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Sarah Diem

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Abstract

A water-induced and particularly damaging type of soil erosion is the so-called gully erosion. Gully erosion occurs mostly in agricultural areas, influenced by natural factors such as precipitation and soil properties, as well as anthropogenic influences such as tillage and land use. A gully is caused by linear surface runoff as a result of heavy rainfall events. The forces of the water weaken the soil aggregates, loosen material, and transport it, later depositing the sediments further downslope. This process creates channels, which are referred to as gullies once they reach a depth of 0.3 m.

In Lower Austria, soil erosion plays an important role since many regions are regarded as particularly vulnerable due to the prevailing climate, soil properties, topography, and land use. Since gully erosion in Lower Austria has hardly been studied so far, the aims of this thesis are: a) to develop a hotspot map for the occurrence of gully clusters, b) to assign the erosion phenomena to different gully types, and c) to provide a detailed analysis with information on the geomorphometric properties of the detected gullies.

The focus is placed on the regions north of the Danube, with the research area extending from the eastern Waldviertel to the entire Weinviertel. The study area is characterised by some important influencing factors for the formation of gullies: the areas belong primarily to the dry and low-precipitation Pannonian climate region, the soils were formed from the easily erodible parent material loess, and intensive agriculture has dominated the area for centuries.

Gully erosions were searched and mapped on a hillshade map, generated from a high-resolution Digital Elevation Model (DEM). To show any accumulations of gully erosion, the mappings were converted into a hotspot map according to the Kernel Density standards. Within these hotspot regions, three catchment areas were selected, in which the gullies were assessed in detail, correspondent to their geomorphometric characteristics, with a specific focus on their length, width, depth, and eroded volumes.

The results reveal that gully erosion mainly accumulates in regions with certain slope gradients, climatic conditions, and especially intensive land use. In addition to permanent gullies, sunken lanes dominate in the research area and lead to considerable soil loss. Sediment loss can amount to more than 1,000,000 m³ in smaller catchment areas. Gully erosion is accompanied by severe land degradation in the studied area, leaving sections of fields deeply incised and without any further agricultural benefits.

Zusammenfassung

Eine durch Wasser induzierte und besonders gravierende Art der Bodenerosion ist die sogenannte Graben- oder Gully-Erosion. Gully-Erosion tritt zumeist in landwirtschaftlich genutzten Gebieten auf, beeinflusst durch natürliche Faktoren wie Regen oder Bodeneigenschaften, ebenso wie anthropogene Einflüsse wie Bodenbearbeitung oder Bodennutzung. Ein Gully entsteht durch linearen Oberflächenabfluss infolge von Starkregenereignissen. Die Abflusskräfte des Wassers schwächen die Bodenaggregate, lösen und transportieren diese. Durch diesen Prozess entstehen Gräben, die ab einer Tiefe von 0.3 m als Gullies bezeichnet werden.

In Niederösterreich spielt Bodenerosion eine bedeutende Rolle, da viele Regionen aufgrund des vorherrschenden Klimas, der Bodeneigenschaften, der Topografie und der Landnutzung als besonders gefährdet gelten. Da Gully-Erosion in Niederösterreich bislang nur spärlich untersucht worden ist, sind die Ziele dieser Arbeit: a) eine Hotspot-Karte für das Auftreten von Gully-Clustern zu erstellen, b) die Erosionserscheinungen den verschiedenen Gully-Typen zuzuordnen und c) eine detaillierte Analyse mit Informationen über die geomorphometrischen Eigenschaften der detektierten Gullies zu liefern.

Der Fokus wird dabei auf die Regionen nördlich der Donau gelegt, wobei sich das Untersuchungsgebiet vom östlichen Waldviertel über das gesamte Weinviertel erstreckt. Der Forschungsbereich ist durch einige wichtige Einflussfaktoren für die Bildung von Gully-Erosion gekennzeichnet, da die Gebiete überwiegend zur trockenen und niederschlagsarmen pannonischen Klimaregion gehören, die Böden aus dem leicht erodierbaren Ausgangsmaterial Löss entstanden sind und seit Jahrhunderten eine intensive Landwirtschaft dominiert.

Die Gully-Erosionen wurden auf einer Hillshade-Karte, die aus einem hochaufgelösten digitalen Höhenmodell (DEM) erstellt wurde, gesucht und kartiert. Anschließend wurden die Kartierungen nach den Standards der Kernel Density in eine Hotspot-Karte umgewandelt. Innerhalb dieser Hotspot-Regionen wurden zudem drei Einzugsgebiete erstellt, in welchen die Gullies nach geomorphometrischen Eigenschaften detailliert beschrieben wurden. Hauptaugenmerk wurde auf die Länge, die Breite, die Tiefe und das erodierte Volumen gelegt.

Die Ergebnisse zeigen, dass Gully Erosionen vor allem in Regionen mit bestimmten Hangneigungen, klimatischen Verhältnissen und vor allem intensiver Landnutzung

akkumulieren. Neben permanenten Gullies dominieren auch Hohlwege im Untersuchungsgebiet und führen zu einem beachtlichen Bodenabtrag, der auf kleinere Einzugsgebiete umgerechnet über 1.000.000 m^3 betragen kann. Die Entstehung von Gully-Erosion geht im Untersuchungsgebiet mit einer starken Bodendegradation einher und hinterlässt Abschnitte von Feldern tief eingeschnitten und ohne weiteren Nutzen für die Landwirtschaft.

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1. Introduction

Soil erosion is one of the main causes of land degradation and has serious consequences for ecosystems, nutrient cycling, food supply, and other socio-economic considerations (Borelli et al. 2017). The process of soil erosion describes the detachment, transport, and redistribution of soil particles, conditioned by the forces of wind or water (Morgan 2005). A special type of soil erosion triggered by water is known as gully erosion, which is the formation of channels due to an increased surface runoff following heavy precipitation events. Until 2003, gully erosion was rarely considered in studies and publications because its formation and expansion are based on very complex processes (Valentin et al. 2005), some of which are still not fully understood today. This proves to be problematic as gully erosion is one of the most severe forms of soil degradation on agricultural land due to its very high rates of soil removal.

The complexity of the research is reflected, among other things, in the fact that gullies can be assigned to different types, with differences in local occurrence and impact. While there are gullies that are only temporary and can be reversed by conventional agricultural methods such as ploughing, there are also permanent types that cause long-term damage to a landscape and contribute to a particularly high discharge of material (Castillo et al. 2016).

Depending on its distinctness and commonness of occurrence, gully erosion can have very devastating on-site and off-site effects. Besides the loss of farmable soil, the most important on-site effects include damage to infrastructure, forced changes in land use or, in the worst case, the transformation of regions into badlands. Off-site, gully erosion can permanently alter the hydrologic characteristics of catchments, progressively degrade the water quality of adjacent aquatic systems, or modify the connectivity of landscape components, to name just a few examples (Vanmaercke et al. 2021).

The European Soil Data Centre still identifies some knowledge gaps in the research on gully erosion, especially when it comes to its development and expansion on a larger spatial scale. It is therefore considered a priority to conduct research on the issues of the existence, characteristics, and development of gully erosion. Furthermore, topics such as the large-scale detection of gully systems, long-term observations, and the dynamics in different environmental surroundings continue to be insufficiently investigated (ESDAC n.d.).

In the north-east of Austria, many regions are indicated as particularly susceptible to soil erosion due to the prevailing very dry climate and extremely dry soil conditions. Since heavy precipitation events may increase as a result of climate change, the erosion potential is expected to increase likewise, whereas the erosivity of rainfall is crucial for the initiation of water erosion (BAW 2020).
Back in 1982, Krissl published one of the first and only articles on the occurrence of gully erosion in Lower Austria, along with other types of soil erosion. According to the author, in those days three centres of gully erosion were just developing, all in the northern loess areas of the province. The accelerated development was attributed to the four main factors influencing the development of gullies: topography (hilly landscape, etc.), climatic region (Pannonian basin), soil conditions (loess, fertility, erodibility, etc.), and land use (viticulture, agriculture, etc.). Already at that time it was pointed out that a rapid understanding and counteraction to this erosion process was necessary in order to prevent or at least minimise further developments and expansions (Krissl 1982).
Much more attention has been paid to the formation of sunken lanes, one of the permanent types of gully erosion. Sunken lanes are a common phenomenon in Lower Austria. Their formation history goes back several centuries and can mainly be derived from the use of unpaved roads. Here, too, the four most important influencing factors of gully erosion are predominating as they clearly expedited the development of sunken lanes (Wiesbauer et al. 2014).

As many questions and research gaps on gully erosion in Lower Austria still remain, some of them serve as the basis for the defined objectives and formulated research questions of this thesis. One objective of this master’s thesis is to detect, localise, and map gully erosion in the eastern Waldviertel and the Weinviertel. A further objective is the creation of a hotspot map indicating those regions in which a particularly high density of gully erosion can be observed. Once these two steps have been carried out, some of the erosion phenomena will moreover be analysed in greater detail, focusing on the length, width, depth, and eroded volume of the gullies.
The research questions and hypotheses liable to the objectives are as follows:

Q1: Where are gully erosions and potential hotspot areas of gullying detectable in Lower Austria?

H: *Gully erosions are detectable predominantly in inclined areas with thick loess layers and mostly under the influence of contemporary agricultural land use.*

Q2: Which types of gully erosion can predominantly be observed in Lower Austria?

H: *Permanent gullies and sunken lanes are the predominant gully erosion types as they are irreversible and exhibit high depths.*

Q3: What are the average volumes of sediment loss in relation with the observed gully types in Lower Austria?

H: *Permanent gullies erode a higher amount of sediment per linear metre than sunken lanes; therefore, their average volume loss is higher.*

Chapter 2 serves as a state of research chapter and an introduction to the topics of soil erosion and gully erosion, with a specific focus on gully types, their characteristics, and factors of influence. In chapter 3, the study area is introduced. With regard to the core topic of this thesis, information on the topography, lithology, climate, and land use in the north of Lower Austria is covered.

Chapter 4 is dedicated to the methods used to answer the research questions and hypotheses as listed above. In chapter 5, the results are presented, which are then discussed in chapter 6 with reference to the respective research questions and hypotheses. The last chapter, chapter 7, contains some concluding remarks and perspectives on research needed in the future.

2. State of research

2.1 Soil erosion

Soil erosion constitutes a major process of land degradation worldwide, and its impacts threaten ecosystems, food production, and human health (FAO 2019; Collins et al. 2006). It is a natural phenomenon in which the topsoil is removed by the forces of wind or water. In addition, increased anthropogenic activities lead to an acceleration of soil erosion processes, especially in the agricultural sector (Poesen 2018; Durán Zuazo et al. 2011).

Wind erosion occurs especially in arid and semiarid climate zones. Within this process, fine soil particles are removed by the forces of wind, leading to a changing soil texture. Consequences of this special erosion process are the reduction of soil depth and fertility, the loss of land, and the deterioration of water quality, among others (Pi et al. 2017; Borrelli et al. 2016; Toy et al. 2002).

The erosion process with the greatest impacts and loss rates in Europe, however, is water erosion, which therefore constitutes the biggest threat to arable soils. It is a very common phenomenon, not restricted to special climatic conditions or continents (Borrelli et al. 2017; Panagos et al. 2015).

Four steps constitute the process of water erosion: precipitation, detachment, transport, and deposition (see Fig. 1). In the first step, single soil particles get detached from the mass due to flowing water, freezing and thawing, or the energy released by falling raindrops. Once released, the particles are transported by being either floated, rolled, dragged, or splashed. In the process, the pores of the soil may get clogged by the detached particles, increasing water runoff and facilitating the overall erosion of the soil. The last step is the deposition of the detached and transported soil particles somewhere lower in elevation once the runoff energy has decreased and the material cannot be transported further (FAO 2019; Durán Zuazo et al. 2011; Morgan 2005).

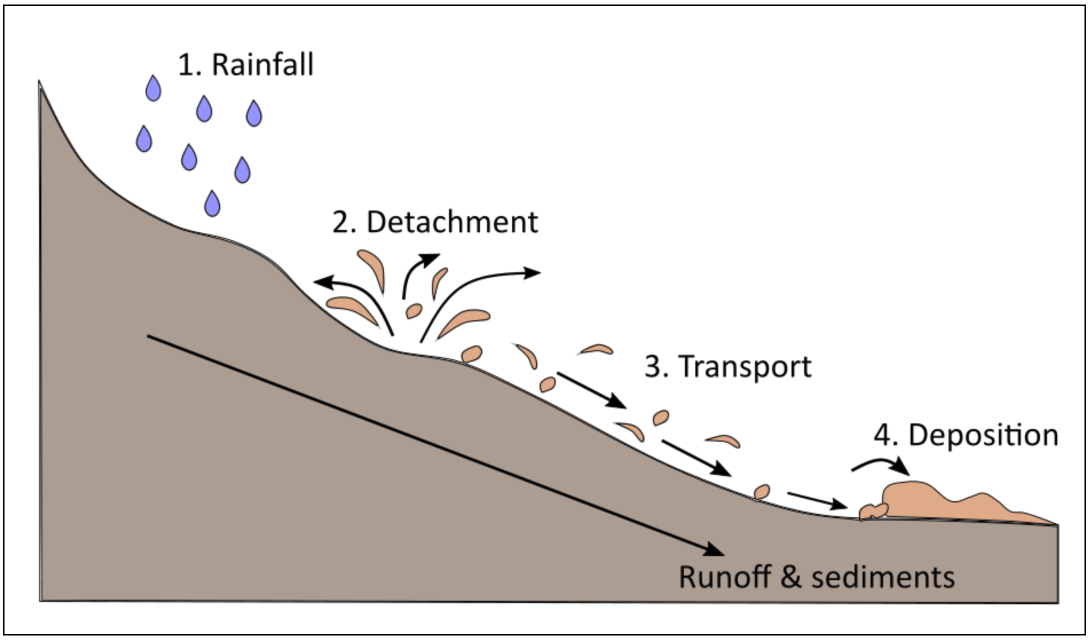

Fig. 1: Process chain of water erosion (after: Durán Zuazo 2011)

Different forms of soil erosion can be attributed to water erosion, including sheet erosion, rill erosion, and gully erosion. Sheet erosion delineates a process of shallow surface runoff without a defined width. The second type, rill erosion, happens when runoff is gathered in small channels, emerging for example from ploughing, and material gets entrained and transported within these rills. Gully erosion is an extension of rill erosion, once the channels become bigger and permanent. Consequently, the process of water erosion is characterised by the pathways and movements that the runoff takes during an erosion event (Ketema et al. 2019; Morgan 2005; Toy et al. 2002).

Several factors are responsible for the manner and intensity in which the soil gets eroded. Regarding climatic agents, the **erosivity of rainfall** stands out as the most important climate variable influencing soil erosion. The erosivity of rainfall describes the kinetic energy with which raindrops strike against the soil surface, in combination with the resulting runoff. With a high rainfall erosivity, raindrops break down the soil aggregate, whereupon loose particles get entrained by the runoff and redistributed somewhere downslope. Runoff starts once the rate of a precipitation event exceeds the infiltration capacity of the soil. It tends to be highest when the peak period of erosivity occurs at the same time as the exposure of the soil to raindrop impact and runoff hits its maximum (Nearing et al. 2017; Toy et al. 2002). The surface runoff emerging from precipitation events that happen within a short timespan but with an extremely high intensity often causes the strongest soil movements (Durán Zuazo 2011).

Another factor contributing to the intensity of an eroding event is **soil erodibility**. Soil erodibility provides information about the soil’s resistance to being detached and transported. Soil texture, infiltration capacity, aggregate stability, shear strength, and organic/chemical content of soil can influence the erodibility factor (Poesen et al. 2018; Morgan 2005). Soils that are rich in clay exhibit a low erodibility as they are able to form strong aggregates, resistant to entrainment and transport (Morgan 2005). The same also applies to soils characterised by a greater grain size, such as sandy soils. On the one hand, they are marked with a high infiltration capacity; on the other hand, to be able to detach these particles, the rainfall intensity needs to be very high. Medium-textured soils, particularly soils rich in silt, are predominantly prone to erosion. The particles get easily detached and transported, and the surface consisting of such soil textures facilitates an increased runoff (Schmidt et al. 2018; Wang et al. 2013; Toy et al. 2002).

The **topography** is a third factor that can contribute positively to an increase in soil erosion. The most important characteristics within topography are the degree and length of a slope. As the slope gets longer and steeper, soil erosion increases since the volume and the velocity of surface runoff expand (Poesen 2018; Durán Zuazo et al. 2011). The distance from the initiating point of the runoff and the steepness of the slope prescribe the erosion rate at specific locations within a field. Resulting from this function, erosion rates are the highest downslope, where surface runoff accumulates (Sabzevari et al. 2019; Toy et al. 2002).

Land use and management is a further influencing factor that needs to be considered when looking at soil erosion rates. Within land use, vegetation cover plays a prominent role as it has the capability to protect soil from eroding. Aboveground parts of plants (leaves, stems, etc.) reduce the kinetic energy of raindrops, which is why less rain falls directly onto the ground. Additionally, they slow down surface runoff, which makes it less hazardous in terms of soil particle detachment. Beside this, components below ground (roots, etc.) stabilize and strengthen the soil so that cohesiveness and aggregate stability are improved (Liu et al. 2018; Morgan 2005). Since vegetation is crucial for the protection of soils, crop rotation or continuous cover crops enable a sustainable cultivation of arable land. Moreover, soil can be protected by applying conservative land management. The usage of heavy machinery or tillage while soil moisture is high leads to a reduction of the infiltration capacity as the surface gets compressed. Other inaccurate management practices, such as ploughing in line of the slope instead of contour ploughing, also enhance erosion rates (Strauss et al. 2020).

Soil erosion can have severe consequences both on-site and off-site. On the field it may deteriorate the quality of soil material; in extreme cases, it leads to land degradation, leaving productive land without any further use. Likewise, nutrients, fertile soil layers, and high infiltration capacities get lost. Off-site it can destroy infrastructure and buildings, cause eutrophication and siltation of adjacent water bodies, threaten ecosystems, and pollute aquatic systems (Strauss et al. 2020; Borrelli et al. 2017).

As soil erosion by water has become a tremendous hazard for soils in Europe, the European Union has included the topic in its environmental agenda. The resulting Good Agricultural and Environmental Conditions (GAEC) were developed to achieve sustainable agriculture and mitigate soil loss (Panagos et al. 2015). The importance and urgency to act in this regard are also reflected in the Sustainable Development Goals (SDG's) (Panagos et al. 2019). Goal No.2 calls for food security and the promotion of sustainable agriculture, and goal No.15 aims to "protect, restore and promote sustainable use of terrestrial ecosystems, […] combat desertification and halt and reverse land degradation […]" (United Nations n.d.).

2.2 Gully erosion

Gully erosion is a specific form of water-induced soil erosion and belongs to the linear flow processes. The water of surface runoff accumulates in narrow rills and channels, leaving incisions of noteworthy depths. This process mostly occurs within small timescales, which is why gully erosion is considered particularly disastrous as very large amounts of sediment are detached and transported even in very short periods. Especially in early stages, when gullies are too big to be removed and vegetation has not yet developed, they tend to expand very fast (Frankl et al. 2020; Chaplot 2013; Poesen et al. 2003).

As a consequence of their often remarkable size, gullies are a particularly serious problem when they occur on arable land. They lead to soil drainage, and in semi-arid zones they can even cause fields to dry out completely (Zgłobicki et al. 2017; Valentin et al. 200). Due to their complex formation (see Fig. 2), gully erosion has been excluded from studies for a long time as this complexity makes investigations and predictions very difficult. Nevertheless, since the years 2003/2004, the topic has received increased attention after being presented and discussed at two international conferences (Valentin et al. 2005). Prevention concepts and control techniques on gully erosion already exist in vast numbers; however, in Europe, they are hardly ever included in soil conservation policies (Vanmaercke et al. 2021).

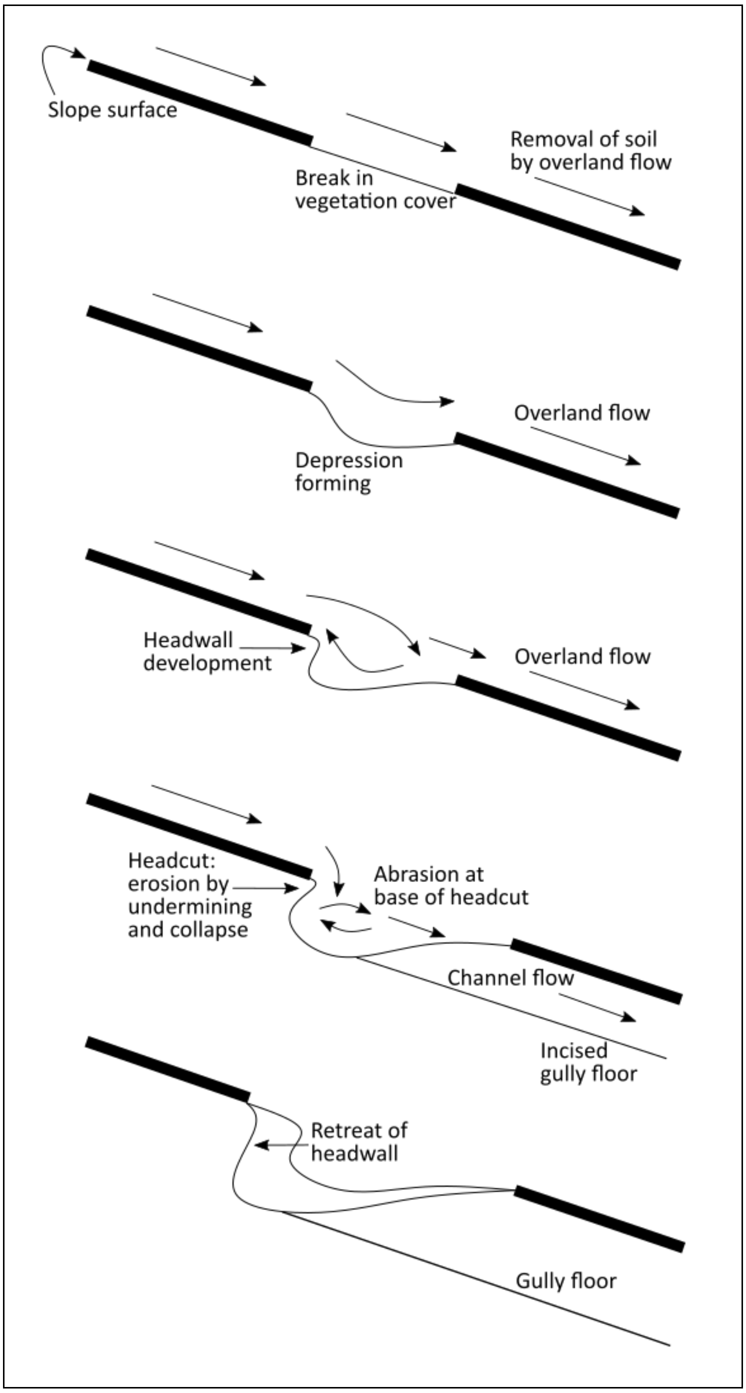

Fig. 2: Incision and expansion of a gully erosion (after: Morgan 2005)

A general description of gully erosion focuses on the landscape processes that happen within this special soil erosion type. With this overarching characterisation, Morgan (2005) distinguishes between valley-floor and valley-side gully erosion. **Valley-floor** gullies occur in swales, mostly in arable land, where the runoff concentrates during intense precipitation events. The soil can be easily removed as it is either freshly tilled, loose, or crusted due to preceding rain events. The main sediment sources are the headcut, which may retreat during following peak runoff charges, and the sidewalls, which either erode continuously or collapse completely. The other landscape type are **valley-side** gullies, which develop more or less at a right angle to the thalweg and at locations where concentrated runoff is established. The runoff of valley-side gullies is discharged into rivers, the bottom of the slope, or into a depositional zone on the slope if the forces are too weak to transport the material to the valley bottom. Combined with piping (soil erosion by subsurface flow) or local mass movements, valley-side gullies can form linear depressions in landscapes (Thwaites et al. 2021; Morgan 2005).

Once developed, gullies commonly expand due to gully headcut retreat or sidewall collapse, including several processes:

- Tension crack development: The kinetic energy of runoff causes an intense splash or hydraulic erosion at the headcut of a gully, which leads to a deepening and widening of the channel (Hayas et al. 2017; Vanmaercke et al. 2016).
- Plunge pools: The pools are formed by falling water, and the erosion is predominantly controlled by rainfall erosivity and soil erodibility. Plunge pools undermine the walls of a gully channel, whereas the overall stability of the sidewalls is decreased (Vanmaercke et al. 2016).
- Gully head/wall collapse: The instability of the gully head or the walls can be caused by recurring surface or subsurface water flow, development of cracks in the channel, or saturation of the soil. Every precipitation event facilitates the next failure until the head or walls are too instable to persist any longer and collapse. As a lot of material is loosened in such an event, soil loss strongly increases after gully head/wall collapse (Thwaites et al. 2021; Vanmaercke et al. 2016; Toy et al. 2002).
- Mass failure: This process is understood to be the movement of material under the influence of gravity and can occur in two different manners. On the one hand, it can act as a continuous, long-term creep movement; on the other hand, it can result in an abrupt movement when shear strengths are exceeded. Both types lead to a removal of soil and, therefore, an expansion of gully size (Vanmaercke et al. 2021; Zegeye et al. 2020).

Gullies and their headcuts mostly stabilize over time, either because of anthropogenic measures (e.g., dam construction) or natural conditions (e.g., development of vegetation) (Vanmaercke et al. 2016).

2.2.1 Types of gully erosion

For decades, the debates about different definitions and gully types have not come to an end; depending on the author, different designations and, above all, varying criteria for determination are represented. The most important criteria include morphological and topographical characteristics of gullies, for example, form of the headcut, cross-sectional shape, location within the catchment, steepness of side walls, and many others. Another focus can be put on the feasibility of agricultural practices, meaning if the gully can still be filled up using common tillage practices or planted with crops. Timescales are also used as defining criterion; for instance, a distinction is made between long-term and short-term gully phenomena (Castillo et al. 2016).

In the following, an overview of various gully types is presented, according to the most common and prevalent definitions in literature.

Ephemeral gullies (see Fig. 3) occur both along natural drainage lines and anthropogenic landscape disturbances, such as drill lines, pathways, and dead furrows. This gully type evolves due to concentrated linear surface flow in smaller channels and is distinguished from traditional rill erosion with a critical cross-sectional area of 929 cm^2 (Thwaites et al. 2021; Poesen et al. 2003). Although ephemeral gullies can be obliterated by common tillage practices such as ploughing, they differ from rill erosion as they tend to reoccur at the same location. This recurrence can take place during the next erosional precipitation event, after some months or even years. Ephemeral gullies are a phenomenon that is not restricted to intensive precipitation events but can also emerge from frequent rainfall events with a moderate magnitude (Capra et al. 2015; Belyaev et al. 2006; Jetten et al. 2006). Despite their smaller size and the possibility to fill up the lost soil, ephemeral gullies are one of the greatest contributors to sediment loss and land degradation in arable landforms (Xu et al. 2017).

When linear surface flow cuts channels into unconsolidated rocks with depths between 0.5 m and 25–30 m, the erosion form is described as **permanent gully** (see Fig. 3). Depending on their depth and width, permanent gullies are usually difficult to cross and impossible to remove with tillage practices. Therefore, these gullies are erosional phenomena that are irreversible and leave parts of arable land degraded and dour (Borrelli et al. 2022; Zgłobicki et al. 2017). In Europe, permanent gullies occur predominantly in areas where the soil is marked by loose sediments, especially in regions with high amounts of loess deposits. The formation of this gully type is strongly dependent on past and current agricultural activities under temperate or continental climate conditions

(Zgłobicki et al. 2017). In permanent gullies, the erosion process happens episodically and can vary annually. It takes place in three phases: in phase one, the loose material from the vertical sidewalls gets removed. Phase two is characterised by the undercut of the sidewall due to waterflow. In phase three, the sidewall collapses into the channel whereupon the whole material gets entrained and transported. Since permanent gullies erode huge amounts of material, they cause severe damage to agricultural fields and produce very high sediment loads (Ma et al. 2021; Toy et al. 2002).

Another permanent form of gully erosion, but with different geomorphic and developing features, is the **bank gully** (see Fig. 3). As the name suggests, bank gullies form where a rill, dead furrow, or wash-line crosses an earth bank. This can be a terrace bank, a lynchet, or any other form of height drop occurring within erodible hillslopes (Thwaites et al. 2021; Vandekerckhove et al. 2000). Like permanent gullies, bank gullies are irreversible and cannot be removed by agricultural operations. What is different, however, is that these gullies are controlled by piping and mass movements, and less by the intensity of overland flow (Poesen et al. 1996).

Another gully erosion that remains permanent in a landscape are **sunken lanes** (see Fig. 3). The development of sunken lanes can be attributed entirely to human activities as they were mainly formed in historic times when streets still used to be unpaved. On these pathways, the surface was frequently loosened by the wheels of carriages or livestock and thus particularly vulnerable to erosion. Due to concentrated surface flow, the floor of the path deepened with every intensive precipitation event, forming steep sidewalls and resulting in a sunken lane (Zgłobicki et al. 2021; Wiesbauer et al. 2014; Boardman 2013). Sunken lanes can be composed of sidewalls which take up several metres in height; various descriptions give a downward limit of 1 m as a guideline (Zgłobicki et al. 2021; Museum Niederösterreich, 2017a).

So far, the inclusion of **badlands** (see Fig. 3) in the categories of gully erosion has been controversial. A badland is an extremely eroded landscape in soft rock terrain, such as shale sedimentary rock. Although badlands are not a gully type per se, they are almost always associated with gully erosions as these regions usually contain lots of gullies, especially of alluvial formation (Thwaites et al. 2021). Another connection between gully erosion and badlands is the assumption that badlands are the result of clustered gully processes. When an environment is susceptible to erosion processes and gets disturbed by inappropriate land use, accumulations of gullies and rills can appear on the valley sides. In addition to these erosion processes, water may collect within the soil, leaving it instable and prone to shallow mass movements. Large amounts of sediment get entrained and redistributed, and the area is left infertile and useless for agriculture (Boardman et al. 2013; Morgan 2005).

Fig. 3: Types of gully erosion: (A) Ephemeral gully (Photo: Antonio Jordán, 2002); (B) Permanent gully (Photo: Elise Monsieurs, 2013); (C) Bank gully (Photo: RCD Monterey, n.d.); (D) Sunken lane (Photo: Sarah Diem, 2021); (E) Badland (Photo: Sarah Diem, 2018)

Permanent gullies can be assigned to different planform shapes (see Fig. 4), and a distinction is made between the following:

– Linear gullies: This planform appears mostly in initial states associated with disturbances in land use. Linear gullies normally concentrate overland flow, leading to an increasing depth.

– Dendritic gullies: These gullies occur in the form of well-defined drainage networks that are separated by areas undisturbed by surface flow. Their headcuts are often less distinct.

– Amphitheatre gullies: When gullies lack structural control, they tend to take the planform shape of an amphitheatre, meaning that they are of greater width than length. Commonly, they drain into channels that are relatively narrow.

– Continuous scarp-front gullies: This planform characterises gullies that run parallel to the main channel and evolve from coalescence of laterally extending amphitheatre or dendritic gullies (Thwaites et al. 2021).

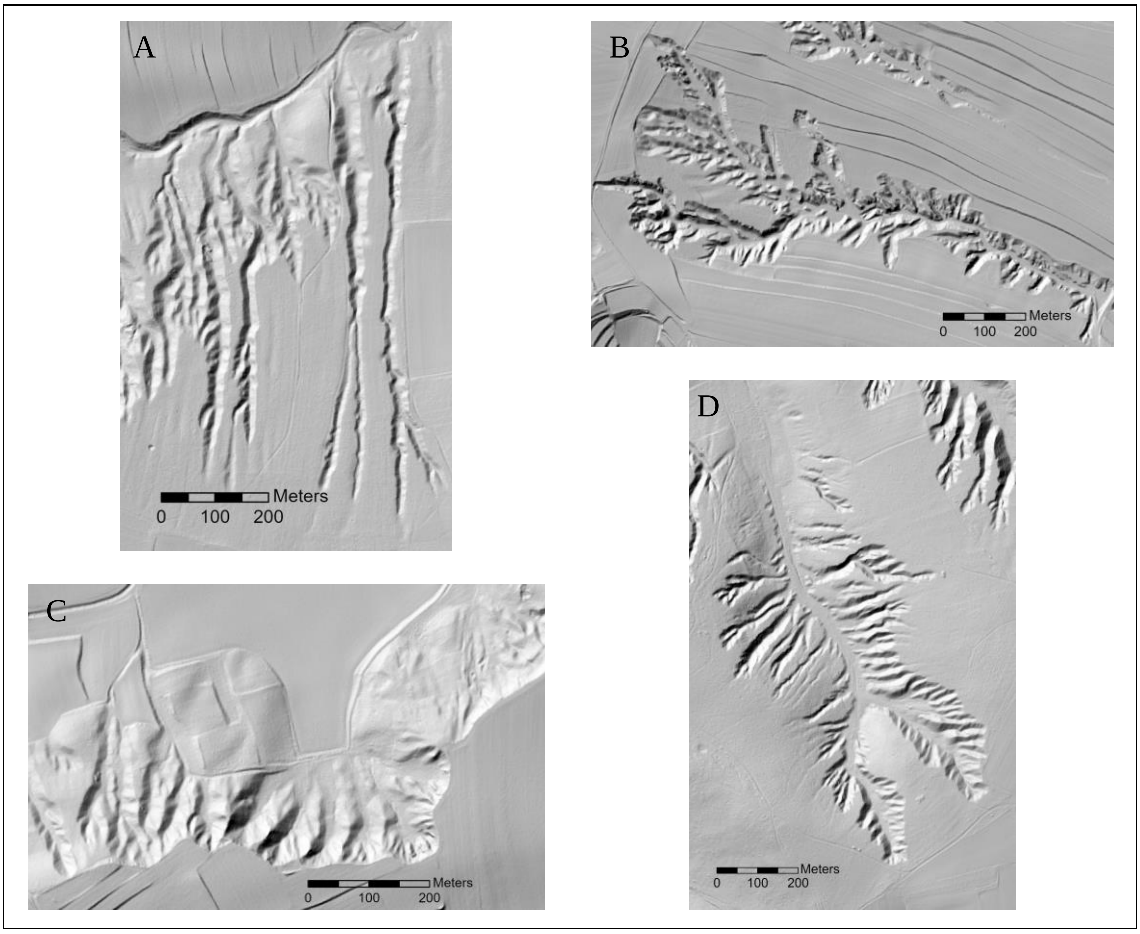

Fig. 4: Planform shapes of gully erosion: (A) Linear gully; (B) Dendritic gully; (C) Amphitheatre gully; (D) Continuous scarp-front gully (Source (DEM): Provincial Government of Lower Austria n.d.)

2.2.2 Influencing factors on gully formation

Just as soil erosion in general, the formation of gullies is influenced by different factors, with each factor contributing in different degrees.

With the exception of the polar climate zone, gully erosion has been recorded in all **climatic conditions** worldwide. Nevertheless, a prevalence can be observed in temperate climate zones, with Spain, the United States, Australia, China, Ethiopia, and South Africa being the leaders in the number of studies conducted (Castillo et al. 2016).

Precipitation events represent the most important climate factor triggering and influencing the formation of gully erosion. On a small timescale, rainfall can act as a trigger for gullying. Here the intensity and quantity are crucial as they affect the volume of surface runoff and the shear stress that is carried out by the flowing water. Looking at a larger timescale, the influence of rainfall is hard to predict. It may act as a conditioning factor since precipitation tends to determine soil moisture, which in turn has a great effect on the development of runoff and the resistance against erosion. The impact of snowmelt on gully erosion is still unclear; far too few studies have been devoted to this topic (Vanmaercke et al. 2021). Another important aspect, which so far has been accompanied by great uncertainty, is the impact of climate change on the development of gully erosion. Prospects predict that intensities of precipitation events will ascend in certain areas, which is why an intensification and spread of gully formation are expected, given that intense rainfalls strongly advance it (Vanmaercke et al. 2016; Kertész et al. 2011). Additionally, changes in rainfall may affect soil loss through gully erosion, especially if these changes occur in dry areas. If precipitation events increase in regions affected by gullying, there will also be more possibilities for soil to be lost, so the overall rate of soil loss will increase simultaneously (Li et al. 2016; Poesen et al. 2003).

The **properties of soil** and the **lithology** of an area also influence the formation of gully erosion. It is worth noting, however, that the role of soil properties has so far been insufficiently understood when it comes to the explanation of gully erosion patterns. What has been studied sufficiently, however, is that soil properties have a great influence on the hydrological functions of soils and that they also determine the resistance to concentrated runoff. Properties such as soil texture, organic content, infiltration capacity, bulk density, and underlying lithology condition gully erosion as they affect both the erodibility of soils and the hydrological functioning (Vanmaercke et al. 2021). In some cases, the forces of pressure and tension, such as those caused by tectonic events or freeze-thaw processes, can contribute to the formation of gullies. The resulting fractures are subsequently subject to weathering processes, which can also transform them into gullies (Barnes et al. 2016; Valentin et al. 2005). Sedimentary rocks, to be precise, are the ones most prone to gully erosion as they generally have a very low resistance to detachment. The sediment loess, deposited through aeolian processes, stands out from any other sedimentary rocks because it has a particularly high susceptibility to erosion. It possesses an extremely low resistance to detachment, a predisposition to collapse, and impermeable geological layers (Castillo et al. 2016).

Furthermore, the **topography** of an area impacts the formation of gullies as well. Within the topography, the steepness of a slope and the drainage area are the most relevant factors for gullying. When the surface runoff gets concentrated in channels, the drainage area and the steepness determine the velocity of the waterflow and, consequently, the entrainment of material (Xu et al. 2017). The curvature of a slope is also noteworthy as it is another topographic feature favouring gully incision. The curvature describes the change rate of a slope gradient in a designated direction: slopes can be concave (negative curvature), flat (zero curvature), or convex (positive curvature) (Nicu 2018). The development of gully erosion is reinforced on slopes with an irregular surface geometry, where slope steepness and curvature change abruptly. These areas of abrupt change enhance soil erodibility and concentrated water flow, which is why they are expected to be sources of sediment entrainment (Gómez-Gutiérrez et al. 2015).

The initiation of gully erosion in Europe can be traced back to prehistoric times, such as the Bronze Age, and the Middle Ages. With the transition of agriculture to an advanced level, extensive deforestations took place as woodlands were transformed into arable land or pasture. Today, parts of these prehistoric gullies can still be found in old forests. More large-dimensioned gullies imply that they were formed by the frequent use of unconsolidated pathways (Vanmaercke 2021; Valentin et al. 2005). These historical discoveries clearly indicate that **land use** by humans has had an extraordinary influence on the formation and further development of gully erosion. With every anthropogenic intervention into a landscape, the drainage area and infiltration capacity of soils is changed, which can reinforce gullying. Furthermore, perturbations caused by deforestation, grazing cattle, an increase in agriculture, wildfire, or the construction of infrastructure may reactivate or intensify gully erosion. Conversely, land abandonment can also lead to an increase in gully erosion. When land becomes infertile or shows any other properties that make it partly or entirely unsuitable for agriculture, it is often left fallow without protective vegetation. Since the important protection of plants is thus only sparsely available, the bare soil is exposed to rainfall, and the susceptibility to erosion processes increases significantly (Castillo et al. 2016; Dotterweich et al. 2012; Poesen et al. 2003).

As with any other soil erosion process, the vegetation cover plays a crucial role in protecting soils from gully initiation. Vegetated surfaces are highly resistant to gullying, provided that the vegetation covers most of the field, especially during periods of increased erosion, meaning in times of accumulated precipitation events. In addition, the plants must already be in an advanced stage of growth as only strong roots and abundant canopies act as valuable erosion protection. Any change in land use, followed by a degradation of the vegetation cover and decrease in erosion resistance (e.g., by tillage practices such as ploughing), increases the possibilities of gully development in concentrated flow zones (Vanmaercke et al. 2021; Poesen 2018; Poesen et al. 2003).

3. Research area

The research was conducted in the northern part of Lower Austria, in the regions Waldviertel (eastern part) and Weinviertel (whole region). The following boundaries were used to define the study area: in the north, the state border with the Czech Republic; in the east, the state border with Slovakia; in the south, the river Danube; and in the west, the administrative borders of the districts Horn and Krems-Land. In total, the research area covers around 7,055 km² (see Fig. 5) (Provincial Government of Lower Austria 2012).

The study area was chosen since the north-east of Austria is characterized by dry soils and climate, so soil erosion plays an important role (BAW 2020). Moreover, both regions are marked by intensive agricultural land use, where fields are mainly used for the cultivation of corn, potatoes, sugar beets, and rape, as well as for vineyards (Lamm 2010). Since many of these crop plants are commonly planted in rows, where the spaces between the seedbeds are left uncultivated, the respective fields are especially prone to erosion. Furthermore, the vegetation cover is extremely low during periods of sowing and early growth rates. This is also the time when intense rainfall is most frequent and thus drives up erosion rates (BAW 2020; Klik et al. 2010).

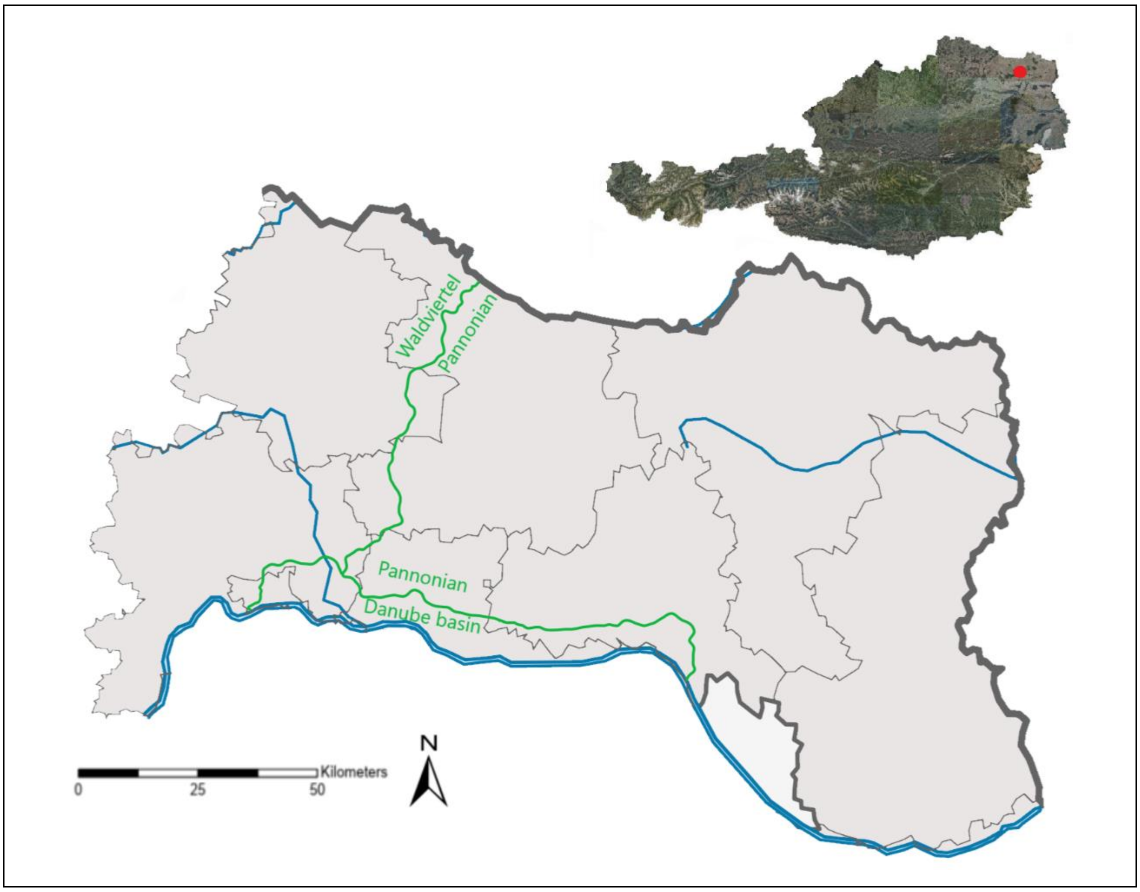

Fig. 5: Research area with climatic borders (Adapted from BMDW 2021)

3.1 Geology and soil types

The north of Austria is characterised by a low mountain range, shaped by plateaus and gentle hills. In the south of this region, basin landscapes and wide valleys can be found, interspersed by the Danube and its inflows. Due to the presence of soft and erosion-prone rocks, the shapes of the terrain are of a gentle character (Schuster et al. 2015).

The Waldviertel is part of the Bohemian Massif, characterized by slender, tessellated, cultivated landscapes. The massif is a pronounced low mountain landscape with a wavy upland, intersected gorge-like by the Danube and its tributaries. Granite and gneiss from the Moldanubic determine the geology of the Waldviertel. The further south, the more sedimentary and magmatic rocks are mixed in, and the flatter the landscape becomes (cf. Schuster et al. 2015; Hofmann 2003).

The Weinviertel is partly occupied by the molasse-belt. This zone is characterised by sedimentary deposits from the Late Palaeogene and Neogene. These can be marine deposits as well as freshwater deposits. Gravels, sands, and clays from different sedimentary environments (e.g., coasts, deltas, etc.) can be found in the molasse-belt.

The Vienna Basin is also part of the geological landscape of the Weinviertel. It belongs to the Inneralpine Basins, of which there are four in Austria. The Inneralpine Basins were formed from the Early Neogene onwards and consist of gravels, sands, and clays deposited by rivers and lakes. The Vienna Basin has a gentle and hilly terrain, characterised by soft and incompletely consolidated sediments (Wagreich et al. 2008). The majority of the Vienna Basin is covered by partially thick layers of loess, which can be dated back to the Ice Age. In a recently published research paper, Boemke et al. (2021) assume that the loess landscapes in Lower Austria are composed of loess-paleosol deposits up to 40 m thick. Due to these characteristics, the soils are fertile and supplied with sufficient water, which is why settlements and intensive agricultural use occurred early on (cf. Schuster et al. 2015).

Among others, four soil types characterise the studied area: chernozem, colluvium, cambisol, and humid black chernozem. These four soil types are characterised by the following properties:

- Chernozem: This type is a soil that was strongly shaped by the steppe climate during the Ice Age. It consists of thick humus horizons and constitutes one of the most fertile soils in Austria.
- Cambisol: Cambisol is the soil type that occurs most frequently in the temperate climate zones of Austria. Iron oxides that were formed through weathering

processes have coloured this soil brownish-red. Depending on the water conditions and nutrient content, cambisol can be valuable for agricultural purposes.

– Colluvium: Colluvium is a soil material that moves downslope due to gravitational forces and gets deposited there. It can be parent material for soil formation processes as well as overlaying existing soils.
– Humid black chernozem: This soil type usually has its origin in soils similar to those of peatlands. Due to changes in the phreatic level or draining by anthropogenic activities, the humid black chernozem develops. It is an extraordinarily fertile soil that mostly serves as arable land (NÖ Agrarsbezirksbehörde n.d.).

The parent material, in other words the material that has been eroded or transported and deposited by water or wind, is primarily loess, colluvial material, and fine sediments (see Fig. 6) (BFW 2007).

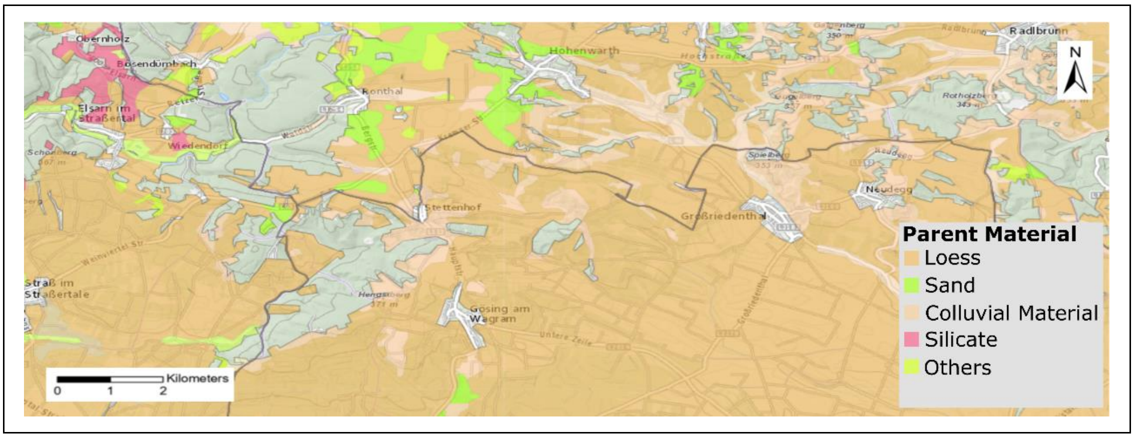

Fig. 6: Parent material of soils in an extract of the hot spot areas of gully occurrence (Source (Map): BFW 2007)

Loess plays an outstanding role with regard to soil erosion in Lower Austria. This aeolian sediment was deposited during cold periods and has formed loose and unconsolidated layers at the soil’s surface (Hofmann 2003; Rungaldier 1960). Loess consists of grain sizes between 0.02 and 0.05 mm, making it susceptible to soil erosion. Since there is relatively little clay in loess, it loses aggregate stability; therefore, the soils erode easily. A major reason for the fertility of loess is its exceptionally high pore volume. However, during heavy precipitation events, loess tends towards siltation (see Fig. 7). Because of the low aggregate stability, soil particles are separated from each other, washed into depressions, and wedged, resulting in an increase of runoff. Without an appropriate protective vegetation layer, loess soils experience extremely high runoff rates and thus severe amounts of soil loss (Wiesbauer et al. 2014).

Fig. 7: Siltation of loess after rainfall (Photo: Sarah Diem, 2021)

3.2 Climate

The study area can be divided into three climatic regions (see Fig. 5). The climatic region Waldviertel encompasses the Bohemian Massif in north-western Austria. The climate in this area is cool-temperate, and vegetation periods are therefore shorter than in other studied parts of Lower Austria. In winter, there can be frequent frost, and in summer, the nights are relatively chilly. Nevertheless, the influence of the Pannonian climate is already noticeable in the Waldviertel, which is why the annual precipitation is limited, despite thunderstorms and more intense rainfall events in summer. The average temperature amounts to 8.9 °C, and the annual precipitation lies around 676 mm (Provincial Government of Lower Austria 2017a).

A small part of the research area is covered by the climate region called Danube basin. It is influenced by the cool and humid weather conditions of the Atlantic, but simultaneously the Pannonian climate appears with a significant impact. Atlantic weather occasionally leads to floods, while the Pannonian climate ensures long dry periods and high day temperatures in summer. The average annual temperature is 11 °C, and the yearly average precipitation sum is 838 mm (Provincial Government of Lower Austria 2017b).

The largest part of the study area lies in the climatic region of Pannonia. The Pannonian-continental climate is characteristic here: the winters are dry and cold, and the summers are also dry but very warm. The region experiences very low precipitation: more than 250 days per year are without rainfall. The annual amount of precipitation takes up 639 mm, and the average temperature per year lies around 11.2 °C (Provincial Government of Lower Austria 2017c).

Climate change will have a great impact on all of the climate zones described above. The annual average temperature is expected to increase significantly. For the period 2021–2050, two scenarios have been calculated: RCP4.5 (climate protection scenario) assumes a temperature increase of 1.3 °C. RCP8.5 (business-as-usual scenario) predicts a temperature rise of 1.4 °C. Looking at a longer period (2071–2100), it is expected that the average temperature under RCP4.5 will increase by about 2.2 °C, whereas RCP8.5 suggests a rise of 3.9 °C (ZAMG et al. 2016).

The annual precipitation rate for Lower Austria is expected to increase only slightly in both scenarios. Whether there will be significant increases in a distant future cannot be said with certainty, as the models come with great fluctuations (ZAMG et al. 2016; Strauss et al. 2013). Regionally, a significant increase in precipitation events is expected for the Danube and Pannonian regions in the longer term, but these forecasts should be treated with caution due to strong ranges of variation (Provincial Government of Lower Austria 2017b, 2017c).

3.3 Land use and management

The northern part of Lower Austria looks back on a long history of settlement. The Waldviertel, for example, has been settled since the Ice Age. At that time, the loess steppe spread into eastern Austria, which led to an attraction of hunting cultures. In the Neolithic period (ca. 6^{th} century BC), the development of farming cultures began in the loess-covered lowlands (Vienna Basin/Weinviertel). This was also the time when clearing of forests began.

The north of Lower Austria experienced a period of prosperity from the High Middle Ages onwards. Deforestation was on the advance, fields were increasingly cultivated, and in both the Waldviertel and the Weinviertel, there were expansions of settlements due to viticulture. Until around 1600, viticulture led to an intensification of agriculture and an increase in population in both regions. After some crises in the 17th century, agriculture was further intensified (see Fig. 8), and from about 1740 onwards, the cultivation of potatoes and other crops was introduced (Krawarik 2006; ÖBIG 1985).

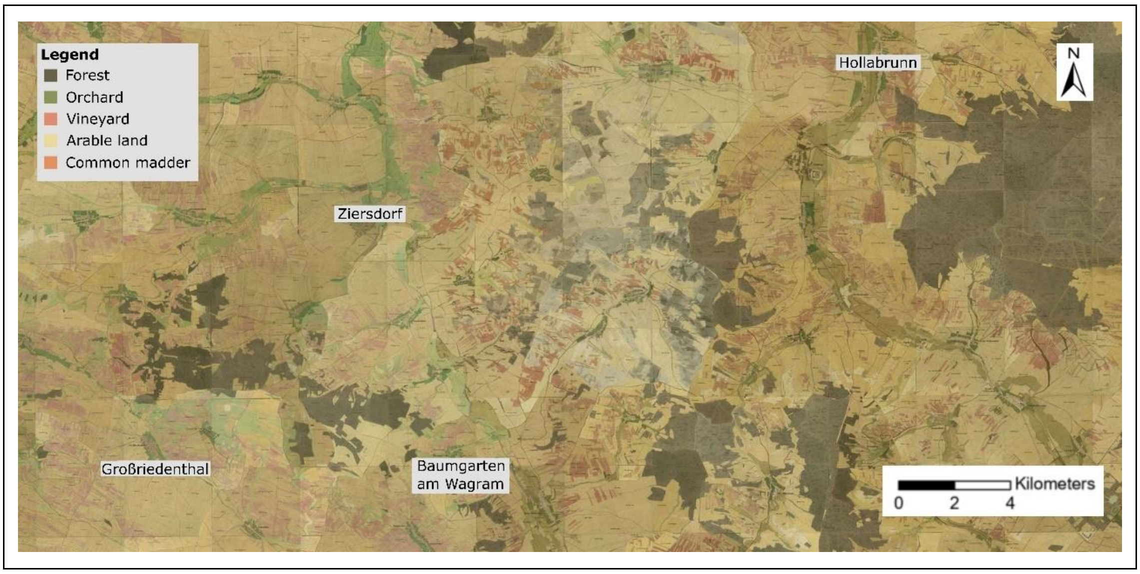

Fig. 8: Franziszeische cadastre 1823: extract from the research area
(Source (Map): Arcanum n.d.a)

Around 17 % of the Weinviertel (Weinviertel Tourismus n.d.) and 41.8 % of the Waldviertel are covered by forests (Regionalentwicklung Waldviertel n.d.). Due to clearing and monocultures, the condition of the forests was very poor, especially in the 1990s. Intensive agricultural use also made its contribution as fertilisers and pesticides affected the vegetation, particularly at the edges of the forests (Provincial Government of Lower Austria 1993).

One of the most important forests in Lower Austria, concurrently the largest closed mixed oak forest in Central Europe, is the Ernstbrunn Forest, which lies entirely in the Weinviertel and thus within the study area (TU Graz 2020). This forest was also heavily cleared. The wood was used for the construction of tools and buildings and, during the industrialisation, for charcoal. In addition, the Ernstbrunn Forest was used as pasture land and for agricultural purposes. The names of many places still indicate that cows, pigs, goats, and other livestock were kept in this area. Furthermore, young forest cuts were used for cultivation, for example, of potatoes. Along with other forests, the region around Ernsbrunn was included in several reforestation programs (Denner 2020).

49.7 % of the Waldviertel (Regionalentwicklung Waldviertel n.d.) and around 57 % of the Weinviertel are allocated to agricultural land (see Fig. 9) (BMLRT n.d.). Viticulture was the most important agricultural source in historic times. During the rule of the Romans, the wine culture was intensified and practised on a large scale. For this purpose, large areas and slopes were terraced; even exposed sites and less fertile land were used for vineyards. Already then, the winegrowers struggled with soil erosion, which is why catch basins were often built below the terraces to hold back the water and to capture the eroded soil (Wiesbauer et al. 2014).

Due to the great fertility of the soils, both regions are still used for intensive agriculture today. Nowadays, mainly different types of cereals, potatoes, sugar beet, pumpkins, and rape are cultivated. Extensive vineyards have remained to this day (Lamm 2010).

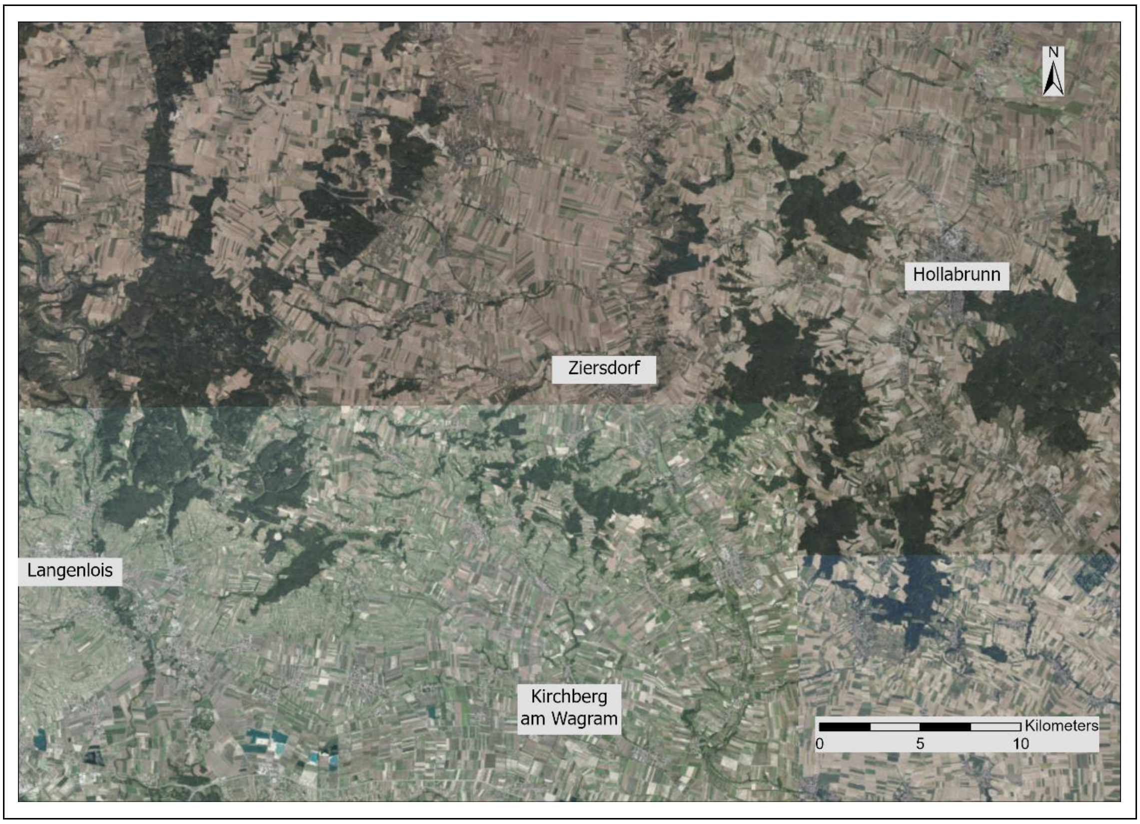

Fig. 9: Land cover in an extract of the research area (Source (Orthophoto): BMDW 2021)

3.4 Gully formation in Lower Austria

Investigations into the millennium catastrophe of 1342, the so-called St. Mary Magdalene’s Flood, provide one of the first indications of a possible origin of gully erosion in Austria. The 1340s were characterised by a particularly strong climatic instability as it was the seventh-coldest decade of the last 2,500 years. In 1342 and 1343, particular peaks of this exceptional period occurred, when there was a two-year flood disaster that reached levels unparalleled to this day and caused severe destruction (Bauch 2019). Large parts of Central Europe, including Austria, were affected by the floods (Bauch 2014). In those days, a wet spring was followed by a heat wave in early July, which caused the soils to strongly dry out. When heavy rainfall events occurred towards the end of July, infiltration was hardly possible, which is why there was inconceivable surface runoff (Lingenhöhl 2013). As the forest cover was particularly low during the Middle Ages and intensive land use prevailed, a large proportion of fertile land was lost due to the floods and had to be abandoned as a result (Schreg 2021; Bauch 2014). According to various calculations, around 13 billion tonnes of soil were lost as a consequence of the St. Mary Magdalene's Flood (Lingenhöhl 2013).

It can still be proven today that this soil loss was caused mainly by sheet erosion and linear soil erosion. As there was no protective vegetation in most locations, a so-called *Schluchtenreißen* occurred. Due to the heavy precipitation, linear water runoff deepened already existing notches and depressions, whereupon gullies evolved that were up to 14 m deep. Gully erosion was not limited to agriculturally used areas but affected forested areas to the same extent. While some studies indicate that some of these gullies collapsed in the following years due to further precipitation events and were therefore filled up with material, other sources assume that many of these prehistoric gullies still characterise our landscapes today (Zbinden 2011).

In 1982, Krissl published one of the first and few articles about an accelerated development of gully erosion in the loess areas of Lower Austria, indicating that a total of three centres can be identified where gullying occurs. These centres were located south-east of Langenlois, north-east of Gänserndorf, and in the Pulkau valley, all based in the north of Lower Austria. All three areas are part of the Pannonian climate region and have a high proportion of loess-covered soils. At that time, the areas were mainly used for viticulture, and the tree population was indicated as very low to non-existent. The author assumed that the cause of the strong development of gully erosion was an innovation in the wine culture. It was a time when a larger distance between the rows of vine plants was emphasised so that fungal diseases and other pest infestations could be avoided. Because of this, more bare soil was exposed to rainfall, which increased the susceptibility to erosion. Increasingly, new cultivation methods, especially mechanical ones, were also used, so the soil got more consolidated. A third aspect advancing the development of gully erosion was identified in the construction of pathways, which led to a decline in the soil infiltration capacity (Krissl 1982).

Research on different types of gully erosion in Lower Austria is very limited. Mostly, the literature only includes marginal notes on general gully erosion. Only the formation and usage of sunken lanes has been studied more extensively.

In 1995, a survey on the prevalence of sunken lanes in Lower Austria was carried out – 950 sunken lanes were registered at that time. 90 % of these sunken lanes were located in the loess areas of Lower Austria north of the Danube. The strongest accumulations were found in the regions around the Danube terrace Wagram (Museum Niederösterreich 2017b).

One of the first mentions of sunken lanes, back in 1853, comes from Johann Cžižek, who created a geological map of the Weinviertel. In the attached description of the map, he remarks on a thick loess cover in which channels can be discovered, some of which even turn into ravines and are more than 50 feet deep. Rainfalls were supposed to be the cause of these channels (Wiesbauer 2020).

The formation of sunken lanes in the study area can generally be attributed to anthropogenic influences. The loess soils in Lower Austria were cultivated early on, so soil cultivation and the creation of pathways were not unusual. Especially the unpaved roads in the past made a major contribution to the formation of sunken lanes. They were regularly loosened by human and animal use. Rainfall subsequently washed out the loose material and thus led to a deepening of the paths. Today, especially pronounced sunken lanes have side walls that are up to 15 m high (Wiesbauer 2014).

4. Data and methods

4.1 Digital Elevation Model (DEM)

To enable the search and mapping of gully erosion in northern Lower Austria, and to answer the research questions of this thesis, a Digital Elevation Model (DEM) was used as data basis. The DEM is based on aerial laser scanning data and comes with a resolution of 1 x 1 m. The aerial photographs were taken between 2011/12 (small parts in the south of the Weinviertel) and 2020. The majority of the data was gathered between 2018 and 2020. The DEM was provided by the General Building Services Department of the Provincial Government of Lower Austria.

Airborne DEMs are considered especially useful for assessing gully erosion as they provide a high spatial resolution and very high accuracies. They are also particularly well-suited for geomorphological and hydrological analyses of the landscape. In recent years, high-resolution DEMs have increasingly been used for analysing the properties of gully erosion. Combining DEMs with classification procedures comes with the benefits of increased automatization, high accuracy, and efficiency. Working with high-resolution DEMs allows for detailed analysis, for example, of gully locations and areal density of erosion processes (Vanmaercke et al. 2021).

- **Preparation of DEM**

Before the DEM could be inserted into ArcGIS (version 2.7), two fundamental steps had to be carried out: firstly, restrict the DEM to the research area; secondly, georeferencing. Since the DEM was delivered without a description of the projection, it was automatically assigned to the geographic zero point, which is why all the data was situated around the Gulf of Guinea, west of Africa. To enable a data readout for the study area, the coordinates (unknown projection) had to be assigned to a point in the coordinate system 'MGI (Ferro) Austria GK East'. To render this possible, the coordinates of the study area were determined, converted to the projection of the dataset, and a Python code was written that automatically selected the correct tiles. The code (see appendix) accessed the boundary information of each item of raster data and created a new dataset containing only the DEM for the selected study area. With this selection, a new dataset, scaled down by 62 %, was generated and introduced to the GIS programme, which significantly increased the computer performance.

After this step, the selected data was combined into a mosaic to enable the subsequent actions. Next, the mosaic was mapped into a projection so that the DEM matched the other maps used in parallel during the search and analysis of gully erosion. As the raster data with the coordinate system 'WGS 1984' specified by ArcGIS was located in France and not in Austria, the projection 'MGI (Ferro) Austria GK East' had to be used. This was the only projection that matched all the other coordinate systems underlying other maps needed for the study. Initially, problems arose during the georeferencing because the DEM consisted of grid-files, and the system required these to be converted into tiff-files to allow for the projection to be defined. In order to visualize the topography and to enable the mapping, the DEM was then converted into a hillshade.

4.2 Mapping of gully erosion

The aim of this study was to find and map various gully erosion types in the defined study area. However, the underlying DEM did not provide a spatio-temporal resolution high enough to enable a detection of ephemeral gullies. Due to their smaller size, width, and depth, ephemeral gullies are not as distinctive as permanent gullies, which makes searching them in a DEM very difficult to nearly impossible. Additionally, as they tend to be filled only shortly after evolving, the recording of ephemeral gullies in a DEM is highly improbable.

Similarly, the identification of bank gullies also turned out to be too difficult. The difference between agricultural terraces, river terraces, and actual bank gullies was not clearly identifiable in the DEM. Especially in the regions where viticulture dominates the landscape, there is a constant drop in the terrain due to terracing. Based solely on the DEM, it is therefore not possible to presume with certainty whether a bank gully may have developed, or whether it is indeed only a construction measure. In order to eliminate this uncertainty, a field inspection would have been necessary to correctly determine possible bank gullies. However, due to the size of the research area and the requirements of this thesis, this was not possible, which is why the search for bank gullies had to be relinquished.

The results therefore focus only on permanent gullies and sunken lanes. These two erosion types were clearly recognisable in the DEM, as well as distinguishable from each other.

- **Hillshade and mensuration tools**

The hillshade created from the DEM served as basis for searching and mapping gully erosion in the study area. To organise this process, a grid was laid over the area, and, starting from the west, each column was searched manually from south to north for erosion phenomena. The grid size was determined at 2 x 2 km as this size allowed for a quick scanning of the area, and the resolution was still high enough to show different gully erosion types. For the mapping, it was possible to zoom in so that the extent of the gully was measured as accurately as possible.

The ArcGIS 'Image Mensuration' tool was used for the mapping of the erosion phenomena. With this tool, distances, heights, and areas of 2-dimensional and 3-dimensional surfaces can be calculated. The different measurement types are automatically saved in the project as a feature class. For gully mapping the measurement type 'Distance' was used because it makes it possible to map the erosion according to their shape. The distance line does not have to be drawn from gully head to drainage area at once but can also be dropped in between – all according to the shape of the measured object. The programme then calculates the length for each individual section, but at the same time it also calculates the total length of the marked gully erosion. Every distance measurement can be assigned an individual designation before it is saved as a polygon feature class within the project. Each time the dataset is opened, the measurements are displayed in a separate table. This table contains information about the name, measurement type, time of the measurement, length/height/area that was calculated, and the coordinates. If desired, a short description can also be added (Esri n.d.a).

- **Orthophotos and eBOD**

The project in ArcGIS was additionally underlaid with orthophotos that covered the entire research area. The orthophotos were obtained from the website data.gv.at, provided by the Federal Ministry for Digital and Economic Affairs (BMDW 2021), and inserted into ArcGIS via a WMTS server connection. This meant that the dataset did not have to be downloaded separately as ArcGIS could always access the orthophotos via the link. The regions were surveyed in 2018 and 2020. Between Krems an der Donau and Tulln an der Donau, the orthophotos were compiled in 2020; the remaining areas were surveyed in 2018.

The orthophotos were particularly important for the additional validation of the erosion types found. If any gully erosion was discovered in the DEM, it was possible to use the orthophotos to control whether the object found could indeed be an erosion phenomenon. In addition, permanent gullies could be clearly distinguished from sunken lanes with the help of these photos. Especially the sunken lanes that can still be walked on today were clearly visible on the orthophotos, which made the mapping verifiable.

For further clarifications, the digital soil map of Austria (eBOD) was also used in parallel with the mapping. This map provides information on the properties of agriculturally used and other mapped soils. The following information was of particular interest for this research:

- water conditions (very dry – wet)
- permeability (very low – very high)
- soil types (chernozem, cambisol, etc.)
- parent material (alluvial material, loess, etc.) (BFW 2007).

- **Statistics**

Besides the mapping in ArcGIS, an Excel file was created. Each gully erosion that was found was entered into this file, with information about its length, location (coordinates), and the associated district. Furthermore, a distinction between permanent gullies and sunken lanes was made in this file. With this Excel sheet, a statistical analysis of the number of erosion types that were found could be created at the end. Likewise, statistics on the distribution of gully erosion per district could be carried out (see appendix).

4.3 Hotspot map

To completely answer the first research question, which focuses on the distribution and clusters of gully erosion in northern Lower Austria, a hotspot map was created out of the previously rendered mapping. A Heat Map as well as a Kernel Density were initially considered to create such a hotspot map. The creation of both a Heat Map and a Kernel Density requires feature classes as input. Although the gullies were mapped with the Distance Mensuration Tool, which automatically creates a polygon feature class, the classes were not accepted by either of the hotspot map creators, which require point features. Therefore, the entire mapping had to be converted. First, the whole Image Mensuration had to be selected and exported under the command “Feature to Feature Class”. Next, the programme created new line features, which then had to be converted into point features (“Generate Point Along Lines”) (Esri n.d.b; Esri n.d.c).

- **Heat Map**

A Heat Map was created, but it was not suitable for the representation of gully erosion clusters. The Heat Map in ArcGIS is used to display point features in juxtaposition, not easily differentiable and overlapping. However, the result showed that the mapped gullies have a point density far too low for such a heat map, and that there is no overlap in the whole study area. Therefore, the hotspot areas were categorized in areas too large to really represent a hotspot, and they were even illustrated in some locations where no real accumulation could be detected (Esri n.d.b).

- **Kernel Density**

To circumvent this problem, the Kernel Density was selected to create the hotspot map. The Kernel Density requires point or polyline features as input dataset, which is why the previously created point data was ideally suited. With the Kernel Density, a radius can be set automatically or manually, within which the features are counted. The more features lie within a radius, the denser the representation. 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.c).
For the creation of such a map, the density of point features is calculated as follows (cf. Esri n.d.c):

$$Density = \frac{1}{(radius)^2} \sum_{i=1}^{n} \left[\frac{3}{\pi} \cdot \left(1 - \left(\frac{dist_i}{radius} \right)^2 \right)^2 \right] \quad with\ dist_i < radius$$

$i = 1,\ldots,n$ … input points

$dist_i$ = distance between point i and the (x,y) location

The formula is applied to the entire area where the Kernel Density calculation is desired, in this specific case in the whole study area. For this purpose, a grid is constructed, and the calculations according to the formula are applied in the centre of each of these grid cells. The input points are only included in the sum if they lie within the radius distance of the location (Esri n.d.c).

As this particular example shows, another surveying tool would probably be better suited for mapping the gullies since the Distance Mensuration Tool does not allow for a

differentiation by erosion type. Nonetheless, it was possible to code the point features, rendered as input layer for the Kernel Density, after their creation and thus distinguish permanent gullies from sunken lanes. Since permanent gullies and sunken lanes had already been separated from each other in the statistical survey carried out in Excel, it was possible to use this information to also code the phenomena in ArcGIS (code: “1” permanent gully, “2” sunken lane). After the complete coding of the mapped erosions in the attribute table, two separate layers were created for each category. The layers could then be displayed simultaneously or separately from each other, and they likewise allowed for different colouring so that the two gully types became distinguishable.
Based on the newly generated layers, it was possible to create a Kernel Density for all permanent gullies, as well as one for the sunken lanes, whereby the respective hotspot areas became clearly visible.

4.4 Geomorphometric analysis

Before the creation of catchment areas in which all the erosion located therein was measured, exemplary locations were selected between Langenlois and the Ernstbrunn Forest. With the intention to capture as many characteristics and appearances of gully erosion and sunken lanes as possible, the selection of the specimens focused on a wide range of different forms of the phenomenon. Five permanent gullies or sunken lanes were selected for each location, whereby care was taken to ensure that they differed as much as possible in their geomorphological characteristics. This first analysis aimed to show the diversity of gully erosion in the study area, especially within a single type. As with the geomorphometric analysis in the catchments, the focus was put on the length, width, depth and discharge volume of each gully erosion.

The creation of catchment areas and the precise measurement of the gullies in them served to answer the third research question. This issue focuses on the average volume of sediment loss due to the erosion. Since the study area is very large, and a high number of gullies were mapped, especially in the hotspot areas, it was not possible to calculate the soil loss rate for all of them. Therefore, the focus was placed on only a few catchments so that an overview of the erosion events, their forms, characteristics, and losses of material could be gained. The restriction accordingly allowed for a detailed investigation of each occurring phenomenon.

- **Catchment areas**

Within the regions where clusters of erosion occurred according to the Kernel Density, streams were searched into which a large number of gullies drained. For the three catchment areas, the streams Ebersbrunner Bach, Rabischwasser/Krampugraben, and Baritz were selected due to the large number of different gully erosion forms in their vicinity, which proved to be particularly representative and suitable for a more detailed analysis.

Like the previous methodological steps, the creation of the catchment areas was performed in ArcGIS, more precisely with the watershed function.

- **Calculations**

Once the three catchments were created, all permanent gullies and sunken lanes within them were calculated according to their length, width, depth, and volume (see Fig. 10). The calculations of these geomorphological properties of the gully erosion could be carried out with the Mensuration Tool, which has already been briefly described in chapter 4.2.

- Distance calculation: The Distance calculation tool was used for measuring the length and the width of the gullies. As with the mapping of the gullies, the erosion in the catchments was measured from the gully headcut to the drainage area. The survey was repeated for organisational reasons, on the one hand, and for accuracy on the other. In order to obtain the total length, the permanent gullies and sunken lanes were traced according to their form, whereby the GIS programme automatically carried out and saved the calculations (Esri n.d.a).

  The same tool was applied to calculate the width, which was measured at the point where the cross-sectional shape was the largest.
- Point calculation: The 3D point tool was used to measure the depth of the gully erosion. Although there exists a tool designed specifically for depth measurement, it could not be used with the underlying dataset. The 3D point tool has the additional function of indicating the location along the elevation (Esri n.d.a). Thus, to measure the depth of the gullies, two points were set, one in the erosion itself, one outside of it, and the calculated Z-values were subtracted to get the height difference.
- Volume calculation: Also included in the Mensuration Catalogue is a tool that calculates the volumes of objects. It calculates the cut and fill volume of an object

and generates the total volume. The calculations are based on an elevation dataset (Esri n.d.a). In order to calculate the cut and fill volume of the gullies, the line was drawn around the erosion phenomena, whereby the shape had to be traced as accurately as possible for an exact calculation.

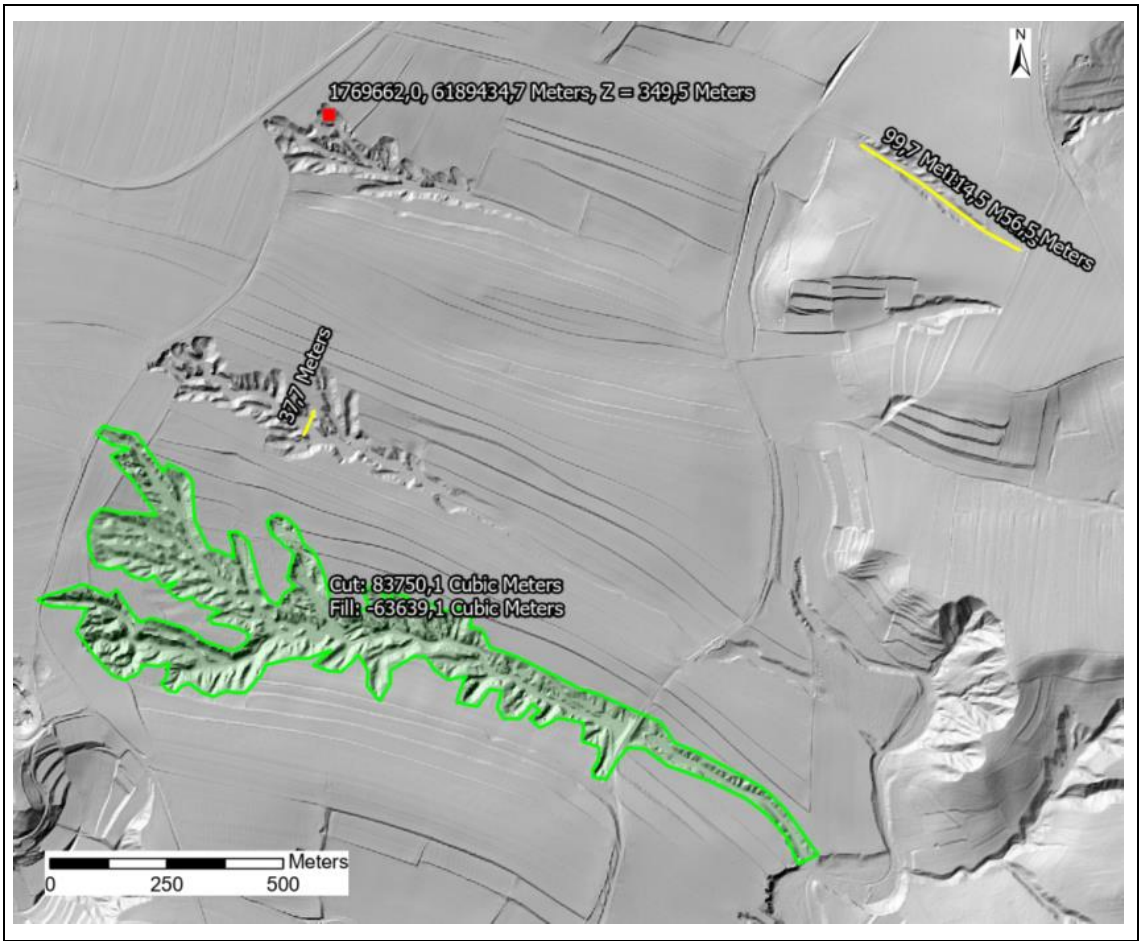

Fig. 10: Calculation methods: Length and width (yellow), depth (red), volume (green) (Source (DEM): Provincial Government of Lower Austria n.d.)

5. Results

5.1 Analysis of gully occurrence

As a result of the mapping, a total of 2,065 permanent gullies and 289 sunken lanes were found in the research area. Permanent gully erosion occurs more frequently in the south of the study area, with clusters extending from Gösing am Wagram to the eastern ends of the Ernstbrunn Forest, Enzersdorf im Thale, and Porrau (see Fig. 11).

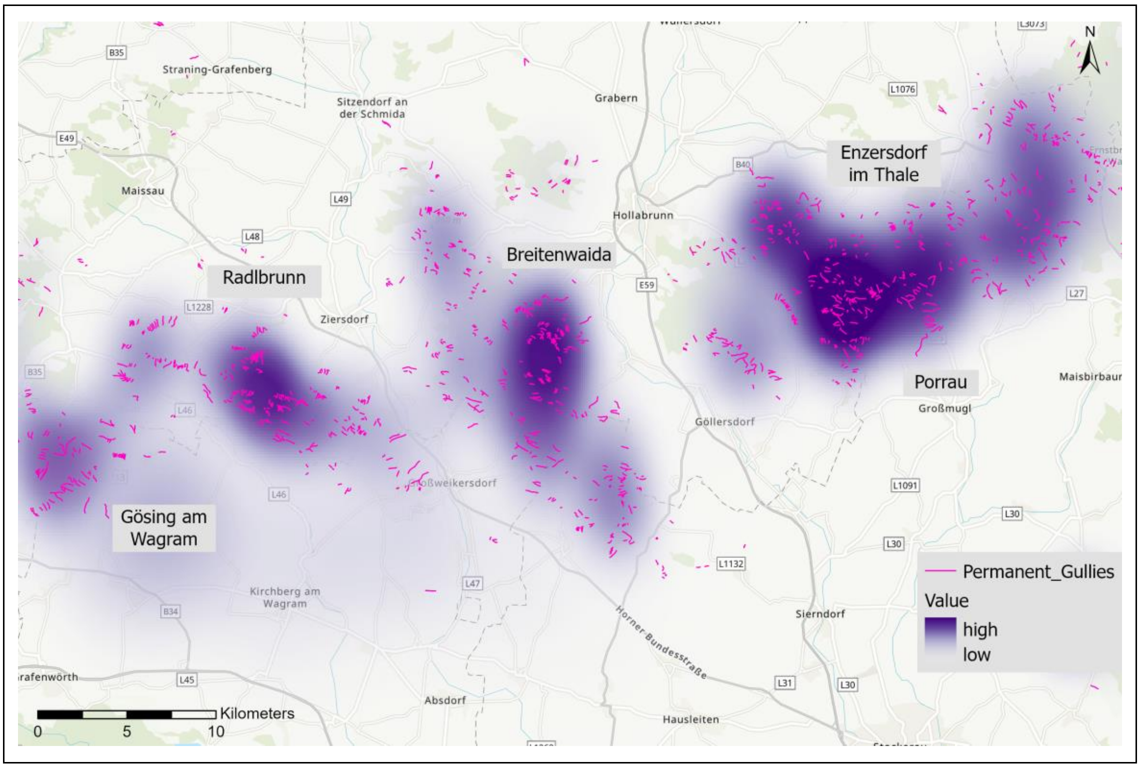

Fig. 11: Hotspot map of permanent gully erosion in the study area

(Source (Map): Esri 2021)

Depending on the colour strength, the hotspots differ in terms of the number of permanent gullies that can be found in them. The values therefore refer to the calculations of the Kernel Density; the higher the density, the darker the colour depicted on the map.

Since fewer sunken lanes than permanent gullies could be mapped overall, there are only two hotspots detectable for this gully type. The cluster in Langenlois has a significantly denser distribution of sunken lanes than the one in Fels am Wagram (see Fig. 12).

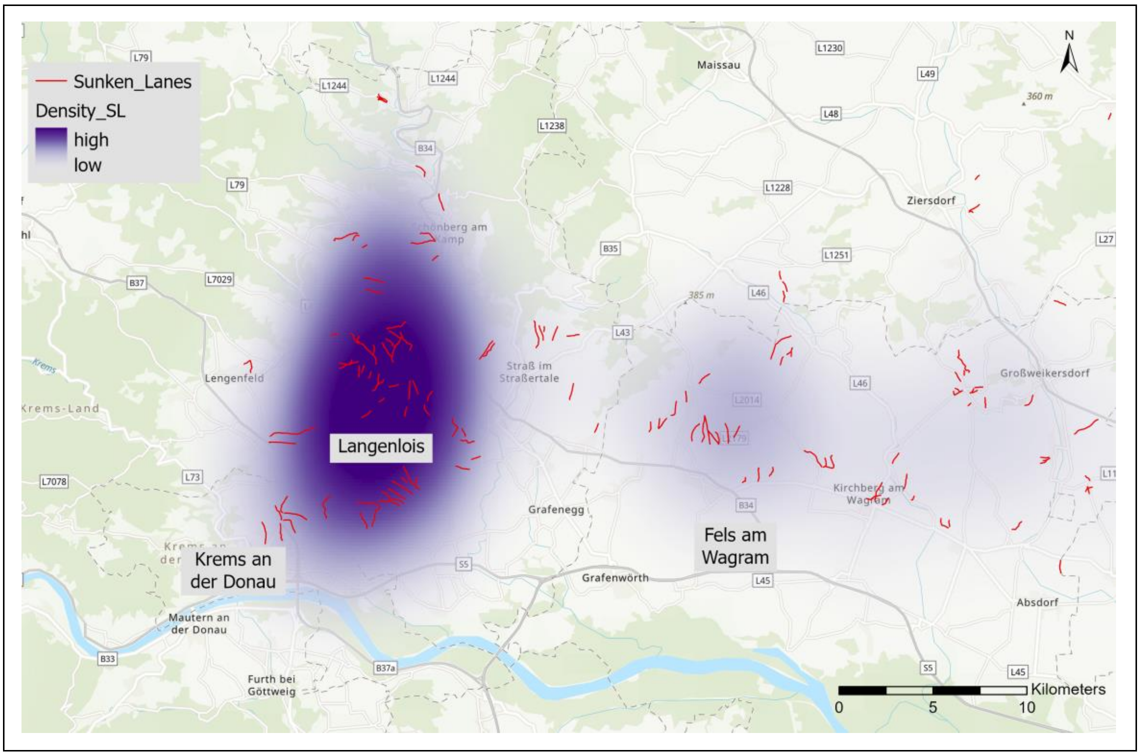

Fig. 12: Hotspot map of sunken lanes in the study area (Source (Map): Esri 2021)

Even though in several regions both gully types occur side by side, the hotspots are clearly separable. In the core of the Langenlois cluster, for example, solely sunken lanes exist, while permanent gullies are only found occasionally in the northern peripheral areas of the hotspot.

Small parts of the western areas that are considered hotspots of both gully types belong to the Danube basin in terms of climate, but most of them belong to the Pannonian climate region. This means that precipitation is rather rare, although heavy rainfall events and thunderstorms can occur. Summers and winters are particularly dry, with many hours of sunshine (Provincial Government of Lower Austria 2017b,c). Due to the high number of sunny days, intensive agricultural use takes place, which, in addition to the climatic conditions, is also linked to the remarkably fertile soils (BAW 2020). The parent material of most soils in the hotspot regions consists of erodible materials; most areas belong to the Lower Austrian loess regions (BFW 2007). Starting from the western part of the hotspot area, a loess thickness of at least 8 m can be found around the city of Krems an der Donau (Meyer-Heintze et al. 2018). Further northeast towards Langenlois and beyond, the loess covers increase strongly in thickness, with up to 20 m located in these regions (Thiel et al. 2011). East of Langenlois, near Hadersdorf-Kammern, the thickness is indicated as up to 13 m (Haesaerts et al. 2016), a thickness that is more or less maintained until Mitterstockstall, where an average of around 10 m of loess cover was detected (Piffl 1951). In the Marchfeld, the most south-eastern part of the study area and thus no longer a hotspot of gully erosion, the loess cover considerably loses volume as it only reaches 2 m of thickness (Brandtner 1954).

5.1.1 Permanent gully clusters

Permanent gullies are the dominant erosion type in the studied areas. They occur both in agricultural fields and in forests. Especially in the Ernstbrunn Forest, a large cluster of permanent gully erosion has been detected.

- **Topography and soil characteristics**

The hotspots of permanent gullies are located in regions with a slope steepness between 2 % and over 50 % (see Fig. 13). While the clusters in the west, around the Wagram, tend to occur in flatter areas, the slope steepness increases significantly towards the east, where gully accumulations are found in regions with an average slope steepness of over 10 %. Around the permanent gullies themselves, however, the slopes are significantly higher than only 2 %. Even in the flat western parts, gullies emerge on slopes characterised by an inclination of at least 10–15 %. The Ernstbrunn Forest exhibits the steepest slopes, where values between 30 % and >50 % are not uncommon.

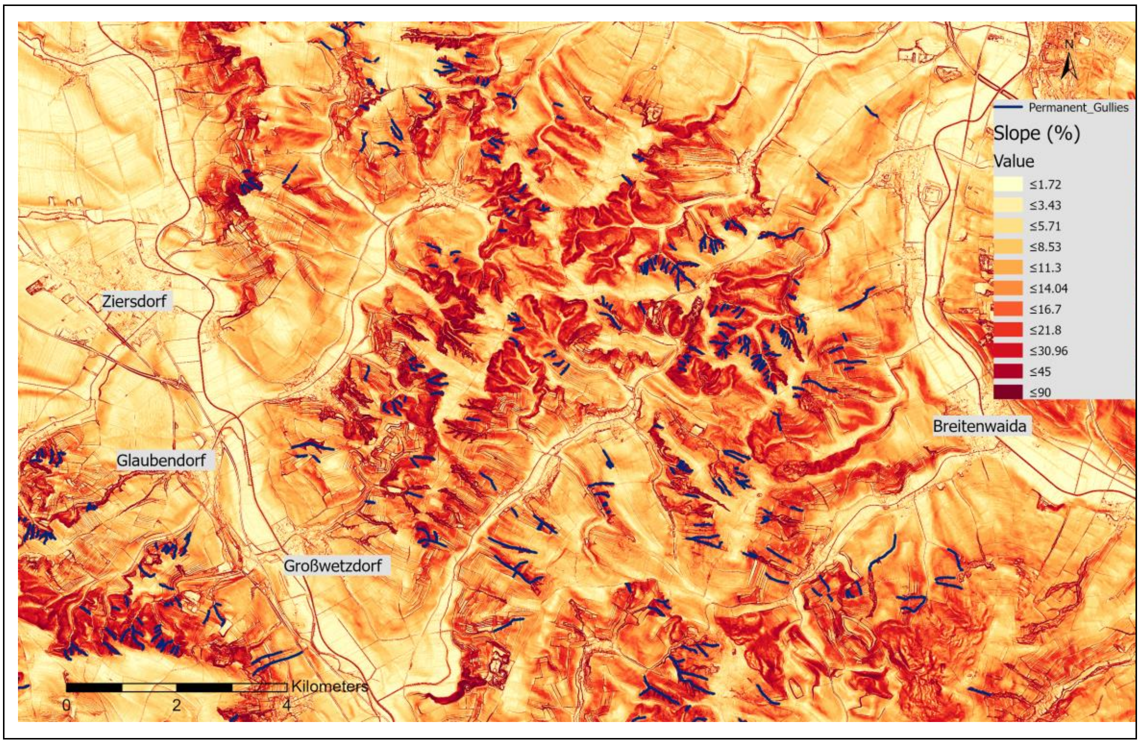

Fig. 13: Slope steepness in an extract of the hotspot area of permanent gullies
(Source (DEM): Provincial Government of Lower Austria n.d.)

The majority of the hotspot area is occupied by the soil types chernozem, cambisol, and rigol soil (Fig. *14* Fig. 14). The first two clearly dominate in the western part of the regions with gully accumulation, while rigol soil is more widespread in the eastern part of the clusters. Chernozem and cambisol, both highly fertile soils, represent a significant basis for agriculture, which is an important economic sector in the study area.

Moreover, the analysis of the parent material reveals why the hotspots of permanent gullies are located in the loess region of Lower Austria – loess is by far the most abundant parent material to be found. In addition, alluvial material is also present in larger quantities; colluvial material, tertiary sediments, and fine sediments exist as well, but to a smaller extent (BFW 2007).

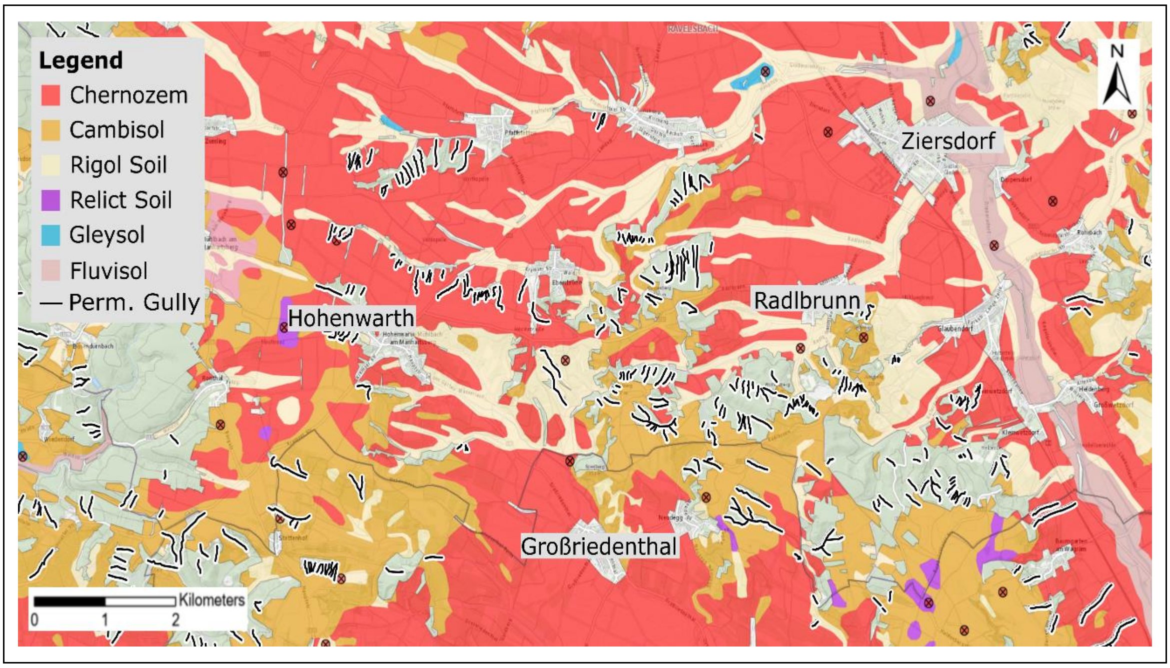

Fig. 14: Predominant soil types in an extract of the hotspot areas of permanent gullies (Source: BFW 2007)

According to the digital soil map of Austria, the soils in which clusters of gullies occur tend to be located in fairly dry zones. The most humid area is in the west, near Gösing am Wagram, where the soils are described as moderately dry to well-supplied. The further east, however, the drier the soils become – at the easternmost hotspot in the Ernstbrunn Forest, the soils are marked on the scale as dry to very dry. The areas between these two marginal points are on average in the range of moderately dry to dry.

Almost the same trend applies to the water permeability of the soils. The soils in the eastern hotspots have very low water permeability, while the central and western clusters are located within soils of moderate porosity. At Radlbrunn, in several places even a high water permeability can be found (BFW 2007).

The information on water conditions indicates how well the water supply of each individual soil functions. As the hotspot areas are predominantly in the range of very dry to moderately dry, precipitation plays an important role in supplying the plants with water. Crops that are accustomed to these arid circumstances are favourable plants to be grown on the cultivated land in these regions. The permeability of the soils in the hotspots is indicated, on average, as moderate, which means that water storage capacity is at least partially available (BFW n.d.).

- **Land use**

From the beginning to the middle of the 19th century, a cadastral system for land tax collection – the Franziszeische cadastre – was commissioned. However, since not only the utilised land but also the unproductive land was included, the generated cadastre served for land tax inquiries as well as for state planning and administration. The Franiszeische cadastre is based on a detailed survey and contains information on property boundaries, property numbers, land use, topographical names, place names, and other land-related information (Fuhrmann 2007). The research area was surveyed during the years 1821 to 1823 (Arcanum n.d.a)

According to this cadastre (see Fig. 15), orchards were planted, fields cultivated, and vineyards maintained in today’s hotspot areas of permanent gully erosion between the localities Gösing am Wagram and Radlbrunn. The Ernstbrunn Forest, meanwhile, was marked as a forest area already at that time. The cadastre characterises this forest as broadleaf forest; only very small parts of the region are attributed to a mixed forest.

Fig. 15: Franziszeische cadastre (1823) between the hotspots of permanent gullies Gösing am Wagram and Großriedenthal (Source (Map): Arcanum n.d.a)

Even in 1823, the agricultural use of the soils in the study area played an outstanding role. All fields around the Ernstbrunn Forest were also cultivated whereas vineyards became scarce there as they were only maintained in the south (Arcanum n.d.a). As a matter of fact, the forest area was used not only for its timber resources but, as the designations on the map suggest, also for agricultural purposes. Names such as 'sheep pasture' *(Schafweide)*, 'cow mountain' *(Kühberg)*, and 'sow yard' *(Saugarten)* expose that various types of livestock were probably kept here (Denner 2020; Arcanum n.d.b).

However, the Ernstbrunn Forest seems to have been important for the local population even before the 19th century. As investigations in this area show, there was a large spread of settlements in the Ernstbrunn Forest during the Middle Ages. Where there is continuous forestland today, it is assumed that fields were laid out, settlements were built, and vineyards were cultivated in earlier times. It is noteworthy that the medieval villages had a comprehensive flood protection system installed. The settlements were surrounded by drainage systems that were supposed to divert the flowing water during heavy rains so that the houses were protected from being flooded (Bidner n.d.a). As reconstructions suggest, the fields were laid out near streams, and there were also settlements dedicated to viticulture and cattle breeding (Bidner n.d.b).

Between the 13th and 15th century, the villages became increasingly desolated, after which the established fields and vineyard terraces were abandoned. Today, the remains of the villages are only visible on a DEM (see Fig. 16) as they sank deeper into the ground over time (Der Standard 2017). The structures of these settlements are also clearly visible on the DEM on which this work is based.

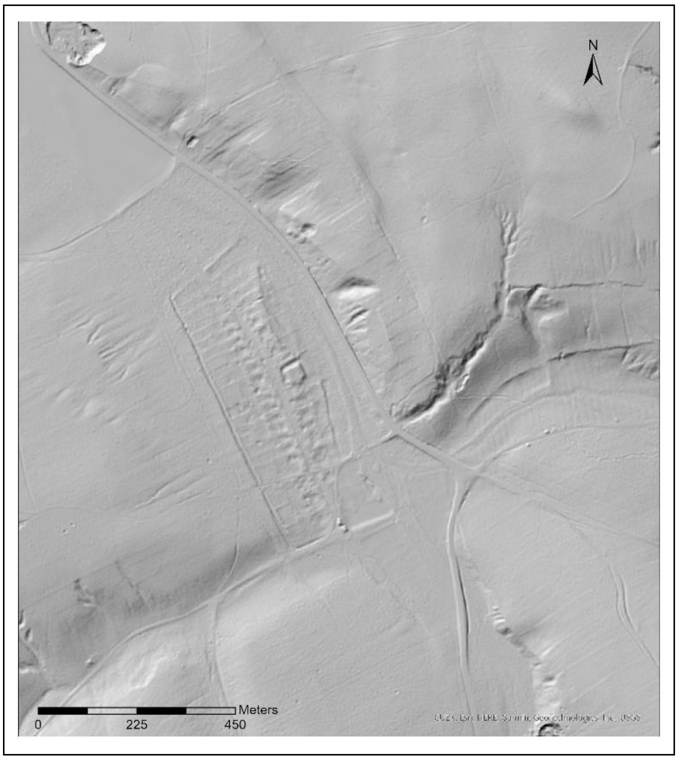

Fig. 16: Sunken medieval villages near Enzersdorf im Thale in the Ernstbrunn Forest (Source (DEM): Provincial Government of Lower Austria)

In the decades from the mid-19th century onwards, the regions around the hotspot areas were further characterised by agricultural use. Viticulture continued to play a particularly important role. In addition to wine, various types of cereals were cultivated, and in the early 20th century there was an increased focus on the cultivation of vegetables and especially sugar beets (Langthaler 2012). With the introduction of the potato and other crops whose cultivation increases the susceptibility of soils to erosion, many areas experienced increased surface runoff as a result of precipitation events and thus an aggravation of soil loss (Jungwirth 2014).

Today, the hotspot areas are still characterised by intensive agricultural use. As in the past, the fields are cultivated primarily with cereals, potatoes, sugar beets, and other vegetables. In between, especially in the west, near Gösing am Wagram and Radlbrunn, there are vineyards predominantly cultivated on terraces (Provincial Government of Lower Austria n.d.).

- **Usage of permanent gullies**

It is evident from the orthophotos that permanent gullies leave scars in the landscape, further affecting land use. Wherever a permanent gully is located within an agricultural field, that part of the field is left fallow and is no longer used for cultivation. In most cases they are covered with vegetation, with smaller trees and shrubs growing up the walls. In forested areas, the gullies are sometimes even more prominent as they cut a swathe through the otherwise continuous vegetation cover. Whether these gullies are also covered by vegetation is not evident from the orthophotos since the surrounding trees surmount them by far and, therefore, restrict the view. Nevertheless, it can be expected that vegetation also affects gullies located in forests. In rather rare cases, it can be concluded that a gully has been created by the use of a field path. As it turned out, in such a case the path is routed around the gully, and the erosion itself is just left as it is. No matter where such a permanent gully occurs, it always leaves the landscape unusable: the previously existing soil is lost, and the severe deepening makes cultivation impossible.

5.1.2 Clusters of sunken lanes

Although sunken lanes occur in other places too, Langenlois and parts of Fels am Wagram are practically the only hotspots for them; by far the most sunken lanes can be found there. The records show that in Langenlois and the surrounding areas sunken lanes dominate, and permanent gullies occur only in isolated cases to the north. Further southwest of Langenlois, in the direction of Krems an der Donau, an increased occurrence of sunken lanes can also be identified.

- **Topography and soil characteristics**

The village of Langenlois has an average slope between 0 and 8 %; nonetheless, the surrounding vineyards are in parts characterised by much steeper slopes. The terracing created for the cultivation of the vines is clearly visible since the height drop of every terrace stands out strongly. Towards the north, the slope increases strongly. The deeply red-coloured areas of the map (see Fig. 17) symbolise a slope inclination of up to 45 %, and in some areas even this mark is exceeded considerably. Meanwhile, the much smaller hotspot at Fels am Wagram is located in a very flat area. The slope remains relatively constant at just over 1 % and only increases slightly to the northwest. The sunken lanes here are cut into the so-called Wagram edge, which is visualised by a steeply inclined red line. Southwest of Langenlois, in the direction of Krems an der Donau, smaller accumulations of sunken lanes can also be found. Here there is a very sharp increase in slope steepness; slopes with a gradient of at least 30 % form the majority.

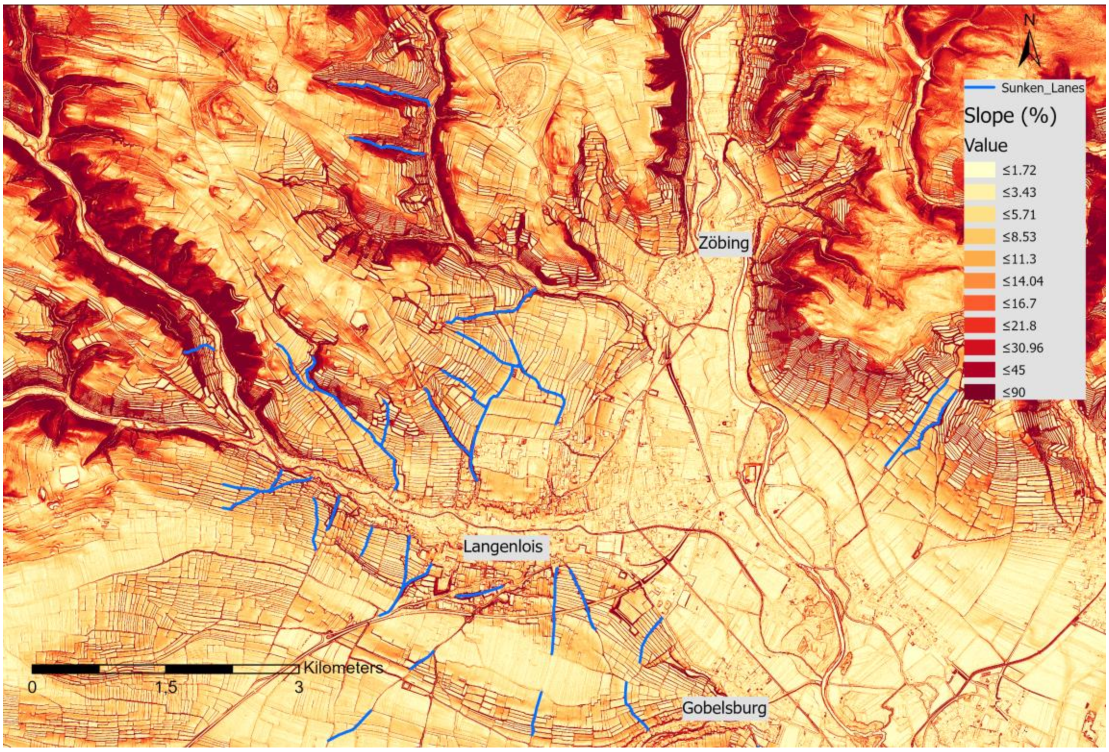

Fig. 17: Slope steepness in Langenlois, hotspot of sunken lanes
(Source: Provincial Government of Lower Austria n.d.)

The hotspot area of sunken lanes is mostly characterised by the soil types chernozem and cambisol (see Fig. 18). In the region around Krems an der Donau, a large area of rigol soil can be found (BFW n.d.). This untypical soil is not uncommon in Austrian wine-growing areas and was formed by human-induced changes in soil conditions. Rigol tillage was used to make furrows of varying depths in the soil, which redistributed the soil layers and was intended to prevent a loss of nutrients, humus, and fine soil (Denk 2000).

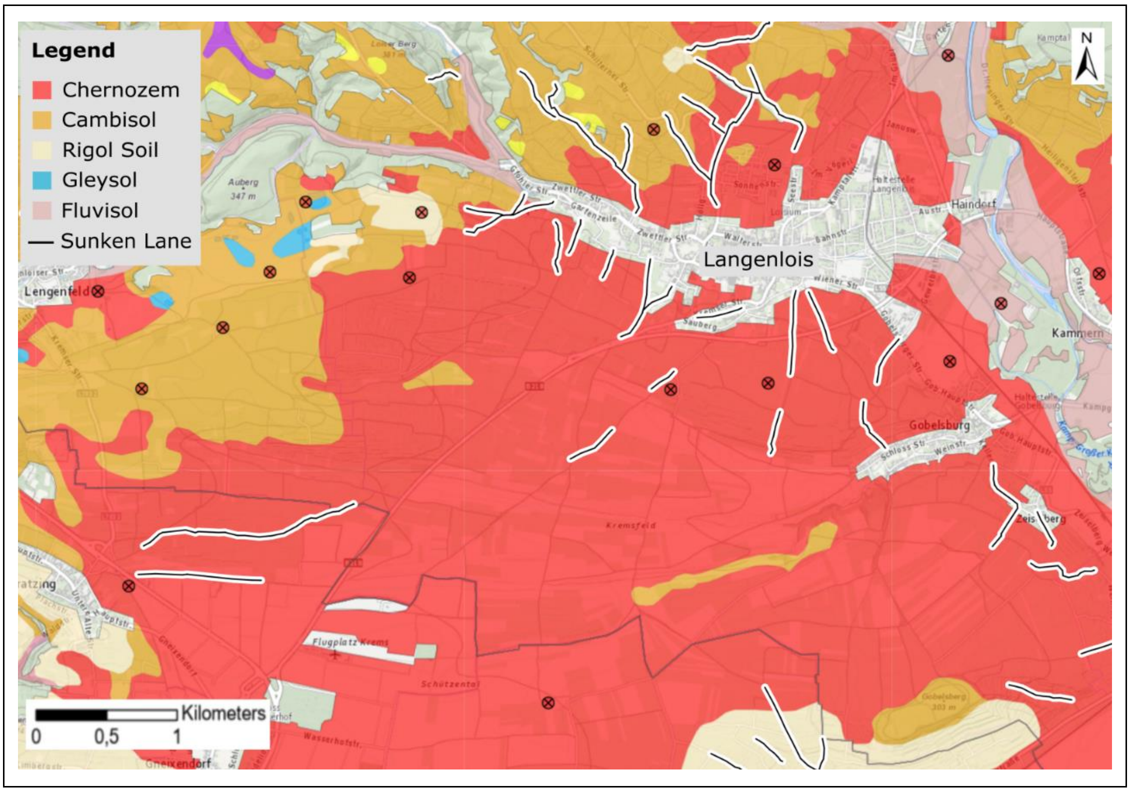

Fig. 18: Predominant soil types in the Langenlois hotspot area of sunken lanes (Source BFW 2007)

Just as with the hotspots of permanent gullies, loess is the parent material in the areas characterised by accumulations of sunken lanes. In addition, there is an increase in alluvial material to the east of Langenlois, as well as silicate to the north. Near Krems an der Donau, fine sediment is also found as parent material besides loess.

The soils around the village of Langenlois have a good water ratio; most fields are reported to be well-supplied, and moderately dry soil occurs only occasionally. In the north, however, the characteristics change considerably in this respect. Here the soils are dry to very dry. The water conditions are also poorer near Krems an der Donau, where the soils are designated as moderately dry to dry.

Water permeability is moderate to high in both areas. Especially the very dry soils in the northern part of the hotspot area have a very high permeability. The same applies to the rigol soils near Krems, whose porosity is likewise marked as high (BFW 2007).

- **Land use**

Both Langenlois and Krems an der Donau were settled very early. Hunting cultures and – later on – farming cultures took up residence. Since the rule of the Romans, viticulture played a particularly important role and provided the regions with prosperity. In the Middle Ages, the clearing of forest areas began in order to facilitate the subsequent use of the land for agriculture. However, as the newly acquired fields were often located on prone terrain, they were quickly abandoned, which is why the forest spread again for the time being. In the Middle Ages, as well as the Neolithic period, so-called *Wölbäcker* were laid out in the analysed area, that is, long ridges and furrows shaped with an asymmetrical plough. The depressions created at the edges collected water easily, which was a favourable condition for the development of linear erosion. In addition to conventional fields, viticulture was also extended to exposed sites in order to once again increase the harvest. However, these areas were abandoned over time as they involved a lot of work. To this day, cairns and terrace residues in the forests testify to the former viticulture in sloping terrain (Wiesbauer et al. 2014).

Vineyards continued to dominate the landscape and economy; in the 18th century, around 75 % of the population were engaged in this economic branch (ÖBIG 1985). The Franziszeische cadastre reveals that viticulture also remained dominant in the 19th century. Especially in Krems this cultivation of land prevailed, whereas in Langenlois orchards and, in some cases, pastures were established, too (Arcanum n.d.a). Although after the Second World War industrialisation found its way into these two regions, viticulture continued to be the most important type of land use, especially in the area around Krems an der Donau (ÖBIG 1985).

The Lower Austrian atlas map and the orthophotos show that the regions of Langenlois and Krems an der Donau are still strongly characterised by agriculture today (Provincial Government of Lower Austria n.d.). Langenlois is called the 'largest wine town in Austria', and the region of Krems an der Donau is not only historically but also currently one of the most important wine regions in Lower Austria (Österreich Wein n.d.).

- **Usage of sunken lanes**

Due to the easy processability and high stability of loess, many sunken lanes were used as *Kellergassen*, lanes with wine cellars on one or both sides. These *Kellergassen* consisted of a wine press house, in which the wine was prepared, and a wine cellar, which was built completely into the side walls of the path or the edge of the terrace of a vineyard. Since the average annual temperature in the wine cellars was between 8–10 °C, they were ideal for storing the wine bottles.

Since the middle of the 20^{th} century, however, many sunken lanes, whether *Kellergasse* or not, have been destroyed or left fallow, leading to a considerable decline. Between 1950 and 1990, about 70 % of Lower Austria's sunken lanes were destroyed. This destruction has a variety of causes: the dumping of rubbish or construction waste, land consolidation, levelling, and intensive agricultural use are just a few of them. Another major problem is the abandonment of sunken lanes. To preserve them, it is necessary that people frequently walk or drive along these lanes. If this is not the case, they are increasingly taken over by vegetation and lose most of their characteristics (see Fig. 19) (Wiesbauer 2020).

Fig. 19: Usage of sunken lanes: (A) Abandoned sunken lane; (B) Wine cellar in a *Kellergasse* (Photo: Sarah Diem)

Around the turn of the millennium, Lower Austrian society and politics began to rethink their approach, which is why an initiative was launched to protect the remaining sunken lanes. The aim of this initiative was to rehabilitate and maintain the sunken lanes in the loess areas so that they could be used again in the future. The dumping of rubbish and construction waste was declared illegal, some paths were defined as natural monuments, and the first European sunken lane nature trail was established in Langenlois. As sunken lanes are important habitats for both animals and plants, there are various laws and regulations to protect them. Many sunken lanes are now located in Natura 2000 regions, which ensures biodiversity and preservation of the habitats. Those paths that are not located in such a nature reserve are still protected by various provincial and federal laws against possible filling or destruction (Wiesbauer et al. 2014).

In addition to the sunken lanes, life has returned to the *Kellergassen*, which in many areas are regarded as culturally and historically significant constructions. Winegrowers have renovated the buildings and open them for several days a year. Municipalities organise festivals, arts and craft markets, and guided tours, and they advertise wine tastings in the historic alleys (Wiesbauer et al. 2014).

5.2 Analysis of gully appearance

Since the study area was too large to analyse the appearance of all permanent gullies and sunken lanes in it, a few exemplary gullies were initially selected for a detailed description. This selection was based on the hotspot map, paying close attention to a high diversity of gullies. After this analysis, additional catchment areas of three streams were created according to the criteria described in chapter 4.4.

5.2.1 Exemplary gullies

The results of the exemplary analysis should be seen as such – exemplary results – as they describe specifically selected cases of gully erosion and are only intended to demonstrate the dimensions that such erosions can take. Since relatively few examples are involved, the values, such as the median, are not necessarily representative for the entire study area, but they are nevertheless cited for the sake of completeness.

The planform shapes of the exemplarily selected permanent gullies are relatively evenly distributed. The most common shape are dendritic gullies, some of which have extensive ramifications. They are closely followed by linear gullies, which mostly occur in smaller accumulations paralleling each other, and by continuous scarp-front gullies. The only form that is not present among the exemplary gullies are amphitheatre gullies.

The table below shows the maximum and minimum values of length, width, depth, and volume of the mapped gullies. In addition, the median of each of these geomorphometric characteristics was determined in order to obtain an overall pattern.

Tabl. 1: Geomorphometric characteristics of exemplarily selected permanent gullies

	Length (m)	Width (m)	Depth (m)	Volume (m^3)
Maximum	793.3	77.1	7.4	149,848.1
Minimum	234.3	26.9	1.4	9,685.3
Median	451.5	37.6	2.4	34,919.7

Likewise, the mapped sunken lanes were analysed according to their geomorphometric characteristics. Since there is no classification in planform shapes for this gully erosion type, considering that it is a simple linear erosion, no distinctions could be made in this regard. The sunken lanes were sorted only according to their local occurrence, i.e., whether they can be found directly in a vineyard or field, or whether it is a sunken lane in a village that is used as *Kellergasse* or street. The erosions found in the exemplarily selected areas all occur directly in the vineyards, partly used as a road, partly unused and overgrown by vegetation.

Tabl. 2: Geomorphometric characteristics of exemplarily selected sunken lanes

	Length (m)	Width (m)	Depth (m)	Volume (m^3)
Maximum	1,647.4	35.2	4.9	71,271.9
Minimum	612.5	14.1	0.5	10,580.6
Median	813.2	29.05	1.9	16,210.45

5.2.2 Permanent gullies in the selected hotspot catchments

To enable the analysis of a larger number of gully erosions in the research area, and to obtain more representative results, the three catchment areas were created within the hotspot map. In the catchment Ebersbrunner Bach, a total of 42 permanent gullies were recorded; there are no sunken lanes in this area. In the second catchment area (Rabischwasser/Krampugraben), the analyses refer to 57 permanent gullies and 16 sunken lanes. In the Baritz catchment, 83 permanent gullies and five sunken lanes were listed. The exact figures for the analysed sunken lanes follow in the subsequent subchapter.

Starting with the planform shapes, a picture emerges that is markedly different from the exemplary analysis. Permanent gullies occur most frequently in the dendritic form: 81 out of a total of 182 analysed gullies could be assigned to this feature. 45 were amphitheatre gullies, just above the linear gullies, of which there were 41. Continuous scarp-front gullies were the least common: only 13 gullies corresponded to this type.

Erosion phenomena in the planform shape of dendritic gullies have the maximum length found in all three catchments. In addition, in at least two catchments, this planform is the one with the largest loss of material. In terms of the greatest depth, the amphitheatre gullies lead in two catchments, while the continuous scarp-front gullies have the largest recorded widths.

Except for the volumes, the calculated medians of the geomorphometric features are very similar, even though there are one or two outliers. The difference between the maximum values is more diverse. While the longest permanent gully in the catchment Ebersbrunner Bach takes up 528.3 m, a gully in the catchment Rabischwasser/Krampugraben is more than twice as long. The same remains valid for the width; for the depth, this value has even tripled. While in the catchments Ebersbrunner Bach and Baritz, the greatest depth is 7.3 m and 6.1 m respectively, in the third catchment (Rabischwasser/Krampugraben), a gully with a depth of 22.8 m was calculated. The latter catchment is also far removed from the other two in terms of volume, with a maximum of 147,389.2 m³ of material loss. If the total volumes of all analysed permanent gullies are added up, this results in 1,316,870.6 m³ of material loss.

Tabl. 3: Geomorphometric characteristics of permanent gullies in the selected hotspot catchments

		Length (m)	Width (m)	Depth (m)	Volume (m³)
Catchment: Ebersbrunner Bach	**Maximum**	528.3	106.7	7.3	64,066.6
	Minimum	49.8	14.2	0.4	101
	Median	108.5	30.05	1.05	1,967.8

		Length (m)	Width (m)	Depth (m)	Volume (m³)
Catchment: Rabischwasser/ Krampugraben	**Maximum**	1,226.7	104.3	22.8	147,389.2
	Minimum	47.3	14.3	0.5	290.2
	Median	107	36.3	2	3,096.2

		Length (m)	Width (m)	Depth (m)	Volume (m³)
Catchment: Baritz	**Maximum**	753.2	58.7	6.1	76,964.1
	Minimum	45.4	12.5	0.5	41
	Median	134.2	26	1.3	3,714.4

If the volume loss of the permanent gullies per linear metre is calculated, the following values result:

- Catchment Ebersbrunner Bach: 42.6 m³ per metre
- Catchment Rabischwasser/Krampugraben: 47.1 m³ per metre
- Catchment Baritz: 42.5 m³ per metre

It clearly emerges that in all three catchments the permanent gullies erode about the same amount of material per linear metre.

5.2.3 Sunken lanes in the selected hotspot catchments

The analysis of sunken lanes is based on much smaller samples than that of permanent gullies, on the one hand, because there are considerably fewer sunken lanes overall, on the other hand, because there are only one big and one smaller hotspot area, which are not part of the catchment areas. To compensate for this, the exemplary analysis (5.2.1) was carried out in the hotspot area of sunken lanes.

Sunken lanes were only recorded in the catchments Rabischwasser/Krampugraben and Baritz, so the focus of the analysis is on these two areas.

In both catchments, there are about the same number of sunken lanes located in vineyards as in the villages. It is remarkable that the paths outside the localities are still in use, and only a few are left to themselves.

The results of the individual calculations differ in some parts greatly in the two catchment areas. For example, in the catchment Baritz, with five sunken lanes, only one third of those of the other catchment were found. The maximum length adds up to 608.8 m, the largest width to 73.1 m. The sunken lanes are generally not as deep as the permanent gullies. 4.5 m is the greatest depth found. While the 14 sunken lanes in the catchment Rabischwasser/Krampugraben lost 30,911.8 m³ of volume, those in the Baritz catchment eroded 4,037.9 m³. Through this type of gully erosion, a total of 101,652.5 m³ of material was lost.

Tabl. 4: Geomorphometric characteristics of sunken lanes in the selected hotspot catchments

		Length (m)	Width (m)	Depth (m)	Volume (m³)
Catchment: Rabischwasser/ Krampugraben	**Maximum**	608.8	73.1	4.5	30,911.8
	Minimum	123.5	10.8	0.4	250.3
	Median	411.45	19.45	1.8	2,784.05

		Length (m)	Width (m)	Depth (m)	Volume (m³)
Catchment: Baritz	**Maximum**	488.9	21.9	1.6	4,037.9
	Minimum	262.1	8.1	0.5	156.9
	Median	273.9	12.8	0.9	726.6

Just as for the permanent gullies, the loss of material per linear metre was calculated for the sunken lanes. Here, too, there is a clear difference to the former gully type as the calculated values are significantly lower. In addition, it is evident that the geomorphometric properties of the sunken lanes can vary greatly. The results for the material discharge per metre for the two investigated catchments differ strongly from each other:

- Catchment Rabischwasser/Krampugraben: 17.1 m³ per metre
- Catchment Baritz: 4.3 m³ per metre

At 17.1 m³ per linear metre, almost four times as much material was eroded in the first catchment as in the second one.

6. Discussion

6.1 Distribution of gully erosion

One of the main objectives of this thesis was to find out where gully erosion can be found in the research area in north-eastern Lower Austria. In pursuit of this objective, the first research question was formulated as stated below, accompanied by a hypothesis expressing the expected results. An attempt is made to answer the question with regard to the four most important influencing factors, which are also characteristics of a region.

Q1. Where are gully erosions and potential hotspot areas of gullying detectable in Lower Austria?

> ***H:*** *Gully erosions are detectable predominantly in inclined areas with thick loess layers and mostly under the influence of contemporary agricultural land use.*

Starting with the **topographic factors**, the analysis of gully occurrence showed that a certain slope must be present to cause this water erosion type. In the hotspot regions, the slopes have an average inclination between 0 % and >25 %; this applies to areas with permanent gullies as well as sunken lanes. Most erosion occurs in areas where viticulture dominates, meaning that agriculture is not only practised on the plain but also in hilly areas. In addition, one of the largest hotspot areas is located in the Ernstbrunn Forest, where there are sometimes even far more exposed slopes with gradients over 50 %.

A comparison with the literature shows that the topography, especially the slope, plays an important role in the development of gully erosion. The length and steepness are the most important geometric variables for the initiation of gullying (Durán Zuazo et al. 2011). Erosion rates are particularly high on slopes where the gradient is relatively constant as this allows runoff to accumulate and gain more power to detach material. Furthermore, the erosion rate is significantly higher at the bottom of slopes because overland flow also accumulates here and has high erosive forces that can release soil particles from their aggregates (Sabzevari et al. 2019; Toy et al. 2002).

Even though the exact location of the occurrence of gully erosion on a slope has not been assessed in the study, a correlation between slope steepness and gully initiation is evident. In shallower, intensively used agricultural areas, such as the Marchfeld/district Gänserndorf, no permanent gullies or sunken lanes could be detected.

As a further influencing factor of gully erosion in Lower Austria, **soil properties** were examined in more detail. The hotspots are all located in areas where loess and alluvial sediments form the parent material. Despite the high pore volume of these materials, they tend to be highly erodible when (heavy) precipitation events occur. Although almost the entire study area, with the exception of some locations in the north and southeast, belongs to the loess region of Lower Austria (see Fig. 6), and despite the fact that gully erosion occurs in every administrative district, only five hotspots of permanent gullies and two hotspots of sunken lanes were detected (see Fig. 11 and Fig. 12). This indicates that the thickness of the material and the deposits may also play a role in the gully development. As it turns out, permanent gullies and sunken lanes occur in areas that, among other influencing factors, have a considerable thickness of loess deposits. The erosion phenomena were found mainly in regions with loess deposits at least 8 m thick (Meyer-Heintze et al. 2018). While the loess thickness increased up to 20 m in the hotspot areas (Thiel et al. 2011), no clusters could be found in more eastern regions of the study area, despite the presence of similar influencing factors such as intensive land use or loess covers. The thickness, however, decreases considerably here, amounting to a maximum of 2 m (Brandtner 1954), a very clear difference to the average thickness of 10 m of loess deposits in the hotspots (Haesaerts et al. 2016; Piffl 1951). Even though the thickness of loess deposits seems to be of importance in this study, the literature suggests that soil conditions alone are not sufficient to explain the initiation of gully erosion. In Europe, for example, it is evident that, historically and presently, most loess areas are subject to intensive agriculture due to their fertile soils, which suggests that it is mainly the combination of soil and tillage (and others) that contributes to the initiation of this erosion type (Zgłobicki et al. 2017).

The main influences on gully erosion also include **climatic conditions**. The identified hotspots are located in two different climatic regions, those to the west in the Danube basin and those to the east in the Pannonian. Notwithstanding the above, the Danube basin already shows a remarkable influence of the Pannonian climate, which is why high temperatures and long dry periods occur in all hotspot areas. Continental influences can lead to thunderstorms and occasional heavy rainfall events in both climate zones; nonetheless, the average precipitation rate per year is relatively low. Precipitation is a particularly important element when it comes to gully initiation and expansion. The factors of quantity and intensity not only affect the volume of surface runoff but also the shear stress of the water. In the long term, rain additionally determines soil moisture and soil erodibility (Vanmaercke et al. 2021). As explained in the presentation of the results, the hotspots are located in areas where the soils are relatively dry and, despite an occasionally high water permeability, have properties that lead to a rapid destruction of existing aggregate conditions. Loess as a foundation furthermore tends to have a low resistance to rainfall erosivity; moreover, it quickly causes siltation, which increases surface runoff (Castillo et al. 2016). The climatic conditions for the development of gully erosion are thus ideal in the studied area. The erosion-prone soils dry out enough in the summer to contribute to the detachment of material in case of heavy precipitation events. The latter are a phenomenon that occurs despite the low annual precipitation sum.

With a dedicated land share of 57 %, the hotspot areas of gully erosion are located in regions with intensive **agricultural use**. The fertile soils were already crucial for settlement decisions and prosperity of cultures in the past. Viticulture, in particular, is one of the dominant agricultural branches in the study area, although other varieties were introduced as early as the 18th century and have been cultivated ever since. Today the main crops cultivated are wine, potatoes, sugar beet, pumpkins, and rape. Since some of these crops are grown in rows with large distances between them, the susceptibility of the respective arable land to erosion increases: the rain can hit the soil unhindered by vegetation and detach soil particles from their aggregates. But gully erosion in Lower Austria occurs not only in areas used purely agriculturally, but also in the largest forest area located in the Weinviertel. The Ernstbrunn Forest belongs to those regions that are subject to intensive use, also utilised as settlement areas in historical times. In the Middle Ages, at least five villages were established in this forest area, the remains of which are still visible in a DEM today (see Fig. *16*). It is assumed that for the construction of the villages, the forest – already present at that time – was cleared in places in order to build houses, fields, vineyards, and floodplains (Bidner n.d.a). After the last settlements were abandoned, by the 15th century at the latest, there is no further evidence that the forest was again used for residential purposes in the following centuries (Der Standard 2017). However, the names of some places suggest that the agricultural use of the forest was maintained for some decades and that, in addition to potato fields, livestock was kept on the edges of the forest area. Especially during the industrialisation, the Ernstbrunn Forest was subject to strong clearing as the wood was needed for charcoal. Yet later on, attempts were made to compensate for this by reforestation, and today the Ernstbrunn Forest is the largest closed mixed oak forest in Europe (Denner 2020). General studies on the origin of gully erosion reveal that in Europe the development of gully erosion began in the

Bronze Age or later in the Middle Ages. Many forests were cleared at that time in order to convert the reclaimed land into fields or pastures. Along with this new form of land use came the construction of paths, the intensification of tillage practices, and overgrazing. Especially the tillage of soils leads to noteworthy changes in drainage, infiltration capacity, and susceptibility to erosion (Castillo et al. 2016). Events such as the St. Mary Magdalene's Flood around 1342 still testify to the fact that, as a result of this field cultivation, the soils of Central Europe have been subject to severe erosion since at least the Middle Ages. In addition, this specific once-in-a-millennium event can be seen as tipping point for an accumulation of gully formation in many European areas (Zbinden 2011). In recent times, the use of heavy machinery, which leads to soil compaction, is seen as the main cause of increased water erosion rates (Klik et al. 2010).

Accordingly, agriculture is likely to have a major influence on the development of gully erosion in the study area. As in comparable regions also surveyed in this regard, intensive use of the soils took place very early on and has continued throughout the centuries until today. The mechanical cultivation of soils, ploughing and planting in rows (e.g., vineyards), strongly disturbed and influenced the previously natural conditions. Likewise, the assumption that the onset of gully erosion was triggered by the clearing of forests in the Middle Ages could be verified in the research area. The Ernstbrunn Forest became important for settlement precisely at this time, for which parts of the area were cut down and instead used for housing and agriculture. As described in the literature, such interventions may have led to an increase in the susceptibility of the soils to erosion and influenced gully incision.

Considering all these characteristics of the hotspot areas, topography and land use seem to be of particular importance for the initiation of gully erosion. When it comes to soil properties, the thickness of the parent material loess appears to be of special significance. At least in the regions studied, both types of gully erosion, but especially sunken lanes, occur in areas characterised by a particularly strong thickness of loess (average around 10 m). As a fourth influencing factor, climate was also discussed; although it seems to play a role in Lower Austria, it is strongly dependent on the coexistence of several factors. The hypothesis assigned to the research question can therefore be verified with regard to the listed influencing factors because a) gully erosion in Lower Austria occurs mainly in areas with a certain slope inclination (on average around 10 %), b) erosion phenomena were found predominantly in regions with thick loess layers, and c) the hotspots of gullies are characterised by particularly heavy agricultural use. To substantiate these assertions, attention can once again be drawn to the eastern regions of the research area, where similar circumstances such as climate, intensive land use, and loess covers prevail, but to such a small extent and in an area too flat to cause gully accumulations.

6.2 Types of gully erosion

Another objective of this thesis was to find out which gully types can be found in Lower Austria. To answer this, the second research question was created, together with the hypothesis listed below.

Q2: Which types of gully erosion can predominantly be observed in Lower Austria?

> ***H:*** *Permanent gullies and sunken lanes are the predominant gully erosion types as they are irreversible and exhibit high depths.*

It became apparent very early in the working process that the search for different types of gully erosion could only be carried out to a limited extent using the selected methods. While the initial aim was to look for ephemeral gullies, bank gullies, permanent gullies, and sunken lanes, the search for the first two had to be abandoned after several attempts. Since bank gullies are recognisable by a drop in elevation in the landscape and are created primarily by terracing or riverbanks (Vandekerckhove et al. 2000), they could be easily confused in the DEM with the many wine terraces located in the study area. Based solely on the work with the DEM, it was not possible to conclude with certainty if bank gullies occur or not. In order to avoid falsifying the results, it was therefore decided to exclude this gully type and concentrate the search on other types.

The search for ephemeral gullies posed another problem. A reason for this is the fact that ephemeral gullies are filled up again within a very short time after their formation, or they are reversed with some other tillage practices. Due to this obliteration, it is very likely that the evolved ephemeral gullies would have no longer existed at the time of the aerial survey for the DEM and thus could never have been included in the dataset. A check with the orthophotos would have posed a further difficulty since these were not created during the same period as the DEM. Ephemeral gullies could therefore have been present in one dataset but already disappeared in the other. Vanmaercke et al. (2021) reviewed over 500 published articles and documents on “Measuring, modelling and managing gully erosion […]” and were able to show that other studies have come to nearly the same conclusion.

According to the authors, mapping the characteristics of ephemeral gullies within a DEM, despite the high resolution, is based on very subjective assessments.
In the end, only permanent gullies and sunken lanes could be found because of these limitations. Due to the average depth between 0.9 m and 2 m calculated with the median, these two types are not only clearly recognizable in the DEM, but also irreversible and therefore everlasting. However, not only the depth but also the other geomorphometric characteristics and the planform shape clarified why these gullies occurred especially frequently in the research area. Most of the permanent gullies studied in more detail in the hotspots were of a widely fanning, dendritic shape. The fact that they were able to grow so large is a testament to their long lasting existence. While the linear form is characteristic for rather younger generations of gullies, these dendritic or also amphitheatre forms indicate that a gully is not only permanent but has formed and evolved for a long time (Thwaites et al. 2021).
Sunken lanes are also one of the dominant forms because, like permanent gullies, they can become very long and deep from a geomorphometric point of view. Due to the peculiarity that in the study area viticulture is a defining feature and has attracted settlers for centuries, this type of gully had enough time to spread and incise the landscapes.
The hypothesis that permanent gullies and sunken lanes are the dominant types in the study area can only be treated with reservations. Since the methodology was insufficient for the finding of other types, it is not safe to say that this assumption is true. However, it can be surmised that, even with better methods that are able to consider all types, permanent gullies and sunken lanes would top the list. Because both types are irreversible and lead to substantial damage of a landscape, they are definitely more pronounced and longer-lasting than ephemeral gullies. Furthermore, given that such high numbers of permanent gullies were found, an immense number of ephemeral gullies would have to exist and be surveyed within the same time period to out-compete the others.
The claims about bank gullies are somewhat more difficult. In the research area, there are a lot of terraces due to practices of viticulture, so the circumstances for the development of bank gullies are definitely given. Notwithstanding, surveys show that many of these terraces were consolidated with bricks, walls, and similar material in the past, or that retention basins were built (Wiesbauer et al. 2014). Whether bank gullies would have been able to develop despite these constructions is questionable. Also, as with ephemeral gullies, there would have to be a very high number of bank gullies to surpass the dominance of permanent gullies and sunken lanes.

6.3 Geomorphometric characteristics

In addition to the two objectives already discussed, the third aim was to obtain an overview of soil loss in the hotspot regions in order to determine the seriousness of the problem. The third research question and the corresponding hypothesis are as follows:

Q3: What are the average volumes of sediment loss in relation with the observed gully types in Lower Austria?

> ***H:*** *Permanent gullies erode a higher amount of sediment per linear metre than sunken lanes; therefore, their average volume loss is higher.*

Gully erosion is a type of water erosion that can lead to extraordinarily severe land degradation. The volumes of sediment discharge vary greatly depending on the gully type, but irreversible gullies, in particular, contribute to very high soil loss (Poesen et al. 2003). When gully erosion occurs in a landscape, it is usually the main source of sediment loss and can significantly increase sediment connectivity. This high loss of soil not only leads to the degradation of entire landscapes, but also to the destruction of infrastructure, hydrological functions of soils, and contamination of adjacent water bodies (Vanmaercke et al. 2016).

The calculations in the catchments show that the loss of material from permanent gullies is on average (median) higher than the loss through sunken lanes. The numbers from permanent gullies range from 1,967.8 m³ to 3,714.4 m³ of soil loss per gully in the three catchments studied. Although the calculations also show an average loss of 2,784.05 m³ for the sunken lanes, i.e., an erosion volume in the same range as the one of permanent gullies, in the second catchment the material loss is far behind, with only 726.6 m³ per sunken lane. In the exemplary calculations, the permanent gullies are also ahead: they eroded almost twice as much volume as the sunken lanes, according to these calculations. Apart from the average values, the calculation of the maximum loss is noteworthy. The longest sunken lane mapped, at almost 1,700 m in length, eroded a little over 71,000 m³, which is also the highest volume loss caused by any of the sunken lanes analysed. In contrast, the highest observed soil loss through permanent gullies is almost 150,000 m³, which is a remarkable difference. If the whole calculations are broken down to make the two erosion types even more comparable, it becomes apparent that permanent gullies erode far more material per linear metre than sunken lanes. In all three catchments, the permanent gullies eroded on average between 42.6 m³/m and 47.1 m³/m, while the sunken

lanes “only” eroded 4.3 m^3/m and 17.1 m^3/m, respectively, thus a fourth of the material. The latter results additionally reveal that the material discharge varies greatly within the sunken lanes themselves.
The fact that permanent gullies erode so much more material than sunken lanes could be due to the circumstance that, despite their often shorter length, they achieve much higher values in width, depth and, above all, dissemination. The study clearly revealed that dendritic gullies and amphitheatre gullies can reach great expansions and can thus be extremely disruptive for a landscape. Both planform shapes exhibit the highest values of lost volume measured in the catchment areas and are also leading the average calculations. Conversely, sunken lanes are usually longer than permanent gullies, but they are only paths or roads that have no ramifications or any other extensions. They therefore erode and detach the sediments to a lesser extent. Another reason for the more severe effects of permanent gullies may be that both gully types are formed in very different ways. While one evolves out of the use of a path, the other is formed by tillage practices and agricultural use of land, which is why the latter has more space to develop.

Considering the calculations, the hypothesis created to set suggestions for this third research question can be verified. With a total volume of more than 1.3 million m^3, the permanent gullies detached significantly more material from the three catchments than the sunken lanes with a bit over 100,000 m^3. The permanent gullies are also ahead in the calculations of erosion rates per linear metre, eroding four times as much material per metre as the sunken lanes surveyed. Also, in any other calculations on the average soil loss of the two erosion types, the permanent gullies achieve much higher values than the sunken lanes. It is this latter type of calculation that may counter the argument that far fewer sunken lanes than permanent gullies were analysed, as the outcoming results are independent of the number of documented cases.

With these figures in mind, it is not surprising that gully erosion is one of the biggest initiation factors of land degradation. Moreover, if this type of erosion occurs more frequently, it can conceivably lead to the desertification of entire areas (Vanmaercke et al. 2021).

7. Conclusions and perspectives

The occurrence of gully erosion in the north of Lower Austria is not an isolated case and is therefore by no means negligible. The creation of a hotspot map revealed that in some places entire clusters of this soil erosion type occur, which cause lasting damage to the landscape and leave it worthless.

Gully erosion occurs in hilly regions where soil properties additionally favour channel initiation, climatic conditions lead to precipitation events with high erosivity rates, and intensive agricultural land use is commonplace. Even though it has already become clear from the research that soil loss through gullies is pervasive and that agricultural land is reduced as a result, far more studies in this direction are needed to fully capture the actual problem of gully erosion in Lower Austria. More detailed studies are required to generate knowledge about the exact influencing factors in hotspot areas, the dominating gully types, and the overall rates of soil loss.

In order to really understand gullying and make predictions about possible future scenarios in a region, it is indispensable to study all conditioning factors and determine which driving forces are behind the initiation and expansion. Since it is not possible to extrapolate from one country or region to another in every aspect, it would make sense to limit the areas of investigation and focus on just a few targets.

Moreover, for the purpose of finding out more about the different gully types, a reduction in the size of the research area is unavoidable. The present thesis has clearly demonstrated the limitations of the applied methods; other approaches are needed to learn more about the existing gully types and their damage potential. A combination of working with digital datasets and field surveys could make mapping and type determination more accurate and provide even more region-specific information. Furthermore, in smaller samples, all the gullies found could be included in calculations and thus illustrate the actual soil loss of a study area.

At a later stage, further studies and surveys are needed to determine possible mitigation measures capable of a reduction of soil loss or even prevention of this severe erosion process. Only once all these presently still unresolved questions have been clarified, it will become clear what significance gully erosion actually has in Lower Austria, and what actions must follow to prevent soils from degrading even more in the future.

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Appendix

1.) Python code for confining the raster dataset on the research area:

```
import argparse
import glob
import os
import shutil
from tqdm import tqdm
from pyproj import Transformer

def parse_grd(filename):
    x = 0
    y = 0

    with open(filename) as f:
        try:
            # skip the first two lines
            f.readline()
            f.readline()
            # read the x/y coordinate
            text = f.readline().lower()
            x = float(text.split(' ')[-1].strip())
            text = f.readline()
            y = float(text.split(' ')[-1].strip())
        except Exception as e:
            print(f"Error at file: {filename}. Exception: {e}")

    return (x, y)



if __name__ == "__main__":
    parser = argparse.ArgumentParser()
    parser.add_argument("lon", nargs=2, type=float, help="Longitudinal 
coordinate bounds (min, max)")
    parser.add_argument("lat", nargs=2, type=float, help="Latitudinal 
coordinate bounds (min, max)")
    parser.add_argument("output_dir", help="Output directory")
    parser.add_argument("--crs_from", default='EPSG:31256', help="From 
Transformation (CRS Format, default=EPSG:31256). You can find the 
transforms here: https://epsg.io")
    parser.add_argument("--crs_to", default='EPSG:4326', help="To 
Transformation (CRS Format, default=EPSG:4326. You can find the 
transforms here: https://epsg.io")
    args = parser.parse_args()
```

```
    lon_bounds = sorted(args.lon)
    lat_bounds = sorted(args.lat)
    print(f"Bounds: Lon={lon_bounds}, Lat={lat_bounds}")
    print(f"Output Folder: {args.output_dir}")

    try:
        os.mkdir(args.output_dir)
    except:
        pass

    grd_files = glob.glob("*.grd")

    # setup the coordinate transformation
    # from: MGI / Austria GK East => to: WGS 84
    transformer = Transformer.from_crs(args.crs_from, args.crs_to)


    for filename in tqdm(grd_files):
        x, y = parse_grd(filename)
        # transform the coordinates
        lat, lon = transformer.transform(y, x)
        text = f"{filename},{x},{y},{lon},{lat}\n"

        if (lon_bounds[0] <= lon <= lon_bounds[1]) and (lat_bounds[0]
<= lat <= lat_bounds[1]):
            shutil.copy(filename, args.output_dir)
```

Repository of all Python codes and exe-files used in Chapter 4:

https://github.com/lukasdiem/gis-filter-grd-by-coordinate/tree/v1.0.0

https://github.com/lukasdiem/gis-filter-grd-by-coordinate/releases/tag/v1.0.0

2.) Statistics on gully erosion per district in the research area: