only 4.3 m³/m (Table 2).

5 Discussion

The survey revealed that gully erosion constitutes a problem in Lower Austria and occurs frequently in certain regions. Accumulations were found in areas with a certain slope gradient, where a clear difference between the two types examined became apparent. While permanent gullies occurred mainly on slopes with a gradient of at least 10 percent (usually even steeper), sunken lanes could also be identified in flatter areas.

In general, the slope gradient is considered to be one of the most important geometric variables influencing the development of gully erosion (VANMAERCKE et al. 2021; CHAPLOT 2013; DURÁN ZUAZO et al. 2011; POESEN et al. 2003). Slopes with gradients of 15 percent or more are assumed to be particularly susceptible to gully erosion (DESMET et al. 1999; VANDEKERCKHOVE et al. 2000; VALENTIN et al. 2005; LIU et al. 2021). In this respect, the study was able to confirm this assumption, at least with regard to permanent gullies. Nevertheless, gullies can also be detected on gentler slopes, provided that other influencing factors are present, too (DESCROIX et al. 2008; YIBELTAL et al. 2019; LIU et al. 2021). Sunken lanes, in particular, were identified in much flatter areas, with only a few emerging on slopes with a steeper gradient. This could possibly be due to the fact that sunken lanes are heavily dependent on anthropogenic influences. They are created, for example, by the use of unpaved roads where cart wheels (whether from former carriages or modern machinery) loosen the soil structure, create artificial channels and provide material, which can be easily entrained during subsequent rainfall events (ZGŁOBICKI et al. 2021; WIESBAUER and ZETTEL 2014; BOARDMAN 2013). Accordingly, in this case, the anthropogenic impact clearly outweighs the slope gradient.

Soil properties are considered to be another influencing factor in the formation of gully erosion. The investigated area is located almost exclusively in the so-called 'loess region' of Lower Austria, where different degrees of thickness prevail. Although gully erosion could be mapped across the entire study area, the phenomena accumulated predominantly in those regions characterised by thick loess layers. Permanent gullies accumulate in regions with loess layers of 8 metres in extent or even more (MEYER-HEINTZE et al. 2018). Only one cluster is located in an area where the parent material is considerably thinner or only present as fragmented layer (BRANDTNER 1954). The accumulations of sunken lanes were also concentrated in areas with thick loess layers. The cluster near Langenlois, in particular, is located in a region with layers amounting to 20 metres in extent (THIEL et al. 2011). Loess is therefore considered an important factor influencing soil erosion phenomena such as gullies since it exhibits characteristics such as high erodibility and a tendency to silt up (CASTILLO and GÓMEZ 2016; WIESBAUER and ZETTEL 2014). Accordingly, soil particles are rapidly degraded during intense precipitation events, and siltation leads to increased surface runoff, which might gather in depressions and rills (CASTILLO and GÓMEZ 2016; DURÁN ZUAZO et al. 2011).

Although the study area is located in a climate zone influenced by the Continental-Pannonian climate, resulting in a rather dry region, precipitation occurs continuously throughout the year, with peak values occurring between May and September (Provincial Government of Lower Austria 2025b). Erosive precipitation occurs mainly in late spring and early summer. At this time, the soil is often uncovered, as the growing season is just beginning,

which means that the soil is more exposed to the erosive forces of precipitation. In addition, thunderstorms occur repeatedly during the summer months, accompanied by heavy precipitation and higher erosive forces (VÁSQUEZ et al. 2024; JOHANNSEN et al. 2022).

Another distinctive feature regarding the occurrence of gully erosion in Lower Austria can be attributed to the land use. Hotspots were located almost exclusively in areas that have been subject to intensive anthropogenic utilisation, both historically and in the present day. The regions were settled very early, with wine having been cultivated since Roman times. Even though land use has changed over the centuries, and other crops such as cereals and vegetables have also been harvested since the 18th century, viticulture continues to play an important role. In viticulture, in particular, plants are grown in rows with large spaces between them. If, in addition, the cultivation is carried out in the direction of the slope, soil erosion can be further exacerbated. In unplanted rows, which may serve as paths for machinery, the soil is exposed to climatic influences without protection (BAW 2020; KLIK and EITZINGER 2010). All of this is consistent with the general assumption that agricultural usage constitutes an important influencing factor in gully erosion. Deforestation and the mechanical cultivation of fields (e.g., ploughing, row planting) (ZGŁOBICKI et al. 2017; CASTILLO and GÓMEZ 2016), as well as the construction of unpaved paths (WIESBAUER and ZETTEL 2014; KLIK and EITZINGER 2010), are important factors affecting the development of gully erosion, particularly in the studied regions.

When considering the impact factors of gully erosion, the variable ‘climate’ is likely to change significantly in the near future. According to the status report published by the Austrian Panel on Climate Change (APCC 2025), ongoing climate change will lead to alterations in Austria’s water and temperature balance. Convective events and extreme precipitation will likely increase in the future, causing more severe soil erosion. The expected precipitation events, in combination with other influencing factors such as slope gradient and land use, could lead to much more frequent and severe erosion events if no countermeasures are taken (APCC 2025). These assumptions are consistent with various studies conducted on the impact of climate change on soil erosion, which also indicate that increasing extreme precipitation events lead to higher rates of soil erosion (cf. BORRELLI et al. 2020; LUETZENBURG et al. 2020; LI and FANG 2016).

As the geomorphometric analysis revealed, gully erosion in Lower Austria contributes to major soil loss. In this respect, permanent gullies tend to erode more material than sunken lanes. One possible reason for this is that permanent gullies tend to be larger and much more branched than sunken lanes, which were often paved in the past for anthropogenic purposes, inhibiting further downcutting. Overall, permanent gullies located in the exemplary catchment areas led to the erosion of more than 1.3 million m³ of material, while sunken lanes removed slightly more than 100,000 m³. These results support the assumption that gully erosion can lead to serious land degradation and is associated with large amounts of soil loss (VANMAERCKE et al. 2016; POESEN et al. 2003).

Regarding the applied methods, the presented research was able to reveal that working with a Digital Elevation Model (DEM) is well suited for gaining a general overview of gully erosion in a larger study area. Nevertheless, it must be noted that this methodical ap-

proach also comes with certain limitations. Permanent gully types are convenient to search for, mainly because they are irreversible and therefore persistently present in a landscape. However, to identify and map other gully types, such as the smaller and usually only temporary ephemeral gullies, other approaches are needed. In this respect, field studies are better suited than working with a DEM, as aerial laser scanning data is usually not updated at short intervals (VANMAERCKE et al. 2021). Moreover, a DEM only provides insights into the actual state of a gully at a certain point in time. This makes it much more difficult to differentiate between gullies other than permanent ones, as well as to make statements about their emergence and long-term development.

6 Conclusion and Outlook

Gully erosion is a serious issue in the investigated areas in Lower Austria. 2,065 permanent gullies and 289 sunken lanes were mapped, with hotspots concentrated in regions with thick layers of loess. The identified erosion features contribute to major soil loss. Exemplary calculations revealed that permanent gullies eroded more than 1.3 million m³ of soil, whereas sunken lanes led to the loss of more than 100,000 m³ of material. In general, permanent gullies exhibit a greater extent than sunken lanes, especially in width, depth and soil loss. However, both erosion phenomena can occupy remarkable lengths of more than 1,5 km.

Among other factors, the slope gradient was identified as an important influence on the formation of gully erosion, especially for permanent gullies. Sunken lanes, by contrast, do not seem to depend as much on the slope gradient as they do on anthropogenic influences. Soil properties, however, influenced both erosion types equally. Hotspots were concentrated in areas where thick layers of loess constitute the parent material. Land use also plays an important role, as erosion accumulated primarily in regions that have been subject to intensive agricultural use for centuries. Since gully erosion is a water-induced form of erosion, precipitation is of great importance, too. In the study area, erosive precipitation occurs especially in late spring, during the summer months and in early autumn in the form of convective rainfall and thunderstorms. If the vegetation cover is still low during these events or is already absent due to harvesting, the risk of erosion increases significantly (JOHANNSEN et al. 2022).

In view of the climate crisis, it is therefore all the more urgent that further studies are conducted on the subject of soil erosion in general and gully erosion specifically. In Austria, extreme precipitation events and soil erosion are expected to increase (APCC 2025). However, once the problem of soil erosion in certain areas, such as Lower Austria, is apparent, targeted countermeasures can be taken. To this end, it is vital to know where erosion occurs and what specific forms and extents it entails (as this study has attempted to show). Moreover, it is important to conduct more research concerning the factors that influence erosion phenomena, to investigate their exact development and to explore the alteration of already existing types. Once it is understood how all these factors influence soil erosion and interact with each other, research on measures should be continued in order to better prevent future erosion events and protect soils from further degradation.

7 References

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