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Abstract in English

Soil erosion is a big problem for every country, especially for an island like Iceland. The soil cannot be restored again once lost, which leads to problems with farming and living because the space on an island is limited.

Gully erosion is a special form of soil erosion and depends on different factors. Such as, the type of soil and if the soil is covered with vegetation, on the amount and type of precipitation, the inclination of the slope and how the area is used by humans.

The Skagafjörður is a rural area which has been intensely farmed for a long time. (URL-E and DECAULNE et al. 2016: 1308) As a result of this long and intensive farming, the fjord area is highly affected by soil erosion. (CATLIN 2016: 17-18) Erosion gullies occur on the mountain areas which are used as pastures for sheep and horses by the local farmers. (STEINBERG et al. 2016: 391) The large amount of livestock sets the basis for gully erosion on the mountain areas, as a large amount of hooves on a sparsely vegetated ground damages the soil. (SCHUTZBACH 1985: 193) Therefore, there had to be investigated how the area of the Skagafjörður has changed from 1993 to 2016 and which counteractive measures were taken to minimize gully erosion.

Digital elevation models and satellite images in combination are a good basis for investigating gully erosion and to capture how the area has changed. In combination with statistical analytics patterns of gully erosion could be captured. Different information about geology, soil, climate, vegetation, land use and economy are essential to capture the different factors which support gully erosional processes.

The erosion gullies of the Skagafjörður are formed through large amounts of melting water, which can easily erode the unvegetated soil in spring. (GUÐMUNDSSON 2007: 325) If the gully areas are used as pastures, the soil is highly affected by gully erosion. To prevent and minimize the soil against erosional effects, there are different projects in Iceland. Such as, land improvement projects, guidelines for the farmers regarding sustainable land use, regulating the number of grazing livestock, revegetation of sparsely vegetated land like the highland and mountain areas and afforestation projects. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) Therefore, it is also an essential step in minimizing and avoiding soil erosion, that the population is involved in these different projects and knows the risks of soil erosion and what this means for a country. Additionally it is also important to educate the tourists on soil erosion and how to mitigate the risk of contributing to it. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 22)

Abstract in German

Boden Erosion ist ein großes Problem für jedes Land, dies gilt besonders für Inseln. Ist der Boden einmal erodiert, kann er nicht wieder hergestellt werden, was zu einem großen Problem für die Landwirtschaft und für Siedlungen werden kann. Besonders schwerwiegend ist der Verlust von Boden auf Inseln, da hier der Platz beschränkt ist um neue Flächen für Landwirtschaft oder Siedlungen zu finden.

Gully Erosion ist eine besondere Form der Boden Erosion und ist abhängig von verschiedenen Faktoren. Somit hängt Gully Erosion von der Art des Bodens und wie der Boden mit Vegetation bedeckt ist, von der Menge und der Art des Niederschlags, von der Neigung des Hanges und wie ein Gebiet vom Menschen genutzt und beeinflusst wird ab.

Der Skagafjörður ist eine ländliche Gegend, in der seit langer Zeit intensiv Landwirtschaft betrieben wird. (URL-E und DECAULNE et al. 2016: 1308) Durch diese lange und intensive landwirtschaftliche Nutzung, ist diese Gegend stark durch Boden Erosion beeinflusst. (CATLIN 2016: 17-18) Gully Erosion tritt im Skagafjörður an den Berghängen auf, welche von den örtlichen Landwirten als Weideland für ihre Schafe und Pferde genutzt werden. (STEINBERG et al. 2016: 391) Der große Anteil an Weidevieh legt in diesen Bereichen die Grundlage für Gully Erosion, aufgrund der hohen Menge von Hufen auf dem spärlich bewachsenen Untergrund. (SCHUTZBACH 1985: 193) Somit wird untersucht, wie sich das Gebiet des Skagafjörður von 1993 bis 2016 verändert hat und welche Gegenmaßnahmen unternommen wurden um Gully Erosion zu verlangsamen.

Digitale Gelände Modelle und Satelliten Bilder bilden in Kombination eine gute Basis um Gully Erosion zu untersuchen und um festzustellen wie sich diese Gegend verändert hat. In Kombination mit statistischen Analysen können Muster bezüglich der Verbreitung von Gully Erosion festgestellt werden. Verschiedene Informationen über Geologie, Boden, Klima, Vegetation, Landnutzung und Wirtschaft sind wichtige Zusatzinformationen um die verschiedensten Faktoren zu erfassen, die den Prozess der Gully Erosion unterstützen.

Die Erosions Gullys des Skagafjörður wurden durch große Mengen von Schmelzwasser geformt, welches den unbewachsenen Boden im Frühjahr leicht erodieren kann. (GUÐMUNDSSON 2007:325) Wenn diese Gully Gebiete als Weideland genutzt werden, ist der Boden stark anfällig für Gully Erosion. Um den Boden gegen den Prozess der Erosion zu schützen und bestehende Erosionsprozesse zu minimieren, gibt es hierfür verschiedene Projekte in Island. Diese Projekte beschäftigen sich mit Projekten zur Verbesserung von Land, Richtlinien für Landwirte zur nachhaltigen Landnutzung, Regulierung der Anzahl von Weidevieh, Rekultivierung von spärlich bewachsenem Land wie das Hochland und Berghänge und wieder Aufforstung Projekte. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) Ein weiterer wichtiger Schritt um Boden Erosion zu verringern und zu vermeiden, ist die Bevölkerung in diese Projekte zu involvieren und darauf aufmerksam zu machen, welche Risiken Boden Erosion bringt und was dies für ein Land bedeutet. Zusätzlich zu der isländischen Bevölkerung ist es wichtig, auch Touristen auf die Risiken von Boden Erosion aufmerksam zu machen und wie dem Entstehen neuer Erosionsformen entgegen gewirkt werden kann. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001:22)

1 Introduction

This Master-Thesis processes gully erosion in Iceland. Gully erosion is a special form of soil erosion. Soil erosion constitutes itself as a big problem for any country, as soil cannot be restored again once lost. This leads to problems on local, regional and national scales. (TOY et al. 2002: 5) Thus the population had to move to other areas to find new places for farming or living. This problem is a bigger problem for an island, because the space on the island is limited. The population has to handle the soil with care, because if the soil is lost there is not enough space to move away.

Not the whole area of Iceland can be used for settlement or farming, because Iceland has great areas that are covered with glaciers and deserts or are affected by volcanoes. Therefore, the usable areas have to be handled with care, to prevent that they are getting minimized or lost.

PIMENTEL et al. 1995, DUGMORE et al. 2009, ARNALDS 2004, GREIPSSON 2012, ÓLAFSDÓTTIR and GUÐMUNDSSON 2001, GISLADÓTTIR et al. 2009, CATLIN 2016, GISLADÓTTIR et al. 2011, HARTMANN et al. 2003, STREETER and DUGMORE 2014, GEIRSDÓTTIR et al. 2006, MC GOVERN et al. 2007, ARNALDS et al. 2001, BOARDMAN et al. 2003, FOURNIER 2011 and ARNALDS and BARKARSON 2003 have done extensive research on this problem. There are different forms of soil erosion in Iceland. Although soil erosion can be affected by either wind or water, it causes the same results – the soil cannot be used for agriculture and therefore also doesn't allow settlement in respective area.

The research on soil erosion looks at factors influencing soil erosion like soil erodibility, precipitation, hillslope, vegetation cover and constructions which should protect the soil. (TOY et al. 2002: 16) Spatial and temporal scales are investigated to see how the erosion changes and how the influencing factors influence the erosion processes. (TOY et al. 2002: 16-17) "Soil erosion is a growing problem and constitutes a threat to soil quality and to the ability of soils to provide environmental services. That is, water erosion is the most destructive erosion type worldwide, causing serious land degradation and environmental deterioration, inflicting multiple damages in managed systems such as crops, pastures, or forests as well as in natural ecosystems" (ZUAZO et al. 2011: 1). "Long-term shifts may challenge the existing cultivation systems worldwide and eventually alter the spatiotemporal patterns of land use and topography. All these changes will increase pressure on soil erosion and hydrological processes, making accurate erosion prediction and control more difficult. Thus, improved knowledge and understanding the soil-erosion process will be essential for dealing with the forthcoming challenges regarding soil-conservation practices" (ZUAZO et al. 2011: 1).

As a result of global warming the climate in Iceland is also getting warmer. (GOESSLING 2017: 19) Melting permafrost and glaciers support soil erosion. Once the glacier ice has melted the soil is not protected with vegetation which makes it susceptible for soil erosion. Melting permafrost leads to landslides which erode a lot of soil because the soil is loose without ice, which holds it together. Hence, there is a need for protecting areas which are susceptible for soil erosion and protecting usable areas against the impact of landslides and other erosional phenomena. "Mountain areas are particularly prone to erosion, since they are characterised by complex and fragile geo-morpho-pedological systems, where heavy rain intensity and high relief energy determine slope instability, land degradation and soil loss" (BINI and ZILIOLI 2011: 35). These areas are not only susceptible for erosion caused by heavy rain falls. Large amounts of melting water can also lead to land degradation and erosional processes, as is the case in the Skagafjörður. In the north of Iceland there is less precipitation than in other parts of Iceland. But there can be weather phenomena, which bring intense and long-lasting snowfalls to north Iceland, which results in a greater amount of melting water in spring. (URL-A and URL-B)

The geology of the Skagafjörður is manifold. In the western part of the fjord it consists of Tertiary Basalt Formations with rhyolite incidence. There are also accumulations of volcanism, primarily in the northern part of the fjord. The volcanoes which accumulate their material in the northern part of the fjord were active between two million and one million years before present. These accumulations are called, Plio-Pleistocene Formations. The Skagafjörður was not only influenced by volcanoes. The fjord bottom has Holocene sandur deposits, which are accumulated from the glaciers of the highland. (GUÐMUNDSSON 2007: 376) Intensive glacial erosion leads to steep mountains and a deep fjord landscape. (THORDARSSON and HOSKULDSSON 2002: 155) During the Weichselian stage, all of Iceland was glaciated. It was during this time that the glaciers shaped the Skagafjörður into his typical fjord form. (THORDARSSON and HOSKULDSSON 2002: 44-45) Nowadays the volcanoes which formed the geology of the Skagafjörður are extinct and the glaciers which formed the typical fjord form of the Skagafjörður are melted away. Therefore, enough time is given for soil building processes in the Skagafjörður. The soils of the Skagafjörður are typical soils for a volcanic geology. Brown and gleyic Andosol is the main soil of this fjord. This soil has his origin of volcanic ash and can contain layers of tephra. There are no active volcanoes in the Skagafjörður but in other parts of Iceland there are active volcanoes. With the wind, the tephra from these volcanoes is blown to other parts of the country, such as the Skagafjörður. This type of soil is a very porous and light soil, which is good for storing large amounts of water. (BLUME et al. 2010: 358) The fjord bottom and the mountain flanks of the Skagafjörður are covered with Andosol. At the fjord bottom this soil is good for agriculture, because of the good ability of water storage. But a problem of this soil is the ability to act like liquid, if it's saturated with water. (ARNALDS 2008: 416) This isn´t a problem on the flat fjord bottom but for the mountain flanks this is a problem. This behaviour of Andosols can lead to landslides, which destroy the intact vegetation cover and make the soil susceptible for gully erosion. All gullies that are mapped are located in areas with Andosol. It is important that the mountain flanks of the Skagafjörður are covered with undisturbed vegetation, because the vegetation can protect the soil against erosional processes and pull water out of the ground. This stabilizes the soil and avoid that the soil is saturated with water. Hence, there had to be a focus on the vegetation of the gully areas and how these areas can be protected against gully erosion or to slow the gully erosion.

The vegetation of Iceland changed after the first settlers arrived. (HARTMAN et al. 2017: 126) Through the development of traffic, which was after the Second World War, new plant seeds were taken to Iceland. (SCHUTZBACH 1985: 184) Therefore, the vegetation has changed and new plants spread over the whole island. The Skagafjörður is a rural area with fewer villages. (NATIONAL LAND SURVEY OF ICELAND 2006) Marshes and peatbogs cover the fjord bottom, which are representing through sedges. (SCHUTZBACH 1985: 188) The areas at the mountain bottom and on the flanks of the mountains are vegetated with different types of berries, sedges and willows. The difference is that there are less species on the mountain flanks, because in this area, there are not as many nutrients available for the vegetation. (SCHUTZBACH 1985: 193) The vegetation of the higher mountain parts is represented through lichen and moss. (SCHUTZBACH 1985: 193) Therefore, the porous Andosol is sparsely covered with vegetation on the mountain areas, which supports soil erosion. The infrared image from Landsat, shows that the fjord bottom is densely covered with vegetation and the mountain areas are fewer covered. As a result of the short growing period, the vegetation of the higher mountain parts is very sparse or completely lost in autumn, which supports the gully erosion. This matches with the results from mapping and analysing the erosion gullies. Most of strong distinct gullies are on mountain flanks with a high inclination. On the mountain flanks with a slight inclination there are also gullies, but they are distinctively weaker. Therefore, the vegetation on the mountain flanks is similar for the whole fjord, which makes all mountain flanks of the Skagafjörður susceptible for gully erosion. But the erosion gullies occur mainly in areas of the fjord which have a high inclination, which means that in these areas high energy is available for eroding the soil. Therefore, the melting water runoff in spring has more energy on the fjord flanks with a high inclination and supports the gully erosion. This knowledge suggests that trying to conserve and support the vegetation on the mountain areas would be necessary. With a compact vegetation cover on the mountain flanks, the soil is better protected against erosion from wind or water. The roots also play an important role in preventing soil erosion, because they stabilize the soil. (ZUAZO et al. 2011: 22) Hence, those areas which have a short growing season because of the short summer are better protected against gully erosional processes. The pastures in Iceland on the fjord bottom, in the mountain areas or in the highland are equally affected by ash fall events. (HARTMAN et al. 2017: 127) These ash fall events lead to a reduced production of vegetation and overgrazing of the pastures, which also builds a basis for soil erosion processes. (HARTMAN et al. 2017: 135) In the case of such an ash fall event it is necessary to handle the pastures with more care than normally, to avoid a degradation of the meadows. It is not known if there are any restrictions for the farmers to take their livestock on pastures on the mountain areas and highland. If these areas are handled with care and trying to revegetate the overgrazed areas, the soil is better protected against soil erosion through the grazing livestock. But on Iceland there was not only a change in vegetation. There was also a change in livestock and land use. (HARTMAN et al. 2017: 126 and THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47 and THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74)

The Skagafjörður is chosen as research area for this thesis because on the one hand, there are no studies about gully erosion in this area. And on the other hand, this area, as a rural one, shows the effects of soil erosion and farming and how it has changed the landscape over time. The gully erosion of the Skagafjörður is analysed using GIS analyses, satellite images and statistical analyses, to see how good these methods work for answering the hypothesis and research questions which are presented in chapter 2. This thesis also provides a summary of the land use of the Skagafjörður nowadays and in former times, to show the changes in this area over time and how the population has adjusted their way of living and land use practice accordingly. The ongoing gully erosion processes and how they interact with the actual types of land cover, farming and living in this fjord are examined.

2 Definition of the problem

"Soil erosion is defined as the removal of topsoil faster than the soil-forming processes can replace it, due to natural, animal, and human activity (i.e., climate change, numbers of livestock, overgrazing, overcultivation, forest clearing, mechanized farming, etc.)" (ZUAZO et al. 2011: 2). Under natural conditions, the soil forming process is equal than the soil removal process. If the soil removal process is distinctive than the soil forming process, the process of soil erosion is given. (BINI and ZILIOLI 2011: 36) The geomorphological process of gully erosion is influenced by water. Environmental conditions determine the erosion rate. These environmental conditions are land use, climate, vegetation, soil and topography. (TOY et al. 2002: 26)

"Several scientific disciplines study erosion from somewhat different perspectives, for different reasons, and in different parts of the world. Over the years, terminology has emerged to describe erosion and related processes. Unfortunately, the terms are not employed consistently" (TOY et al. 2002: 18).

According to ZEPP 2014, a gully is a big and linear erosion form. HARTMANN et al. 2003 defines the gullies in Iceland as a form that begins "[…] in a narrow furrow partway down the slope and growing wider and deeper downhill" (HARTMANN et al. 2003: 264). This form of gullies can be found in basaltic material which is weak converted. (HARTMANN et al. 2003: 264) "Some of these features form on convex ridge-top parts of slopes, as well as in natural concave valleys whose shapes would focus runoff. These types of features appear likely to form under snow pack during springtime melting, hence that the eroding water is produced locally on the slope, starting with a trickle upslope and with more water available downslope" (HARTMANN et al. 2003: 264).

TOY et al. 2002 defines two types of gully erosion, *ephemeral gully erosion* and *permanent or incised gully erosion*. *Ephemeral gully erosion* is defined after BINI and ZILIOLI 2011 as overland flow which flows in natural drainage lines or other linear elements like furrows and paths or roads. (BINI and ZILIOLI 2011: 41) This thesis looks at the second type of gully erosion, the *permanent or incised gully erosion*. "Permanent, incised gullies occur on both natural and disturbed lands" (TOY et al. 2002: 63). MITCHELL and BUBENZER 1980 define gullies the following way. "The surface channels formed when rills combine and develop to the extent that they cannot be eliminated by normal tillage operations are defined as gullies. Gullies are usually deep, steep-walled upland channels and commonly occur in areas of deep friable subsoils" (MITCHELL and BUBENZER 1980: 48-49).

Gully erosion is formed, when the velocity of the runoff water is high and it has a turbulent flow. This happens because of an increase of the slope gradient and rainfall intensity. (EVANS 1980: 115) "Rills and gullies remove much larger volumes of soil per unit area than does sheet wash" (EVANS 1980: 115). Gully erosion comprises the loss of soil under different land use and climatic conditions and at different scales, like spatial or temporal. (BINI and ZILIOLI 2011: 41) "[…] gullies are effective in transferring surface water and suspended sediment from uplands to valley bottoms and permanent channels, where they interact with hydrological processes, aggravating off site effects of water erosion, and determining consistent impacts on the landscape evolution" (BINI and ZILIOLI 2011: 41).

Thus, in order to develop gully erosion there has to be enough water, a high slope gradient and a friable soil which can easily erode by water. How the Skagafjörður is affected by intense precipitation and what the vegetation cover in this fjord looks like are defined in chapter 3.

For the last 1 200 years, soil erosion has been expanding throughout Iceland, which can be ascribed to the island´s many desert areas. (ARNALDS 2008: 416) There are two erosion categories in Iceland, which are erosion causing the loss of soil under vegetation and erosion of desert areas. The process of gully erosion is categorised as soil erosion under vegetation. (ARNALDS 2008: 417) "Erosion spots that form on slopes with solifluction features are considered separately under the Icelandic erosion classification, as such spots are subjected to running water with the potential development of severe erosion. Water channels or gullies are also common on slopes in certain areas […]" (ARNALDS 2008: 418). The human induced soil erosion processes started with the first settlers of Iceland, which cleared the forests for farmland for their livestock, to get charcoal for the iron production and for building ships and houses. (MC GOVERN et al. 2007: 45-46) At this time 30% of Iceland was covered in forests. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46) Because these interventions were so severe and forests do not grow back fast, nowadays only 6% of Iceland are covered in forests. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74) Therefore, the foundation for human induced soil erosion was given. Soil erosion poses a problem in Iceland to this day. This is partly caused by sheep and horse farming and partly as a result from sparse vegetation and erodible soils. Since 1980 the number of sheep in Iceland is decreasing though, which contributes to deceleration soil erosion. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74) Livestock grazing not only in the lowlands, but also in the highlands and mountain areas, where there is sparse vegetation, causes a problem as the soil is then unprotected against the sheeps´ and horses´ hoof steps. (MARONSSON 2017: 5-6) This is also a problem in the Skagafjörður which is a rural area with many sheep and horse farms. The erosion gullies are easier erodible than other areas of the Skagafjörður which are covered with vegetation. Therefore, these gullies had to protect against erodible processes and damaged caused by sheep and horse farming. To prevent soil erosion Iceland has founded the Soil Conservation Service in 1907 to protect the soil against erosional processes. (ARNALDS 2004: 114) From 1990 to 1996 the Soil Conservation Service organized the first comprehensive survey about soil erosion in Iceland. Through this study strong pronounced erosion problems for half of Iceland were found. Mountains, glaciers and water bodies are not observed in this study. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 52) "Concerning agricultural soils, 5% of permanent grassland is affected by moderate water erosion and 50% by wind erosion; around 230 hectares of soil are lost each year from Iceland´s 2 million hectares of thick, fertile volcanic soil, which is covered with rich vegetation but lacks cohesiveness" (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 52). In contrast to wind erosion, the percentage of water erosion in Iceland is low. But this does not mean that water erosion is negligible, it leads also to loss of soil and makes areas unusable. Therefore, there is an urgent need in slowing soil erosion and protecting the usable lands against erodible processes.

This master thesis tries to uncover the factors contributing to gully erosion in the Skagafjörður, which leads to the following hypothesis:

- Soil erosion consumes agricultural areas in North Iceland. Spatio-temporal patterns of soil erosion can be captured using medium-resolution satellite imagery and digital elevation models.

The research questions to decelerate this hypothesis are:

- How good can remote sensing using medium resolution satellite images and digital elevation models capture gully erosion processes in the study area?
- How has the area affected by erosion changed in the last twenty three years?
- Are there spatial patterns in soil erosion phenomena?
- Which counteractive measures were taken?

Soil erosion not only leads to a loss of soil and areas for agriculture and settlement, but also minimizes nutrients of the soil, plants and microbes. This lack of nutrients then causes sparse surfaces that are difficult to revegetate. (ZUAZO et al. 2011: 1) Soil erosion also causes a number of other issues. "Erosion results in the degradation of a soil's productivity: it reduces the efficiency of plant-nutrient use, damages seedlings, decreases plants' rooting depth, reduces the soil's water-holding capacity, impedes its permeability, increases runoff, and slows the infiltration rate" (ZUAZO et al. 2011: 2). Therefore, it is difficult to restore the soil to its former condition as the process of soil erosion is ongoing and continuously leads to a worsening of the soil state.

The process of water erosion, which leads to gully erosion, can be illustrated in four steps. First heavy rain falls on the ground and as a result, soil particles are disengaged. These soil particles are then transported downhill with the water in form of rolling, floating, splashing, and dragging. Lastly, the detached soil particles are deposited. These four steps of water erosion can be seen in figure 1.

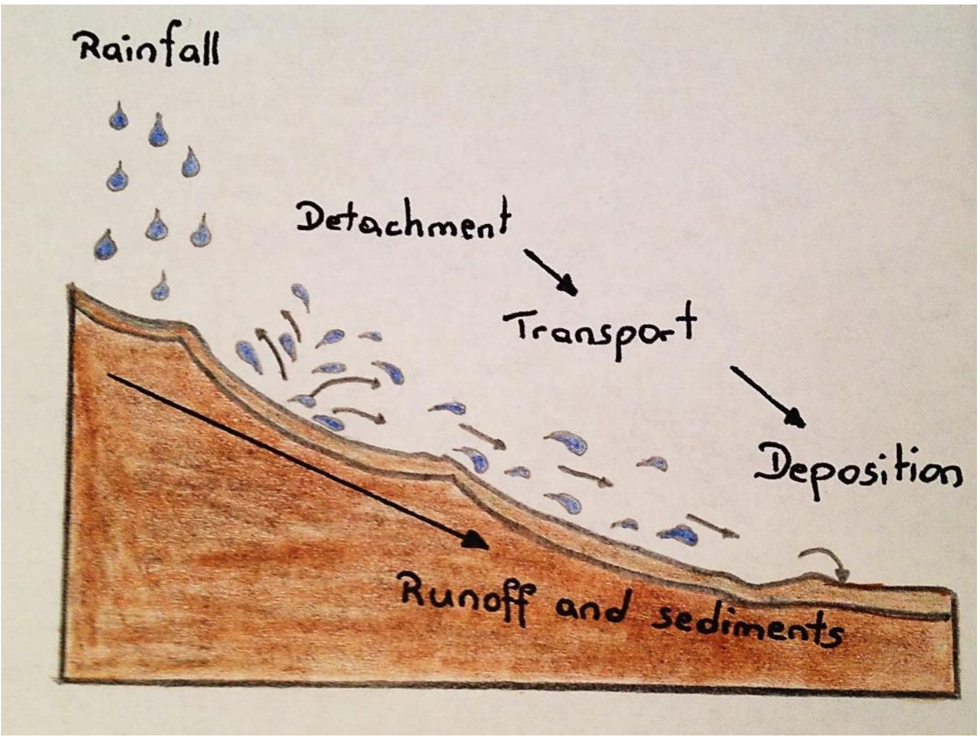

Figure 1: Process of water erosion (Reference: REITER after ZUAZO et al. 2011: 2)

There are on-site and off-site effects of soil erosion. Off-site effects are for example the pollution and aggradation of water bodies, damages on dams or reservoirs and bad air quality as a consequence of dust. On-site effects of soil erosion are the evaluation of the impact from soil erosion of crops, which are determined by the loss of nutrients and water available for the plants assessed. In addition to this, the quality of the soil is evaluated and knowledge is gathered. This gathering of knowledge is an important appliance when working on areas where no quantitative data is available. (ZUAZO et al. 2011: 4) “On the other hand, there is also a need to assess on-site impact of erosion in relation to soil-loss tolerance, soil life, soil resilience or ease of restoration, and in light of soil-management options for sustainable use of soil and water resources” (ZUAZO et al. 2011: 5). The following figure (figure 2) shows a diagram of the on-site and off-site effects of soil erosion on agricultural areas.

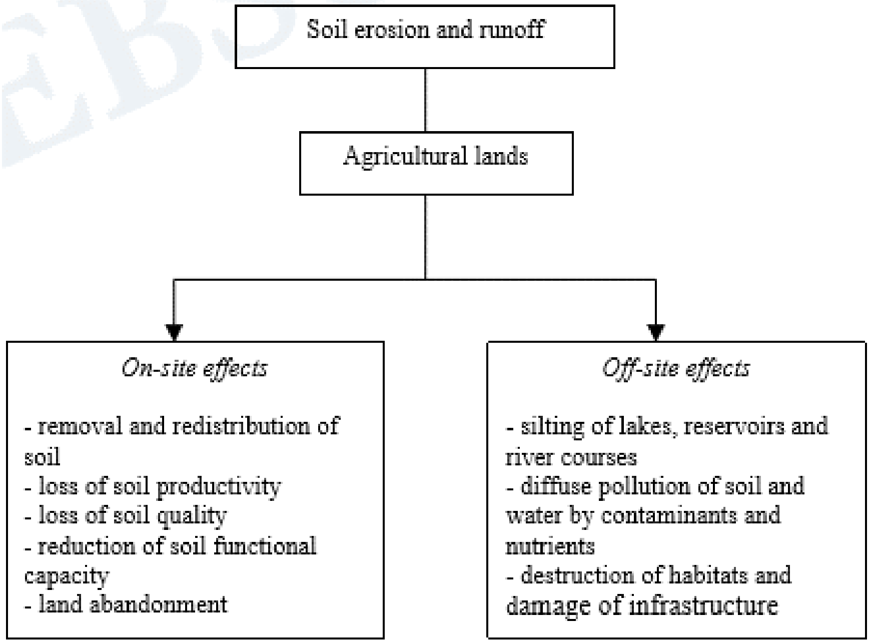

Figure 2: On-site and off-site effects of soil erosion on agricultural areas (Reference: ZUAZO et al. 2011: 17)

Rainfall has a direct impact on the unprotected soil surface and can destroy the soil aggregates and wash the soil particles away. Light soil particles can be eroded through light rain events as a consequence from the splashing raindrops. More energy in form of heavy or long-lasting rainfall is needed for the erosion of bigger soil aggregates. Long lasting rainfall can also lead to soil erosion, even when the actual rainfall is only light. If the soil is saturated with water, there is a higher runoff which can lead to erosional processes. But the soil erosion through precipitation depends also on the soil erodibility. Each *type of soil* is more or less susceptible for soil erosion. As some soils tend to erode more easily and some are resistant against it, the different types of soil and their components need to be considered when trying to prevent soil erosion. (ZUAZO et al. 2011: 7-8) The *vegetation* cover of the soil is also an important factor for the process of soil erosion. If there is much vegetation, the soil surface is protected against the erosional impact of flowing water. Sparse vegetation also only provides sparse protection for the soil beneath and makes the soil susceptible for erosional processes. But it is not only the vegetation above the soil surface that stabilizes the soil against erosional processes. The plant roots also play an important role in stabilizing the soil. “Therefore, any human activity that removes or decreases vegetation cover can cause soil erosion (e.g. deforestation, widespread cropping, and overgrazing). Vegetation cover and land management are the main limiting factors of soil-erosion process […]” (ZUAZO et al. 2011: 10). Another important factor that has an impact on soil erosion is the *topography*. An area with a high slope has a higher potential for soil erosion processes because of the higher energy of the surface runoff. “The degree and length of the slope are two essential features of topography in relation to soil erosion and surface runoff. […] Soil erosion can be expected to increase with slope length and steepness as a result of respective increases in volume and velocities of surface runoff” (ZUAZO et al. 2011: 9). *Human induced processes* are another factor for soil erosion. These processes can reach from farming techniques to overgrazing from livestock. Therefore, it is important that the farmers are aware to the practices that supports soil erosional processes and that they have guidelines for farming techniques that prevent soil erosion. Another important point is that the farmers can farther graze their livestock on pastures but with more awareness to protect the vegetation cover to prevent soil erosion. “Soil erosion and surface runoff are major degradation problems on farmlands. To prevent these processes, appropriate erosion management techniques are essential (ZUAZO et al. 2011: 11).

Therefore, soil erosion is a complex effect, which can’t be easily determined and pictured.

3 Description of the study area

The Skagafjörður is a fjord which is located in the north of Iceland, with the longitude of 19° and the latitude of 65°. This fjord is about 60 km long and 30 km wide and is surrounded by mountains with a height of more than 1000 meters. The Skagafjörður adjoins to peninsula Skagi in the west and the peninsula Tröllaskagi in the east.

Whilst Sauðárkrókur is the biggest town in the Skagafjörður, there are also a few small villages in the fjord. Héraðsvötn, which has its source in the highlands, is the river flowing through the fjord. Figure 3 gives an overview about Iceland and the red polygon marks the position of the Skagafjörður.

Figure 3: Map of Iceland with the Skagafjörður marked with the red polygon. Processed from REITER 2017 (Reference: NATIONAL LAND SURVEY OF ICELAND 2013)

The watershed of the Skagafjörður can be seen in figure 4. It was generated in ArcGIS on base of datasets from the National Land Survey of Iceland. This watershed covers a big area of the fjord, hence there is a big area available for water to run down the fjord and to transfer soil.

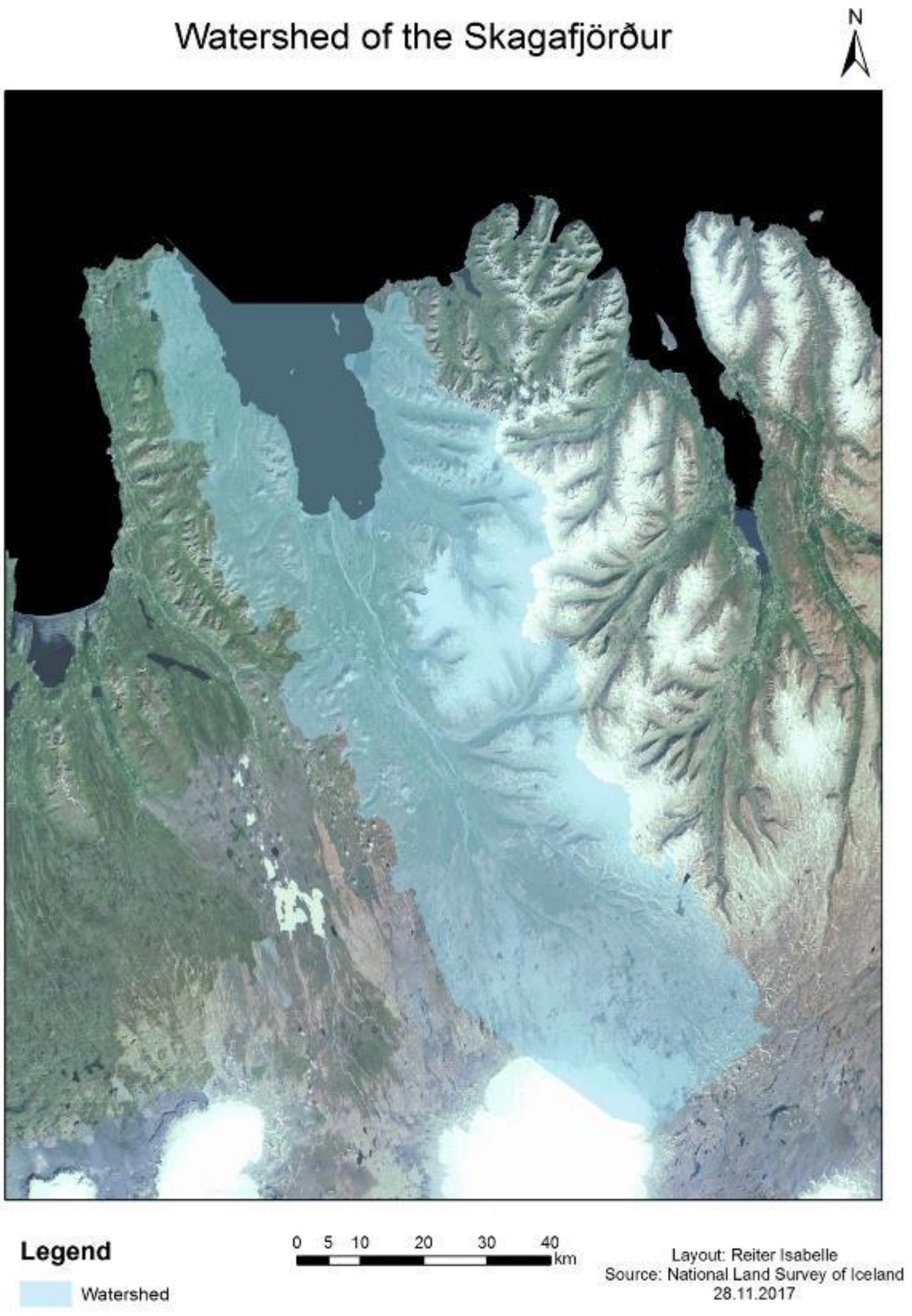

Figure 4: Watershed of the Skagafjörður (Reference: REITER 2017)

The following chapters address climate, geology and soil, vegetation and land use, historical development and population and economics of the Skagafjörður.

3.1 Climate

The climate in Iceland today is very different from the Icelandic climate of former times. 18 000 years before present the glaciers decreased rapidly and covered only high mountain areas. This was followed by the medieval warm period in which the first settlements took place. "[…] the dating of several regional raised beaches in the NW part of Skagafjörður (Skagaheiði) from 12000 BP to 9600 BP suggests that the lower part of the fjord was totally deglaciated during the end of the Younger Dryas or Preboreal […]" (FEUILLET et al. 2011: 579). From 1550 to 1850 was the little ice age, in this time the glaciers increasing mass. (GREIPSSON 2012: 45-46) "The climate during the LIA [A/N: little ice age] was characterized by severe cold inter-decadal periods with slight warming in between. Glaciers advanced and retreated in response to these inter-decadal fluctuations in average temperatures during the LIA" (GREIPSSON 2012: 46). After the little ice age, the temperature rose, but there had also been colder periods. (GREIPSSON 2012: 46) "Since 1981 AD annual temperatures have been gradually rising" (GREIPSSON 2012: 46).

The Icelandic climate is affected by the position of the island in the central north Atlantic, the terrain of the island and the cyclones passing it. Icelandic climate is classified as oceanic boreal to subarctic. (GUÐMUNDSSON 2007: 281) The Gulf stream is the main factor of influence regarding the climate of the coastal areas of Iceland. The Irminger stream, a side stream of the Gulf stream, flows coming from south, around Iceland and causes a temperate climate at the coast. Due to the Gulf stream the climate in the coastal areas is generally warmer than in the highlands. (SCHUTZBACH 1985: 130-131) Figure 5 displays the Gulf stream and the Irminger stream around Iceland.

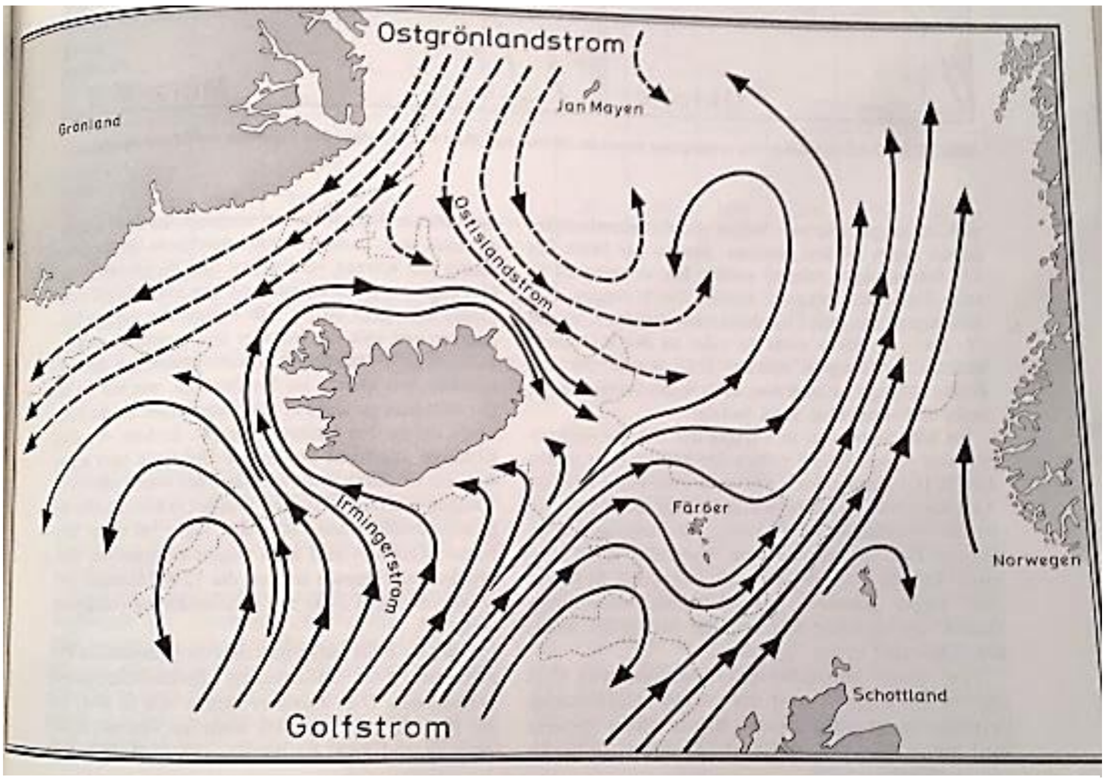

Figure 5: Gulf stream and Irminger stream around Iceland (Reference: SCHUTZBACH 1985: 131)

“Off the northwest and southeast coasts, a temperature front is found between these two different currents. It is obvious that the oceanographic conditions just described must influence weather and climate considerably, both directly at the coasts and also because all air masses arrive in Iceland after having passed over the sea” (EINARSSON 1984: 675).

The current which comes from the north is named the East Iceland stream, which can bring drifting ice to Iceland. (SCHUTZBACH 1985: 131) Because it causes lowering of the air temperature, it also influences the climate. In past times sea ice had negative impacts on crops, vegetation and trading routes of ships. (HARTMAN et al. 2017: 125) The East Iceland stream can be seen in figure 5.

The weather throughout Iceland differs given the topography and varying wind directions. (EINARSSON 1984: 676) Cold Arctic air masses which encounter warm Atlantic air masses create a polar front with a low pressure area (cyclones). These cyclones have their origin mainly in Greenland or Newfoundland. They draw eastward over the north Atlantic, because of the earth rotation and pass Iceland mainly in the north with high wind speed ranging from 50 to 100 km/h, especially in winter. (SCHUTZBACH 1985: 133) As a result from this the main wind direction of Iceland is southwest or south. These winds cause a lot of moisture and clouds around the island. In the south of Iceland precipitation is quite high because of the wet air rising alongside the mountains.

In case the cyclones pass Iceland in the south the winds are coming from north, northwest or northeast. These winds bring cold air masses and precipitation to the north coast. (SCHUTZBACH 1985: 134)

There is a constant change of precipitation, overclouding and temperature as a result from the changing low pressure areas. Precipitation is frequent in Iceland but it is seldom strong. (SCHUTZBACH 1985: 134)

The annual mean temperature of north Iceland is not higher than 4°C. Precipitation occurs in Iceland as a result of cyclones. Those areas with the highest precipitation are located in the south-east of the island. Such as the region of the glacier Vatnajökull with a precipitation of more than 4 000 mm. As opposed to this, areas with precipitation as low as 400 – 600 mm are located in the northern parts of Iceland. Overall, depending on local conditions the precipitation can vary over short distances across the island. (EINARSSON 1984: 684) GOESSLING 2017 has done research about climate trends for Iceland in the 21st century and expects a greater warming of the land than in the ocean. There are also two spatial trends found. These trends lead to a greater rise in temperature on higher elevations in the north of Iceland and on glaciers. (GOESSLING 2017: 16) “The changes in precipitation seem to be connected to changes in temperature. […] It indicates that increasing precipitation is connected to more warming” (GOESSLING 2017: 19). The precipitation in Iceland can be seen in figure 6. The Skagafjörður is located in the precipitation zone of 401 – 800 mm.

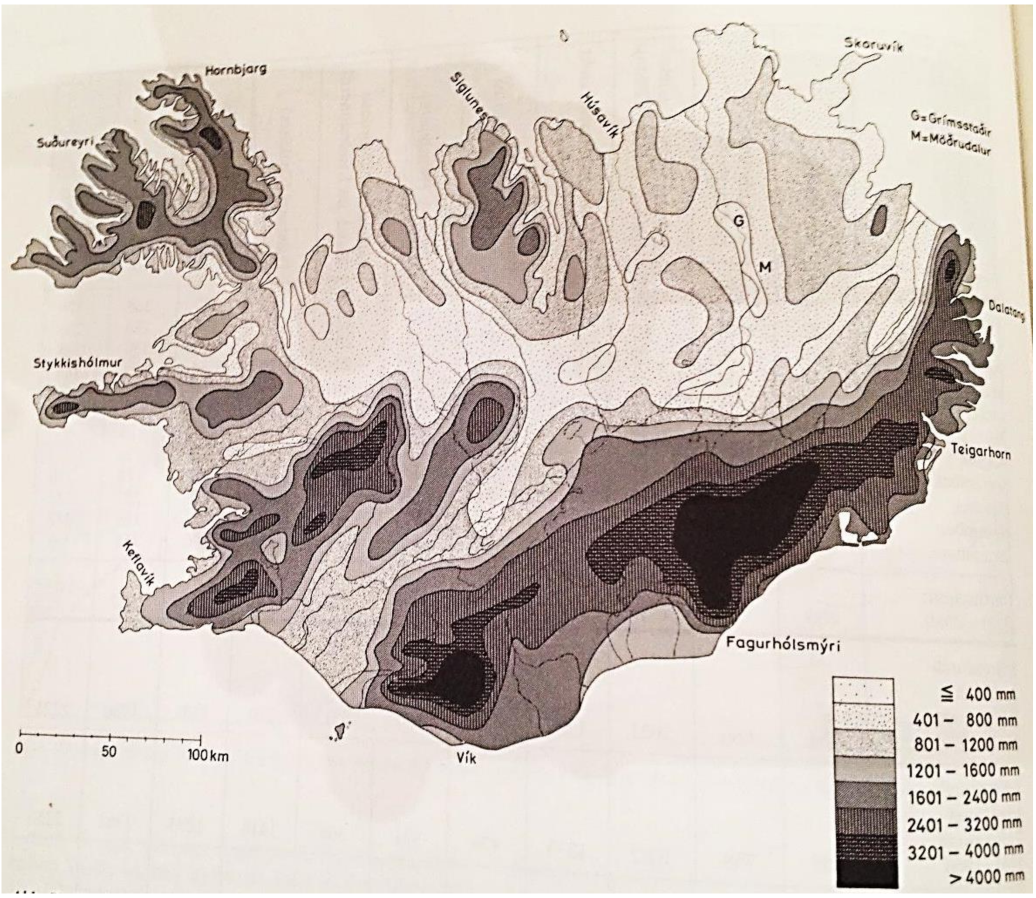

Figure 6: Precipitation map of Iceland (Reference: SCHUTZBACH 1985: 134)

The following table (table 1) shows the average precipitation of selected places in Iceland. It can be seen that the precipitation is higher in the south than in the north and the annual average precipitation is rising in selected places with an exception of Hornbjarg, which is located at Hornstrandir, at the north-west coast. Akureyri which is located in the north of Iceland, near to the Skagafjörður shows with 471 mm annual mean precipitation a typical low precipitation value for the north region of Iceland.

Table 1: Average precipitation from selected places of Iceland (Reference: SCHUTZBACH 1985: 133)

	Reykjavik	Stykkishólmur (auf Snæfellsnes)	Suðureyri (im Súgandafjörður, Nordwestküste)	Hornbjarg (Hornstrandir, Nordwestküste)	Akureyri (Nordküste)	Húsavík (Nordküste)	Grímsstaðir (Nordostisland, im Landesinnern)	Dalatangi (Ostküste)	Teigarhorn (bei Djúpivogur, Ostküste)	Fagurhólsmýri (Öræfasveit, Südküste)	Vík í Mýrdal (Südküste)
Januar	68	64	127	93	53	71	32	133	132	165	179
Februar	78	77	108	104	39	53	23	120	131	183	205
März	82	85	87	89	33	53	20	130	121	150	188
April	53	56	82	65	24	54	23	79	54	105	168
Mai	41	38	35	51	17	38	16	90	90	151	161
Juni	44	41	52	94	35	47	40	82	74	143	–
Juli	51	50	45	75	28	53	38	117	90	114	–
August	73	57	61	80	32	70	46	95	122	156	–
September	72	60	91	112	39	87	36	168	108	174	230
Oktober	93	87	129	128	54	87	27	162	175	222	222
November	79	75	170	114	61	102	28	139	93	169	218
Dezember	66	65	126	96	56	85	24	129	106	155	192
Durchschnitt (1971–1980)	800	755	1113	1101	471	800	353	1444	1296	1887	–
Jahresdurchschnitt der Zeitperiode 1961–1970	764	666	1021	1289	446	786	351	1281	1105	1786	2221
Jahresdurchschnitt der Zeitperiode 1931–1960	805	758	1082	1373	474	531	366	1418	1293	1761	2256
Jahresdurchschnitt der Zeitperiode 1901–1930	904	680	902	–	465	509	–	–	1256	1828	2093

Thus, depending on the weather type either cyclones that cause precipitation, cold winds coming from the Greenland ice cap, tropical air that hits Iceland from the south and leads to fog or strong wind that hits Iceland from the north and causes heavy snowfall in north Iceland, can occur. (EINARSSON 1984: 678)

At the weather station Berdstaðir, which is located in the south west of the Skagafjörður, there is an annual mean air temperature of 3°C and the annual mean precipitation is 634 mm. The extreme values of air temperature at the weather station Berdstaðir are -24,5°C and 25°C. The following figure (figure 7) shows the location of the weather station Berdstaðir and the mean monthly air temperature at this station between 1978 and 2011. (FEUILLET et al. 2011: 579)

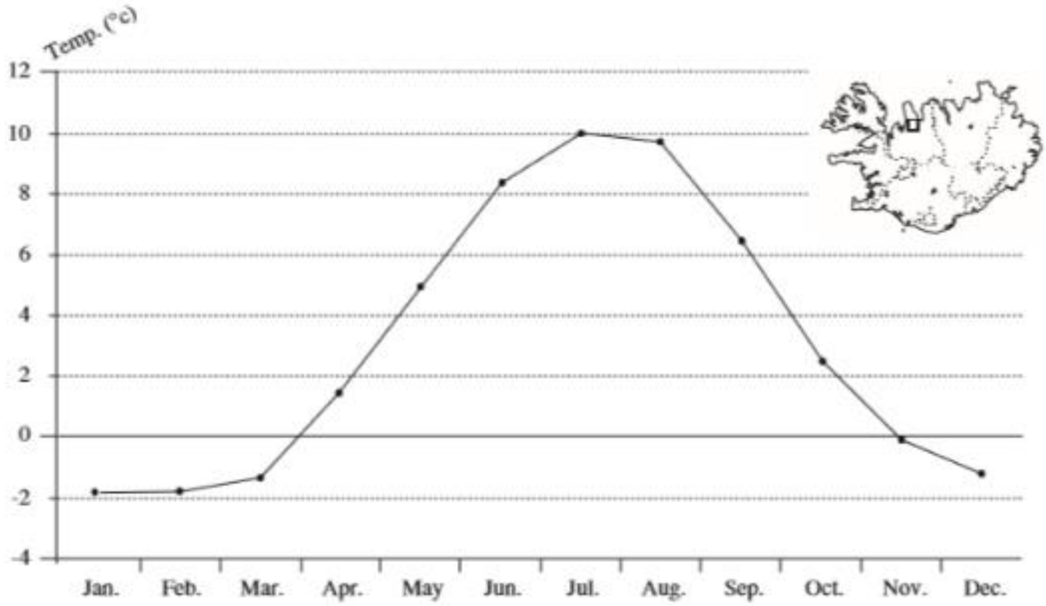

Figure 7: Mean monthly air temperature at the weather station Berdstaðir between 1978 and 2011 (Reference: FEUILLET et al. 2011: 579)

On the 30th of October 2012 the Icelandic Meteorological Office gave a warning of hazardous weather for the next days. A stormy wind with more than 20m/s was expected for the whole country, which lead to continuing snowfalls in the northern part of Iceland. This weather eventually prolonged for a week. (URL-A)

The Icelandic Meteorological Office released a warning of severe weather for the 29th of December 2012. The forecast predicted strong northeast winds (20-25 m/s) in the Westfjords and weaker winds in the other parts of Iceland. For the north of Iceland there are heavy snowfalls were predicted. (URL-B)

Every year there are gale warnings in Iceland mainly concerning the southern parts of the country. (URL-C) The warnings from October and December 2012 are special warnings, because they include strong winds in addition to heavy and continuing snowfalls in the northern parts including the Skagafjörður. These two warnings were based on strong wind that reached Iceland from the north and caused continuous snowfall in the north of Iceland. The massive snow masses that were deposited in autumn and winter of 2012, lead to a rise in meltwater in spring, which can lead to more eroded soil.

2016 was a very warm year in Iceland with records on all climate stations in northwest Iceland. (VEÐURSTOFA ÍSLANDS 2017: 5) "During the first two months of the year temperature were close to long-term means, but the last three months of the year were particularly warm. Wind speed was slightly lower than average. During late winter to mid-summer conditions were rather dry, but the autumn was very wet […]" (VEÐURSTOFA ÍSLANDS 2017: 5). As a result from the warm climate in 2016, the permafrost is melting, which leads to landslides in the north of Iceland. (VEÐURSTOFA ÍSLANDS 2017:7) Glaciers also show melting processes as a result from global warming. (VEÐURSTOFA ÍSLANDS 2017: 13) Therefore, there is more water from the glaciers available for erosion processes, which can erode the melted permafrost and unprotected soil. Should climate warming continue over the years, there would be more melting processes on permafrost and glaciers.

3.2 Geology and soils

The crust of Iceland has oceanic derivation. This results from the fact, that Iceland is divided through the Mid Atlantic Ridge, in the west in the North American plate and in the east in the Eurasian plate. "Rifting plate boundaries that divide the island between the Eurasian and North American plate control the geological structure of Iceland (...)" (GEIRSDÓTTIR et al. 2006:171). The thin black line in figure 8 shows the rift zone of the Mid Atlantic Ridge.

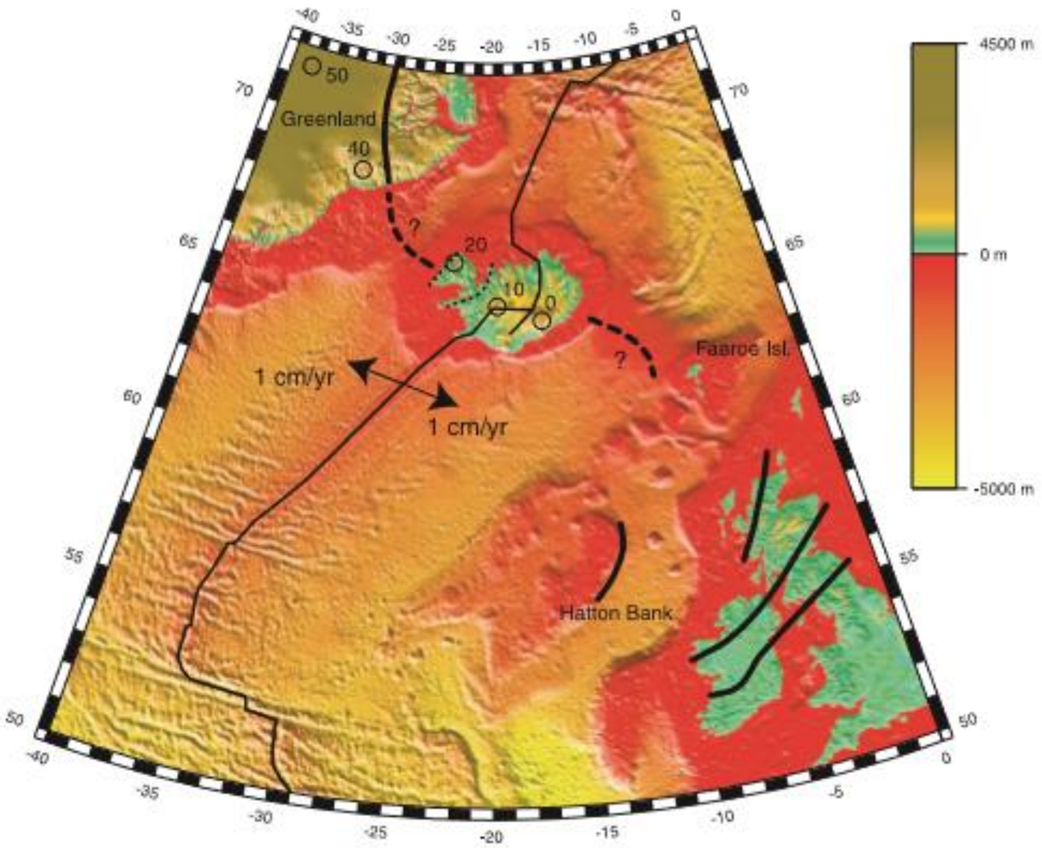

Figure 8: Rift zone of the Mid Atlantic Ridge (Reference: FOULGER et al. 2005: 598)

The plate boundaries of the Mid Atlantic Ridge follow the Northern Volcanic Zone. In the south of Iceland there is the west Western Volcanic Zone and the Eastern Volcanic Zone. Between the Western - and Eastern Volcanic Zone there is a microplate suggested, as a spreading zone of the overlapping Eastern Volcanic Zone and Western Volcanic Zone. This microplate is bordered in the south by the South Iceland Seismic Zone and in the north by the Central Iceland Volcanic Zone. (SAVRY and CAÑÓN-TAPIA 2014: 208) These volcanic zones and the microplate can be seen in figure 9.

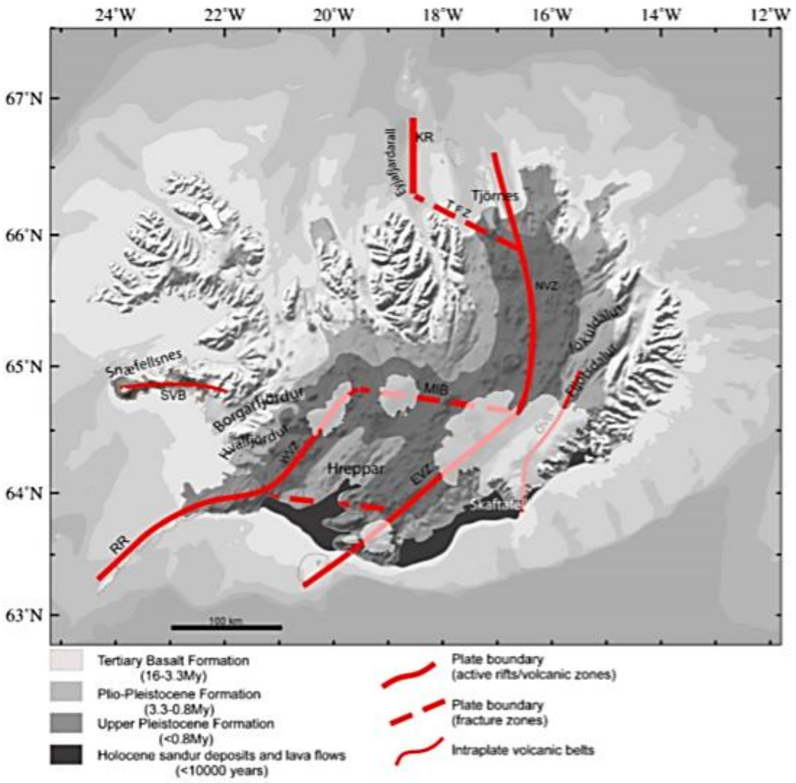

Figure 9: Volcanic zones of Iceland (Reference: GEIRSDÓTTIR et al. 2006: 172)

62 million years ago the magmatism in the north Atlantic started and lead to a continual breakup and the start of seafloor spreading in the Labrador Sea. After 54 million years the north Atlantic was opened. (FOULGER et al. 2005: 598)

There is a hot spot under Iceland which leads to complex configuration of plate margins. (GEIRSDÓTTIR et al. 2006: 171) The mantle plume which leads to this hot spot under Iceland is located under the glacier Vatnajökull in the southeast. (GEIRSDÓTTIR et al. 2006: 171) “Unusually high volcanic productivity caused by the superposition of the mantle plume and mid-ocean-ridge magmatism have made Iceland an environment where constructive geologic processes outweigh destructive processes. The results are an excellent preservation of the Tertiary and Quaternary depositional record in Iceland, where sediment horizons are covered and protected from erosion by basaltic lava flow sequences […]”(GEIRSDÓTTIR et al. 2006: 171).

“North and Northwest Iceland are composed entirely of rocks belonging to the Tertiary Basalt Formation, except for the outlier and extinct Skagi volcanic belt which was formed during the Plio-Pleistocene time” (THORDARSSON and HOSKULDSSON 2002: 155). The Tertiary Basalt Formation in North Iceland is between 12 million years to 7 million years old. The oldest Tertiary Basalt Formation with an age of 12 million years is located at the Tröllaskagi peninsula. (THORDARSSON and HOSKULDSSON 2002: 155) Figure 10 shows that the North Atlantic Rift Zone was located more western seven to four million years ago than today.

Figure 10: North Atlantic Rift Zone from seven million years to four million years before present. (Reference: SCHUTZBACH 1985: 76)

From two million years to 3,3 million years before present, the volcanism of the Skagafjörður area started. The volcanism of this area was active for a period of one to two million years. (GUÐMUNDSSON 2007: 376)

The landscape of the Skagafjörður is distinguished by a fjord and rugged mountains which is an indication of intensive glacial erosion. (THORDARSSON and HOSKULDSSON 2002: 155) During the Weichselian stage, which was from 120 000 to 10 000 years, whole Iceland was glaciated. (THORDARSSON and HOSKULDSSON 2002: 44-45)

The following figure 11 gives an overview of the Geology of the Skagafjörður.

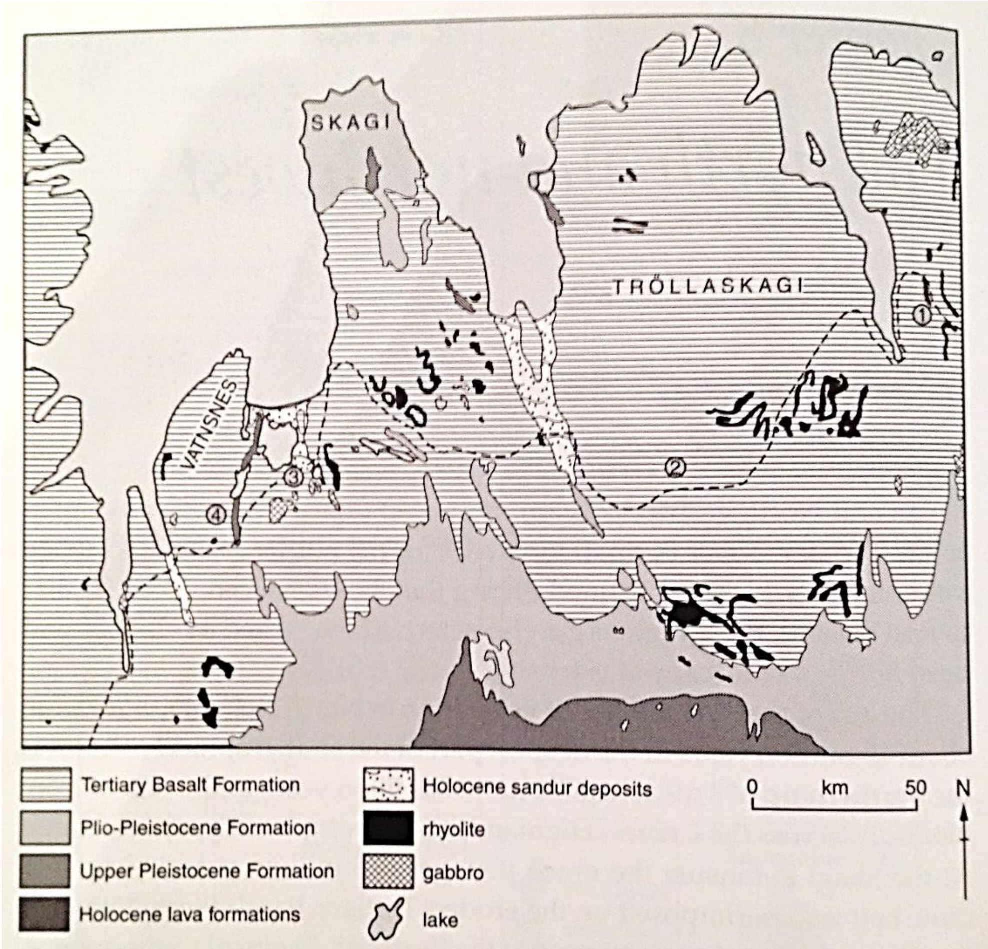

Figure 11: Geology of the Skagafjörður (Reference: THORDARSSON and HOSKULDSSON 2002: 156)

As shown on the geological map, the Skagafjörður exists mainly of Tertiary Basalt Formations with rhyolite incidence appearing in the western part of the fjord. The bottom of the fjord is characterised through Holocene sandur deposits, which have their origin in the glaciers of the highland. The northern part of the Skagi peninsula, the island Drangey and the Þórðarhöfði area which is located on the eastern shore of the Skagafjörður are characterized by accumulations of the volcanism which was active between two million years to one million years before present, marked as Plio-Pleistocene Formations on the geological map. (GUÐMUNDSSON 2007: 376)

Iceland has different types of soil. “Two main groups are distinguished: soils under vegetation and the soils of deserts. Soils under vegetation are andic (Andosol properties) and/or histic (organic) in nature. The soils of the deserts are dominated by poorly weathered volcanic tephra and are termed Vitrisols (Latin ’vitr’: glass). Other groups exist, such as permanently frozen Cryosols in the highlands, calcareous soils near the shoreline in some areas, and both Regosols and Leptosols, but they have limited extent compared to the Andosols, Histosols and Vitrisols […]” (ARNALDS 2008: 411). In Iceland the soil type Andosol appears under vegetated areas, which is a dark soil that is generated from volcanic substrate with a high ratio of Tephra. It consists of Tephra, clay minerals, humus, air and water. The soil comprises fragments of stones, which come from streams, are deflated from glacial areas or deflated from other Badlands of Iceland. As a result from rapid chemical defect with the creation of clay minerals and the hyaline ash, the Icelandic Andosol has a low specific weight with weak internal grain adhesion. (GUÐMUNDSSON 2007: 316) Through chemical defect clay minerals are converted from primary minerals of fragments of stone. Solved substances, which are in the water of the soil, react with the mineral components of fragments of stone, tephra or rock underground. Main clay minerals which are generated as a result from Tephra weathering are named Allophan and Imogolite, as well as Halloysite and Ferrihydrate. Though Halloysite, which is a common clay mineral in Andosol is uncommon in Iceland. (ARNALDS 2008: 413) Ferrihydrates cause the brown colour of the soil. The pH-value of the soil is basic near volcanic zones and acidic with a greater distance to volcanic zones. (GUÐMUNDSSON 2007: 316)

The following figure (figure 12) gives an overview of the distribution of Icelandic soils.

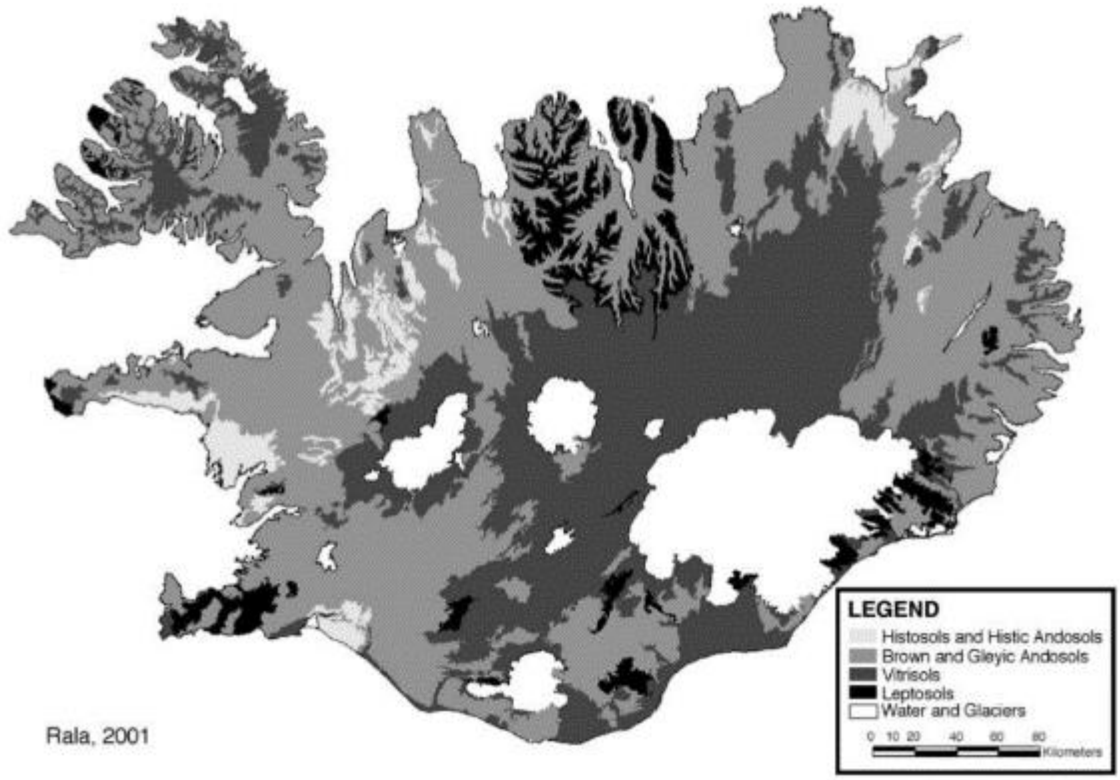

Figure 12: Distribution of Icelandic soil types, generated from ARNALDS based on the map from the Agricultural Research Institute of Iceland (RALA) 2001 (Reference: ARNALDS 2004: 7)

In the Skagafjörður mainly brown and gleyic Andosol can be found. Only in those parts of the fjord that are near to the sea, Histosol and Histic Andosol, which consists of more organic material than Andosols. (ARNALDS 2004: 8) In the high areas of the mountains Leptosols can be found. "Icelandic Leptosols […] include lava surfaces with shallow eolian-andic mantles and scree slopes" (ARNALDS 2004: 10). The highland areas of the Skagafjörður, where Vitrisols are distinctive, are characterized through a limited plant cover on the soil surface and a stone pavement as a result of frost heaving. (ARNALDS 2004: 9) "They are sandy and shallow and the mineralogy is dominated by volcanic glass. […] When vegetation is established on the surface, the soils develop characteristics of Brown Andosols within 50-200 years depending on climatic factors" (ARNALDS 2004: 9-10).

"The soils that form in volcanic deposits are called Andosols and are unique in character. […] Andosols are often sensitive to disturbance because they lack a layer of silicate clay minerals" (ARNALDS et al. 2001: 8). Andosols originated from volcanic ash and have very loose topsoil. (BLUME et al. 2010: 357) Following figure (figure 13) shows an Andosol profile from Iceland.

Figure 13: Andosol profile from Iceland (Reference: URL-F)

“Icelandic Andosols often contain tephra layers, especially in the proximity of the most active volcanoes, such as Mt. Hekla and Katla. Rhyolitic tephra layers are fewer in number than basaltic, but tend to be very distinctive with light color in contrast to the darkish brown colors of the Andosols […]. The rhyolitic tephra weathers much more slowly than the basaltic tephra and seems to have little influence on soil acidity” (ARNALDS 2008: 411). The layers of tephra can be seen as thin black layers in figure 13 at the bottom of the profile. Their dark colour suggests that they are basaltic tephra layers. The clay minerals are mainly Allophane and Imogolite. These clay minerals are originated from volcanic glass. (BLUME et al. 2010: 357) Andosols are very porous and light soils that can store large amounts of water which makes them a good surface for cultivating plants. (BLUME et al. 2010: 358) Other organic soils, for example Histosols, can store less water than Andosols. (URL-F) Andosols have a high nutrient fixation asset and are frequent acidic with a pH-value around 5, as a result from fast weathering in humid climate. (BLUME et al. 2010: 358) Another property of this soil is a problem for managing landslides. Because Andosol have a slight cohesion what means that they can easy act like liquids if the soil is highly saturated with water. (ARNALDS 2008: 416) This leads to a problem in risk management and soil erosion. “Water relations can be disturbed by the presence of coarse grained tephra layers in the soils, which impede unsaturated water movement in soil” (ARNALDS 2008: 416). In the Skagafjörður there are more than over 100 landslides mapped, which reach from rotational landslides to complex landslides. All these occur in areas of the fjord, which are covered with Andosol. (DECAULNE et al. 2016: 1304)

The Gleyic Andosol is a soil which occurs in wetlands. These soils have with 12% a low organic content in the surface horizons and the clay mineral Allophane content reaches from a few percent to over 20%. At the boundary of tephra layers the oxidation is very distinctive and shows evident texture changes where the tephra and the soil converge. In wetland areas and in the highlands, the deposit from eolian processes is occurring very fast, thus Gleyic Andosols are the common soil type. (URL-G)

Histosols have a higher organic content than Andosols. These soils develop in wet areas like pogs or peatlands when organic matter accumulates faster than it decomposes. Because most Histosols are saturated with water all year round, the decomposition is very slow. If Histosols are drained, they are a good soil for farming. But without their natural water content, they are going to decompose very fast or going to subside. Therefore, these areas are not usable for building roads or villages. (URL-H) Figure 14 shows the profile of a Histosol.

Figure 14: Histosol profile (Reference: URL-I)

In contrast to the Andosol profile it can be seen, that the colour of the soil is even darker. This is a result of the high organic matter of the Histosol.

Leptosols are soils that develop on shallow bedrock. (BLUME et al. 2010: 377)

"The Vitrisols are the soils of the deserts. They have dark grayish colors and contain limited amount of organic carbon (<1%). They are in fertile in contrast to the Andosols and are subjected to intense surface processes such as cryoturbation and erosion" (ARNALDS 2008: 411).

"Clay minerals in Andosols are formed in situ, not by translocation or leaching and precipitation in a sub-surface argillic (Bt) horizon" (ARNALDS 2008: 413). In Icelandic soils the clay minerals Allophane and Ferihydrate are common and have clay contents of around ten and 35%. (ARNALDS 2008: 413) "In addition, the cold climate in Iceland favors organic build up, especially in water saturated wetland situations. The steady flux of eolian materials and tephra additions leads to burial of the organic rich surfaces, increasing the total content of organic material in the soils. Icelandic soils therefore tend to have appreciable amounts of organic matter, and the wetland soils exhibit a unique combination of histic (organic) and andic soil characteristics that is uncommon elsewhere" (ARNALDS 2008: 413). Andosols accumulate carbon naturally and have a carbon percentage of 6%.

Although this carbon value is only in layers which are not disturbed by land use or tephra deposits. The organic content of Andosols can be reduced if the soil is near the volcanic belt or through intense aeolian activity. As previously mentioned, Andosols have a high water storing ability. Vitrisols in contrast have low water storing abilities and rapid water infiltrations in the summer months which are typical for sandy soils. Furthermore, Vitrisols have a nutrient deficit and low organic content. (ARNALDS 2008: 416)

3.3 Vegetation and land use

"Over half of the country's vegetation coverage is thought to have disappeared because of erosion since the settlement period. This is particularly due to clearing of woodlands and overgrazing, which have facilitated the erosion of the sensitive volcanic soil. According to the findings of a general survey of soil erosion in Iceland, 52% of the country, excluding that covered by the highest mountains, glaciers and lakes, is seriously eroded. Additionally, information from vegetation maps shows that the condition of soil and vegetation is much poorer than growing conditions would allow" (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46).

At the time of the first settlements, large birch forests were growing on the island. (MC GOVERN et al. 2007: 45-46) Evidence of great areas covered in forests is also recorded in the settlement book (Landnámabók). (SCHUTZBACH 1985: 191) These forests have been cutover, to get pastures for the livestock and areas for farming and living. Another reason for deforestation was iron production. The settlers needed charcoal for producing iron products, which caused a shrinking of the forests. (MC GOVERN et al. 2007: 45-46) The missing vegetation left the soil unprotected against erosion a revegetation of these eroded areas wasn´t possible anymore. (SCHUTZBACH 1985: 192) "It is likely that large areas of moss heathland dominated by Racomitrium moss, and shrub heath, were destroyed in the highlands after the settlement" (ARNALDS and BARKARSON 2003: 107). The vegetation of Iceland is not very rich which is resulting from short summers. In May the vegetation starts growing again, given that the snow from the previous winter has melted. After a short growing season, the weather gets colder in September and limits the growing of plants. The main reason for the species poverty of Iceland is the position in the Atlantic Ocean. As an isolated island it is not easy for new plants to settle on. Two to three quarters of the plants occurring in Iceland today, were there since the Pleistocene. They survived the ice ages in areas around hot springs and spread over Iceland after the ice had melted. Although sea birds and sea currents also bring new plant seeds to the island, the main reason for new plant growing in Iceland has anthropogenic reasons, as the first and following settlers planted new plants in Iceland. (SCHUTZBACH 1985: 184) Some new plants of Iceland are the disc mayweed, which was located in 1895 and the flea sedge, which was located in 1950. Both plants are now spread all over Iceland.

After the Second World War, with the development of traffic many new plant seeds were brought to Iceland, mainly through the import of grass seeds for agriculture. (SCHUTZBACH 1985: 184)

The main Icelandic plants belong to the group of flowering plants which have seeds and spread through these. All of the Icelandic flowering plants belong to the class of angiosperms. This means that the seed bud is imbedded in an ovary. Only one plant in Iceland can be assigned to the gymnosperm class, which is the juniper. Regarding the class of angiosperms there are species from the family of composite plants, pink family, cabbage family, rose family, foxglove family, saxifrage family, crowfoot family and the knotweed family in Iceland. Classes of grass, sedge and rush family are represented as well. Mainly plants on Iceland are from Scandinavia, only a few are from North

America. Two-thirds of Icelandic plants have a boreal distribution and one-third of the plants are arctic alpine. (SCHUTZBACH 1985: 185-186) The arctic bellflower (Campanula uniflora), the many-leaved saxifrage (Saxifraga foliolosa), the mountain rock floret (Draba alpina) and the mountain cat paw (Antennaria alpina) are species that are spread in the Skagafjörður, which can be seen in figure 15. These species need less precipitation and less temperature differences and are usually spread in areas over 1000 meter above sea level. (SCHUTZBACH 1985: 186)

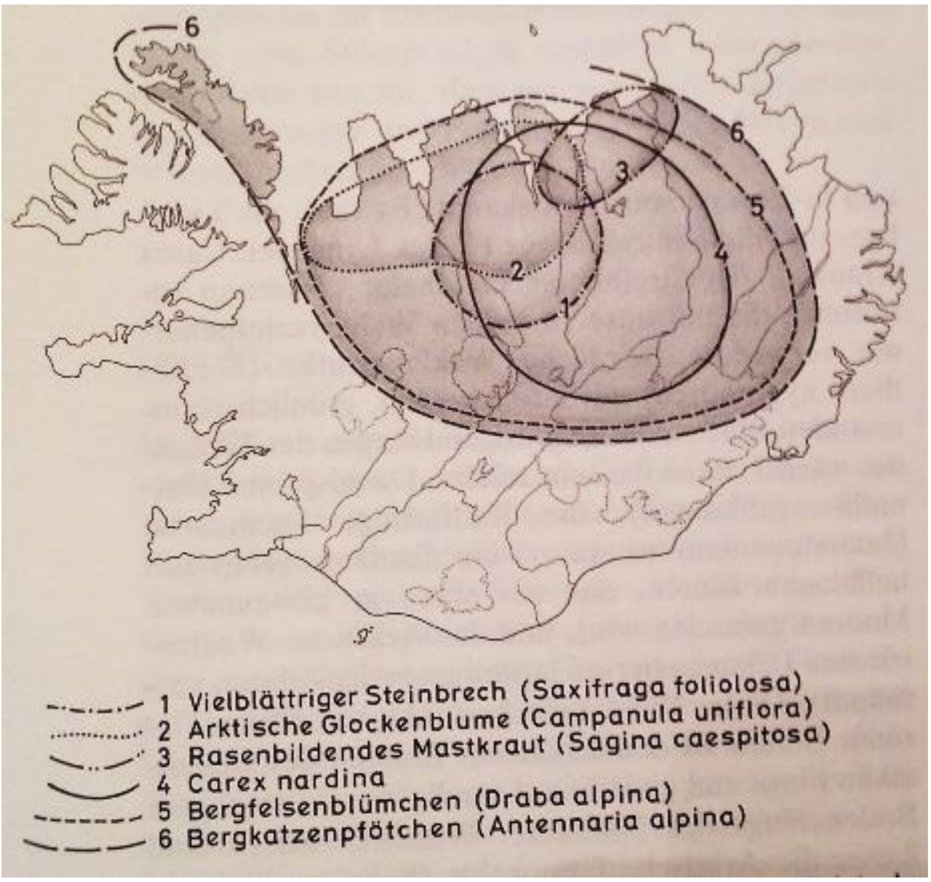

Figure 15: Species which are spread in the Skagafjörður (Reference: SCHUTZBACH 1985: 186)

Figure 16 shows a CORINE Land Cover map of 2006 with the Skagafjörður marked with a red polygon. The legend from the CORINE Land Cover map is in Icelandic, but it can be converted based on the legend of the Austrian Umweltbundesamt (URL-J).

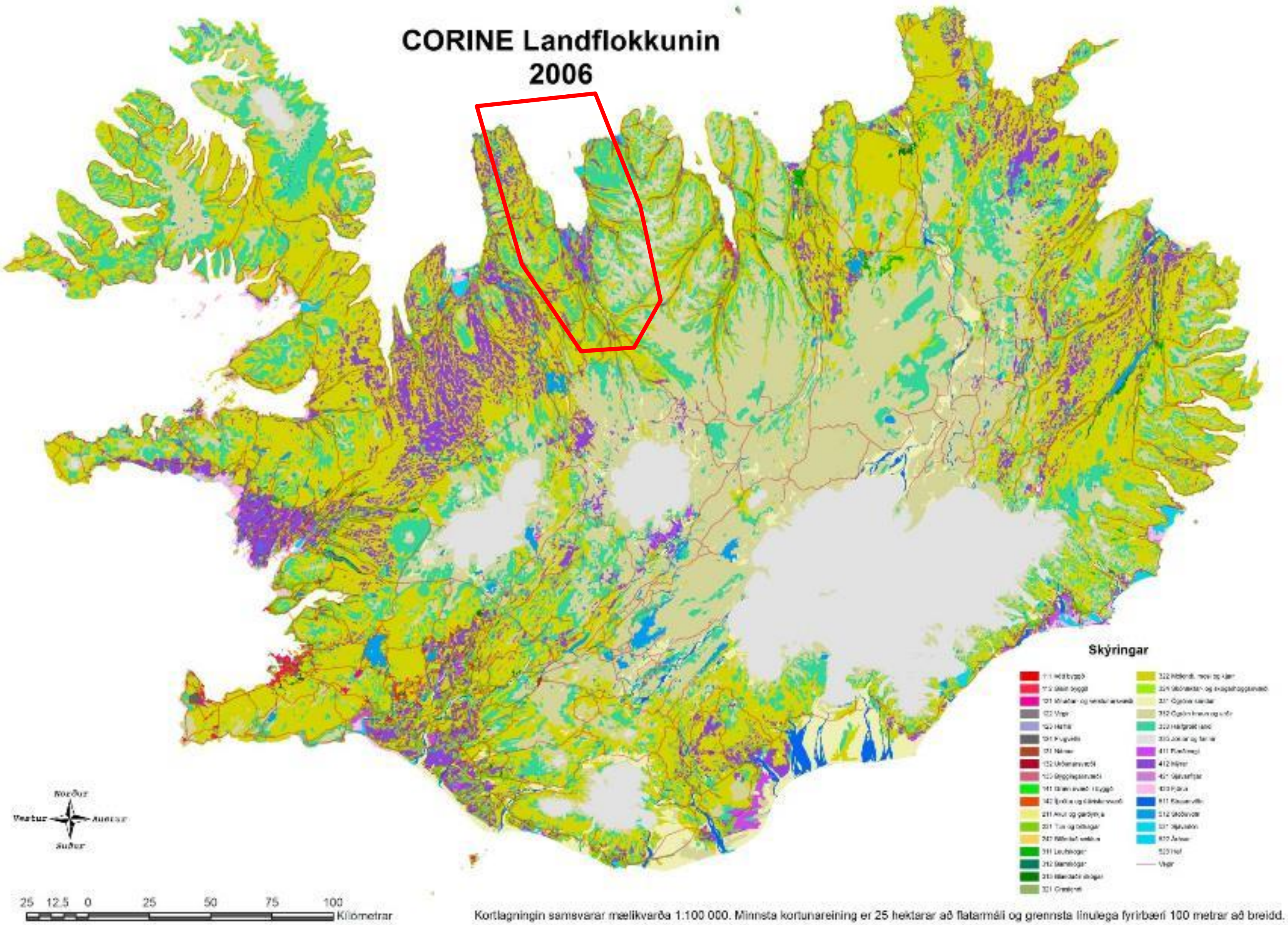

Figure 16: CORINE Land Cover map of Iceland 2006, Processed from REITER 2017 (Reference: NATIONAL LAND SURVEY OF ICELAND 2006)

Table 2: Legend in English from the CORINE Land Cover map of Iceland 2006, Processed from REITER 2017 (URL-J)

111 Continuous urban fabric	321 Natural grassland
112 Discontinuous urban fabric	322 Moors and heathland
121 Industrial or commercial units	324 Transitional woodland shrub
122 Road and rail networks and associated land	331 Beaches, dunes, and sand plains
123 Port areas	332 Bare rock
124 Airports	333 Sparsely vegetated areas
131 Mineral extraction sites	335 Glaciers and perpetual snow
132 Dump sites	411 Inland marshes
133 Construction sites	412 Peatbogs
141 Green urban areas	421 Salt marshes
142 Sport and leisure facilities	423 Intertidal flats
211 Non-irrigated arable land	511 Water courses
231 Pastures	512 Water bodies
242 Complex cultivation patterns	521 Coastal lagoons
311 Broad-leaved forest	522 Estuaries
312 Coniferous forest	523 Sea and ocean
313 Mixed forest	Streets

The Skagafjörður is not inhabited massively. There are only a few areas that are designated urban and fabric areas. Like the red pattern in the north of the Skagafjörður, which is Sauðárkrókur or Varmahlíð a little more south. The bottom of the fjord is mainly marked as inland marshes and peatbogs, with sparsely vegetated areas between. There are also moors and heathland as well as transitional woodland shrub between the wetlands. Bare rock and sparsely vegetated areas are designated on the flanks. The summits in the east of the Skagafjörður are classified as areas with glaciers and perpetual snow. (NATIONAL LAND SURVEY OF ICELAND 2006) The following figure (figure 17) shows the vegetated parts of the fjord on a Landsat infrared image. Vegetated areas appear in red in an infrared image. Plants absorb blue and red light to produce chlorophyll. The more chlorophyll is being produced, the more it reflects the near infrared. (URL-O) It can be seen, that the bottom of the Skagafjörður is covered with vegetation, as it is classified on the CORINE Land Cover map. Those areas are densely covered by many plants and are well taken care of by the farmers. The areas of the mountain flanks have a lighter red than the areas on the bottom of the fjord. These areas are also covered with vegetation but not very dense because it is harder for plants to spread on high slopes, which results in a lighter red. The weakest red shows the areas on top of the mountains and around the snow and ice fields. In these areas there is very sparse vegetation because of the long-lasting snow and stony underground.

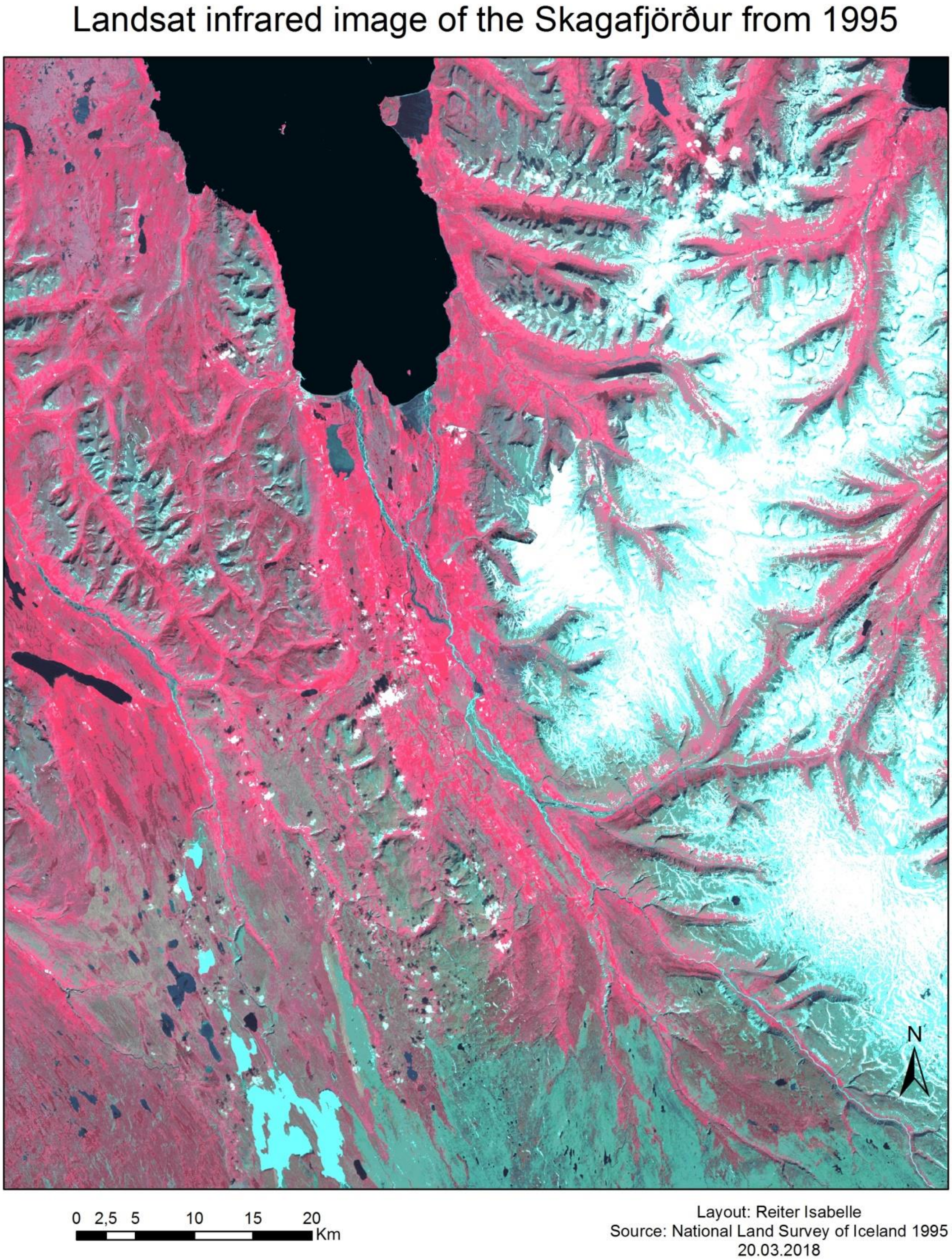

Figure 17: Landsat infrared image of the Skagafjörður from 1995 (Reference: REITER 2018)

The marshes are a predominant landscape of the lowlands of Iceland and make about 10 percent of the land area. (SCHUTZBACH 1985: 188)

The vegetation of marshes is dominated through a few sedges. One of the first plants that occurs in marshes, is the common bog-cotton (Eriophorum angustifolium), which can be seen in figure 18. (SCHUTZBACH 1985: 188)

Figure 18: Common bog-cotton (Eriophorum angustifolium) (Reference: STITZ 2014)

Following table (table 3) shows plants typical for marshes with slight water movement. Marshes with flowing water are dominated by the Lyngbye sedge (figure 19). (SCHUTZBACH 1985: 188)

Figure 19: Lyngbye sedge (Reference: URL-N)

Table 3: Marsh plants of Iceland (Reference: SCHUTZBACH 1985: 188)

Creeping sedge	Carex chordorrhiza
Rock sedge	Carex saxatilis
Beaded sedge	Carex rostrata
Bog sedge	Carex limosa
Black sedge	Carex nigra
Spike-rush	Eleocharis palustris
Bulrush	Scirpus caespitosus
Narrowspike reedgrass	Calamagrostis stricta
Northern bilberry	Polygonum viviparum
Mossberry	Vaccinium uliginosum
Arctic grey willow	Salix callicarpaea
Water horsetail	Equisetum fluviatale
Marsh trefoil	Menyanthes trifoliate
Water milfoil	Myriophyllum alterniflorum
Mares tail	Hippuris vulgaris
Pondweed	Potamogeton

The peatlands of Iceland are mainly low-level-moors which are characterized by many earth hummocks (thufur). (SCHUTZBACH 1985: 188) These earth hummocks arise through frost heave and can be seen in figure 20.

Figure 20: earth hummocks (thufur) (Reference: RANFTL 2014)

Peatlands are also characterized by typical plants, which can be seen in table 4. The Black sedge which grows in marshes can also be found in peatlands.

Table 4: Peatland plants of Iceland (Reference: SCHUTZBACH 1985: 189)

Black sedge	Carex nigra
Dioecious sedge	Carex dioica
Silvery sedge	Carex canescens
Awned sedge	Carex microglochin
Scheuchzer´s cottongrass	Eriophorum Scheuchzeri
Marsh horsetail	Equisetum palustre
Filiform rush	Juncus filiformis
Bog-star	Parnassia palustris
Purple marshlocks	Comarum palustre
Marsh-willow-herb	Epilobium palustre
Marsh violet	Viola palustris
Cuckoo flower	Cardamine pratensis
Water avens	Geum rivale
Common butterwort	Pinguicula vulgaris

Different plants are growing at the bottom of the mountains where it´s dryer and earth hummocks occur. Table 5 lists the plants typical for this these areas.

Table 5: Plants at the bottom of the mountains of Iceland (Reference: SCHUTZBACH 1985: 189-190)

Crowberry	Empetrum nigrum
Mealberry	Arctostaphylos uva-ursi
Blueberry	Vaccinium myrtillus
Bog bilberry	Vaccinium uliginosum
Mountain avens	Dryas octopetala
True heather	Calluna vulgaris
Dwarf birch	Betula nana
Arctic grey willow	Salix cordifolia

Snowbed willow	Salix herbacea
Dwarf juniper	Juniperus communis ssp. nana
Arctic thyme	Thymus praecox ssp. arcticus
Creeping azalea	Loiseleuria procumbens
Cleaver	Galium verum
Scottish asphodel	Tofieldia pusilla
Alpine cinquefoil	Potentilla Crantzii
Spike trisetum	Trisetum spicatum
Dog bentgrass	Agrostis canina
Bellardi bog sedge	Kobresia myosuroides
Bigelow´s sedge	Carex bigelowii
Capillary sedge	Carex capillaris
Rock sedge	Carex rupestris
Spiked woodrush	Luzula spicata
Common woodrush	Luzula multiflora
Highland rush	Juncus trifidus
Alpine meadow-rue	Thalictrum alpinum
Yellow-rattle	Rhinanthus minor
Arctic eyebright	Euphrasia frigida

The flanks of the mountains are sparsely vegetated with plants, which do not need as many nutrients. The vegetation is similar to the areas at the bottom of the mountains but with less species. (SCHUTZBACH 1985: 193) Table 6 shows the typical plants of the mountain flanks.

Table 6: Plants of the mountain flanks of Iceland (Reference: SCHUTZBACH 1985: 193)

Crowberry	Empetrum nigrum
Dwarf birch	Betula nana
Mealberry	Arctostaphylos uva-ursi
True heather	Calluna vulgaris

Blueberry	Vaccinium myrtillus
Bog bilberry	Vaccinium uliginosum
Arctic grey willow	Salix cordifolia
Woolly willow	Salix lanata
Snowbed willow	Salix herbacea
Wavy hair-grass	Deschampsia flexuosa
Sweet vernal grass	Anthoxanthum odoratum
Holy-grass	Hierochloe odorata
Sheathed sedge	Carex vaginata
Highland rush	Juncus trifidus
Spiked woodrush	Luzula spicata
Curved wood-rush	Luzula arcuata
Alpine knotweed	Bistorta vivipara
Common wintergreen	Pyrola minor
Alpine meadow-rue	Thalictrum alpinum

In the higher parts of the mountains mainly lichen and moss can be found. The Silver moss (Racomitrium canescens), the Moss campion (Silene acaulis) and the Hoary rock-moss (Racomitrium lanuginosum) as well as the Reindeer lichen (Cladonia rangiferina) and the Iceland lichen (Cetraria islandica) are dominant in the higher parts of the mountains. (SCHUTZBACH 1985: 193 and DECAULNE et al. 2007: 52-53) Figure 21-24 display those plants.

Figure 21: Moss campion (Reference: REITER 2014)

Figure 22: Hoary rock-moss (Reference: URL-K)

Figure 23: Reindeer lichen (Reference: URL-L)

Figure 24: Iceland lichen (Reference: URL-M)

The first settlers of Iceland practised agriculture and cultivated oat and barley, but as a result of the bad climate the harvest wasn´t very fruitful. By the 16th century there were no crops cultivated throughout Iceland anymore, instead the farmers started practising stock farming. The number of farms in Iceland is shrinking to the 21st century on one side of the new employment opportunities since the economic upturn at the middle of the 19th century and on the other side of the loss of soil through erosion. In the Skagafjörður the relation of sheep and cattle was 16:1 in the 20th century, which means a high pressure for the pastures. (SCHUTZBACH 1985: 205-208) In summer the sheep are grazing on large pastures in the mountains. In autumn the sheep are taken to the farms in the valleys where they are grazing on winter pastures until the next summer. Just like the sheep, horses are also on pastures all year round, though they are kept mainly in the lowlands where they are close to the farms. (SCHUTZBACH 1985: 208-209) There is a guideline from the Ministry for the environment in Iceland about sustainable land use and protection of the nature. "A reduction in the number of sheep has resulted in less pressure from grazing, although grazing must be further reduced in sensitive areas. Through the conservation of land, grazing control and revegetation, conditions can be created for increased utilization of grazing areas in the future" (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 17).

Many farms and important horse breeders of the Skagafjörður are involved in the sustainable land use programme. The number of involved farmers has doubled from 2000 to 2016. (MARONSSON 2017: 3) The following table (table 7) shows the number of farms which are partners of the sustainable land use programme. The Skagafjörður, which abbreviated as Skag, actually shows the highest number of farms involved in this programme.

Table 7: Number of farms which are partner of the sustainable land use programme (Reference: MARONSSON 2017: 4)

Ár	Kjós	Mýr/Borg	V-Hún	A-Hún	Skag	Eyjafj	S-Þing	Rang	Árn	Snæ	Samt.
2000	0	4	1	1	8	3	0	2	2		21
2002	1	4	4	3	13	2	1	5	4		37
2004	1	3	4	3	14	2	1	9	4		41
2006	0	2	5	3	14	2	1	9	5		41
2008	0	2	5	4	14	5	1	10	5		46
2010	0	3	4	5	12	5	0	10	4		43
2012	0	5	4	5	10	5	0	10	5	1	45
2014	0	5	4	5	8	5	0	7	5	1	40
2015	0	5	4	5	8	5	0	7	4	1	39
2016	0	5	4	4	11	5	0	6	4	1	40

Figure 25 shows the distribution of horse farms in the Skagafjörður. It can be seen, that these farms are distributed over the whole fjord. Therefore, there are many places practising sustainable land use, although there is no record of horse farmers also taking care of the mountains affected by gully erosion.

Figure 25: Distribution of horse farms of the Skagafjörður (Reference: MARONSSON 2017: 7)

The number of sheep has been decreasing from 1980 to 2001. In 1980 over 800 000 sheep were distributed all over Iceland, which meant a great pressure for the soil and vegetated areas. In 2001 is the number of sheep declined to almost 500 000, which is also a high number of sheep but the overgrazing which results from sheep farming was lessened. Looking at figure 26 it becomes clear that horse farming wasn´t and still isn´t practised as much in Iceland as sheep farming. In 1980 there were only 50 000 horses in Iceland as opposed to the 800 000 sheep. In 2001 the number of horses in Iceland increased to 70 000. Although there are fewer horses than sheep, they can also cause soil erosion as they are heavier than sheep.

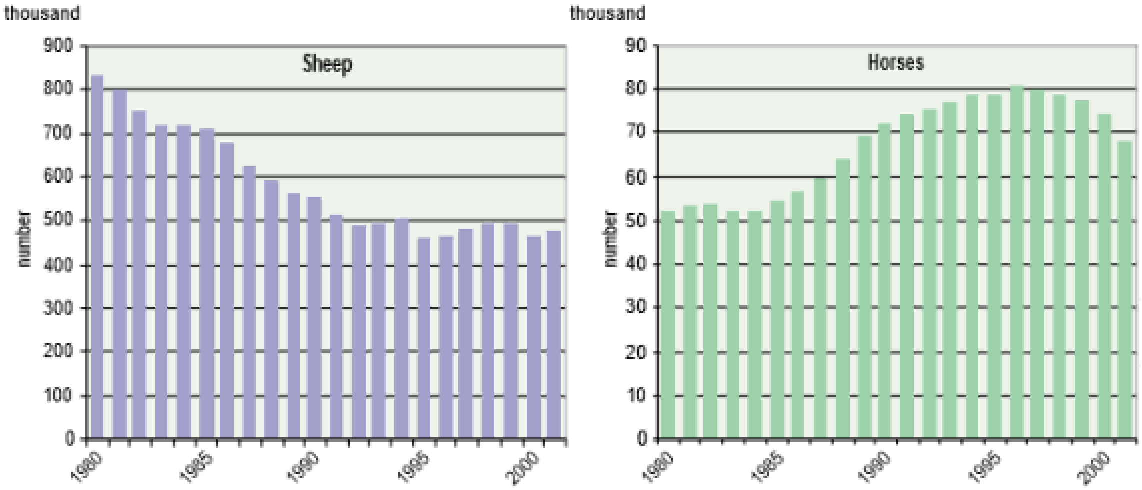

Figure 26: total number of sheep and horses from 1980 to 2001 in Iceland (Reference: THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74)

Besides minimizing the number of sheep and horses to protect the ground against soil erosion, there are afforestation projects. The policy supports the farmers regarding the planting of forests. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74)

In 2001 5% natural birch lands and only 1% planted forests could be found in Iceland. 23% of Iceland is covered with vegetation and the rest of Iceland has no vegetation or is covered with glaciers and lakes. This can be seen in figure 27. Because the first settlers cut down the natural forests, only a small percentage of the Icelandic forests are planted, tough this number will be increasing as a result of the ongoing afforestation projects.

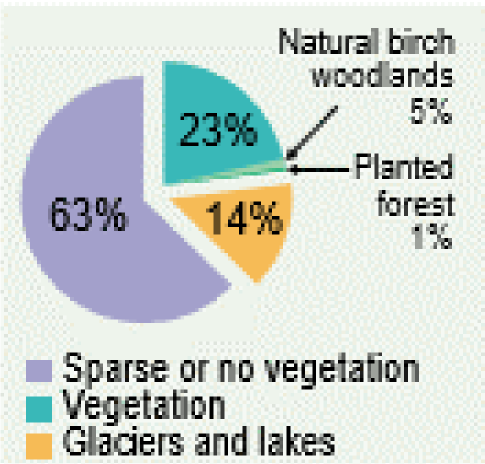

Figure 27: Percentage of vegetated land of Iceland in 2001 (Reference: THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74)

3.4 Historical development of the Skagafjörður

Iceland was settled in the ninth century during the time of Landnám in the Viking Age. When the first settlers from Scandinavia and the British Isles came to Iceland, the island was covered in birches and willows. Before the first settlers arrived in Iceland, no mammals except for the arctic fox had lived there. This changed tough as they brought their livestock, such as horses, sheep, pigs, goats and cattle to the island. The first settlements caused the Icelandic landscape to change – the grazing livestock lead to changes in the vegetation as well as soil erosion. The first settlers decreased the forests for building houses and ships. The existing woodland was decreased to less than 2% of the total land area. (HARTMAN et al. 2017: 126) "[…] settlement was dispersed with scattered farmsteads ranging in size from large manors housing dozens of kin and servants to tiny cottages and seasonally occupied shielings […]" (HARTMAN et al. 2017: 128).

There was a change of livestock in the thirteenth century. The number of pigs and goats decreased while the number of sheep and horses increased. This was due to the higher demand in wool-production for exports to Europe – as during this time Iceland exported fish- and wool-products to Europe. Icelandic exports to Europe at this time are fish- and wool-products, so they need more sheep for the wool production. An increase in grazing livestock on an island which is sensitive to soil erosion, leads to an enhancement in soil erosion. (HARTMAN et al. 2017: 129-130) The farmers of the Skagafjörður moved their livestock to the highlands in summer, as they used the grass in the lowlands for producing winter fodder. (STEINBERG et al. 2016: 391)

The regions of Hegranes and Langholt, which are located in the Skagafjörður had been continuously and active farmed ever since the time of the Landnám. In these areas the soil is deep interspersed or is eroded to the bedrock. (CATLIN 2016: 17-18) "Langholt is a tongue of Upper Tertiary basic and intermediate extrusive basalts […] overlain by morainic glacial till. It is about 8 km long, 2 km wide […].The land is fertile by Icelandic standards […] because of substantial aeolian soil deposition" (STEINBERG et al. 2016: 394). The lowland of the Skagafjörður consisted of peat bog, which was heavily drained for agriculture, and living. (DECAULNE et al. 2016: 1308) In order to build houses and create turf walls around them, the settlers needed to skim the turf from the peat bog. (STEINBERG et al. 2016: 391) Figure 28 shows the location of Hegranes and Langholt as well as eroded areas on the bottom of the fjord and hillsides.

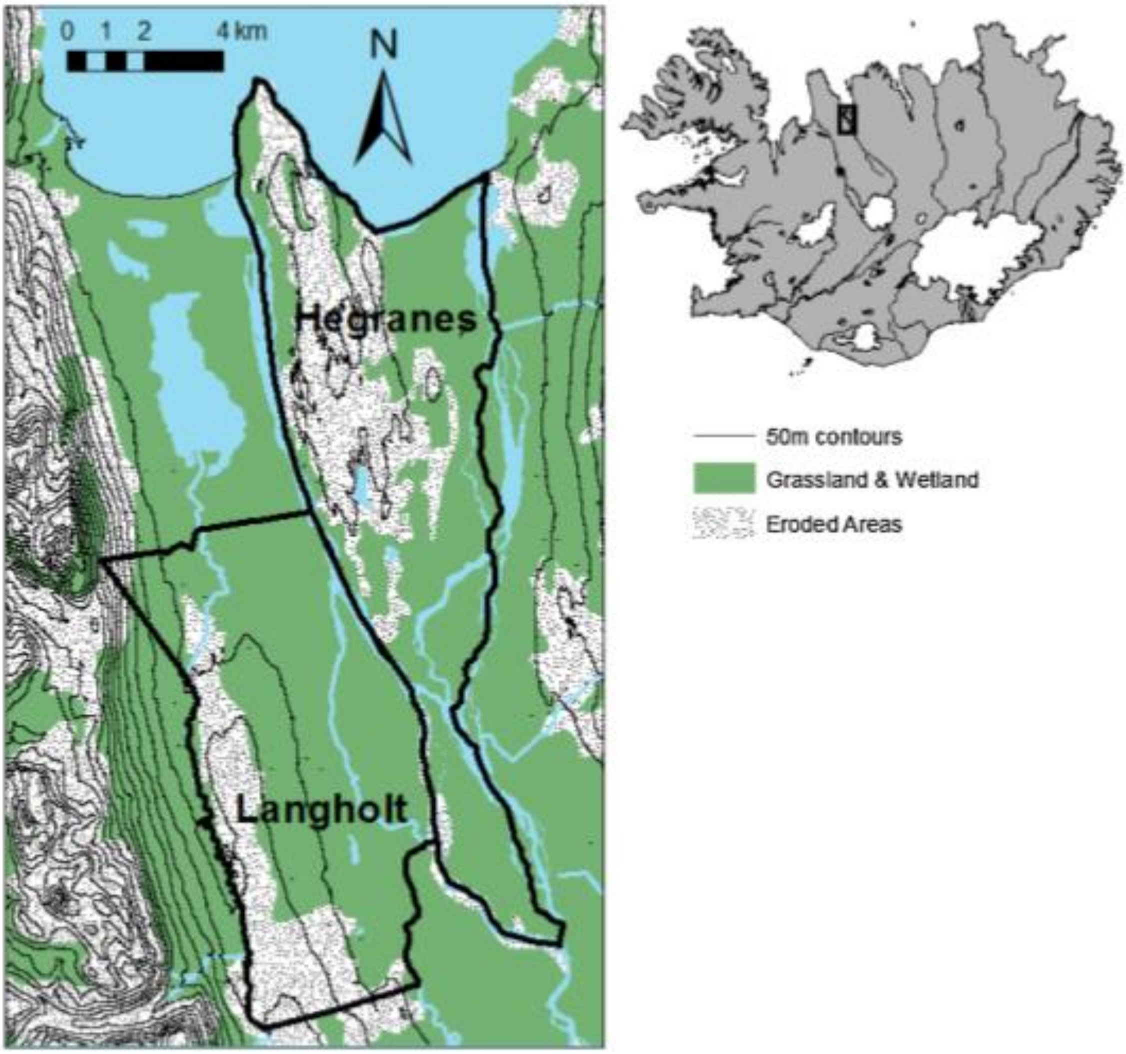

Figure 28: Location of Hegranes and Langholt in the Skagafjörður (Reference: CATLIN 2016: 17)

In summary it can be said, that the lowland and highland of the Skagafjörður were heavily affected by the first settlers. They drained the lowland for settlement and agriculture and their grazing livestock caused vegetation changes and soil erosion.

3.5 Population and economics

The population of Iceland in 2017 amounts to 339 747 with a population growth rate of 1,1%. The median age of the Icelandic population is 36,3 years. While 94,3% of the total population are living in urban areas, the population of the Icelandic capital, Reykjavik, added up to 184 000 in 2014. (URL-D)

Sauðárkrókur which is the biggest city in the Skagafjörður has about 4 400 inhabitants. (URL-E)

After the economic crisis of 2008, Iceland recovered, the growth rate increased and as a result the unemployment rate was quite low. The fishing industry is an important economic part of Iceland. The gross domestic product of the fishing industry accounts to more than 12%. The end-products of the Icelandic fishing industry are important export products, as well as aluminium and ferrosilicon. Agriculture and, since 2010 also tourism, are important factors of economic growth in Iceland. (URL-D) The agriculture has not only the assignment to provide food stuff for the Icelandic population. Agricultural end products range from meat to wool from sheep or horses, which are of big cultural value and are also an important export product. (SCHUTZBACH 1985: 210) Following table (table 8) shows the employment distribution of selected sectors, from 1989 to 1998. It can be seen, that there is a change in employment distribution across the different sectors. While employment rates in the tourism and hospitality sector are increasing, they are decreasing in the agricultural and fishing industries.

Table 8: Employment distribution from selected sectors from 1989 to 1998 in Iceland (Reference: ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 91)

	1989	1992	1995	1998	1989/98 (%)
Fisheries and fish processing[a]	14 893	13 023	13 735	12 795	*–14*
Agriculture[a]	6 399	6 514	5 596	5 160	*–19*
Manufacturing (excluding fish processing)[a]	16 195	14 776	14 022	16 029	*–1*
Hotel and restaurants[b]	..	3 900[c]	4 600	4 400	*+13*[d]
Total services[b]	..	89 700[c]	93 200	97 000	*+8*[d]

a) Person-years.
b) Persons.
c) 1993.
d) 1993-98.
Source: OECD; Statistics Iceland.

“Iceland´s economy relies heavily on natural resources; the fishing industry depends on marine resources, industry on hydropower, and tourism on nature and related resources” (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 19).

In addition to agricultural products, final goods of the fishing industry are also important export products and provide an important source of income. As shown in table 9, export products from the fishing industry made up a higher percentage than agricultural products, aluminium and other export products from 1901 to 1980. (SCHUTZBACH 1985: 210)

Table 9: Export products from 1901 to 1980 of Iceland (Reference: SCHUTZBACH 1985: 210)

	Fisch und Fisch-pro-dukte	Wal-pro-dukte	Land-wirt-schaft-liche Erzeug-nisse*	Alumi-nium	Andere Ex-port-güter**
1901–1905	59,3	17,9	21,0		1,8
1906–1910	64,3	12,2	21,8		1,7
1911–1915	74,1	1,6	22,7		1,6
1916–1920	74,6	–	22,4		3,0
1921–1925	85,1	–	13,1		1,8
1926–1930	87,9	–	11,1		1,0
1931–1935	89,4	–	9,5		1,1
1936–1940	87,4	0,4	11,2		1,0
1941–1945	92,3	–	6,3		1,4
1946–1950	87,2	2,9	7,9		2,0
1951–1955	92,9	1,5	4,5		1,1
1956–1960	90,6	1,5	6,8		1,1
1965	93,4	1,1	4,2		1,3
1970	76,9	1,3	3,4	13,2	5,2
1975	77,8	0,8	2,9	10,6	7,9
1980	73,8	1,1	1,7	12,1	11,3

*Hammelfleisch, Milchprodukte, Wolle, Schaffelle, lebende Pferde.

**Diatomit, Zement, Strickwaren, Lederwaren.

But the employment rate in the different manufacturing industries, such as manufacturing of textiles, electronics, cement, insulating materials, aluminium and iron alloy, is increasing. (SCHUTZBACH 1985: 220-221)

For the last few years the economy has been growing. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 19) "Some weak decoupling of economic growth from environmental pressure is occurring; for example, energy intensity has fallen since 1990 […]. There has also been a degree of progress on pollution management. Some environmentally favourable changes in consumption patterns have been induced, notably the switch from oil to geothermal energy for domestic heating. Iceland has also made progress towards sustainable management of natural resources. Framework conditions (e.g. regarding land ownership rights, municipality boundaries, procedures for planning and building infrastructure, and regional long-term planning) have been established to assure better use and protection of the natural resources of the central highlands" (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 19-20).

Sustainable development is important for an island, because the resources and the space are limited. Therefore, Iceland has since 2 000 in all levels of education the development of the environment in the course of instruction. With this programme the awareness of sustainable development is trained from pre-school to university. But so good the training of the development of the environment in education is, for the public this topic had to be more promoted. There had been tax measures for large cars, charges which relate to waste and water and the consumption pattern, which is influenced by price signals. (ORGANISATION FOR ECONOMIC CO-OPERATION AND

DEVELOPMENT 2001: 21) Although these arrangements are a good starting point, there needs to be a ground understanding for sustainable development in the population and not only sustainable consumption driven by economic arrangements, which Iceland is trying do through implementing the education programme for sustainable environment education. The need for caring for the environment is also driven by volcanic and seismic activity, landslides and avalanches and the wish to be prepared in case of a natural disaster. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 22)

"Agriculture has led to a number of environmental problems: major loss of vegetation cover and soil erosion; and major wetlands drainage, affecting breeding grounds for waterfowl and other species. [...] Agricultural support has been based on economic and social considerations, and environmental problems have been addressed separately, for example by the government soil conservation programme. A contract between sheep farmers and the government regarding government support until 2007 has recently been signed, but legal revision is needed to include payments for positive environmental outcomes: from 2003, farmers who can prove sustainable land use would receive more support than others [...]. There is no comprehensive plan for sustainable agriculture, although the National Sustainable Development Action Plan includes a chapter on agriculture. The National Environmental Strategy undertook to restrict grazing to areas where it would not damage the land, and to encourage people who left farming to increase their involvement in conservation activities. Agricultural subsidies have been replaced by income support measures, and the size of future payments is to be linked to land reclamation" (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 70).

4 Data used for the analyses

For the analyses of soil erosion, satellite datasets and digital elevation models have been used. The satellite datasets are drawn from the satellites Landsat 5, Landsat 7, Landsat 8 and ASTER. These satellites are available for free.

"The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an imaging instrument onboard Terra, the flagship satellite of NASA's Earth Observing System (EOS) launched in December 1999" (URL-P). ASTER accords earth images with a high resolution, from 15 to 90 square meters per pixel, in 14 different wavelengths. This wavelength of the electromagnetic spectrum has a scope from visible to thermal infrared light. (URL-Q)

"Landsat represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data" (URL-R). It has collected over 40 years of spectral information from the surface of the earth. (URL-S) The Landsat sensors have a resolution of 30 meters, therefore even changes on the surface of the earth can be seen. Landsat 8 has eleven bands which measures different ranges of frequencies along the electromagnetic spectrum. (URL-T)

For this master´s thesis, Landsat 5 datasets from 1995, Landsat 7 datasets from October 2012, July 2013 and August 2016, as well as Landsat 8 datasets from March 2013 and October 2016 are being used. The ASTER datasets are from June and July 2016 and May 2012. These datasets provide a good overview of the area of this study at different times.

It was not very easy to find satellite datasets without clouds and a slight snow cover, but a few could be found.

The national land survey of Iceland provides the digital elevation model from 2016, with a resolution of ten meters. In order to do multi temporal analyses of this area, a digital elevation model of earlier years is needed. The national land survey of Iceland also provides a digital elevation model from 2004, but only with a resolution of 20 meters. The national land survey of Iceland also provides aerial photos from 1993. With these aerial photos, digital elevation models with a higher resolution of 5 meters can be generated. Table 10 gives an overview of the different datasets used for analysing gully erosion.

Table 10: Datasets used for analysing gully erosion

Dataset	Year	Resolution	Source
Landsat 5	1995	30m	National Land Survey of Iceland
Landsat 7	2012, 2013, 2016	30m	earthexplorer.usgs.gov
Landsat 8	1995, 2013, 2016	30m	earthexplorer.usgs.gov
ASTER	2012, 2016	15m	earthexplorer.usgs.gov
DEM 2016	2016	10m	National Land Survey of Iceland
DEM 2004	2004	20m	National Land Survey of Iceland
DEM 1993	1993	5m	National Land Survey of Iceland

5 Methods

To get an overview of the workflow of the different methods it is visualized in figure 29.

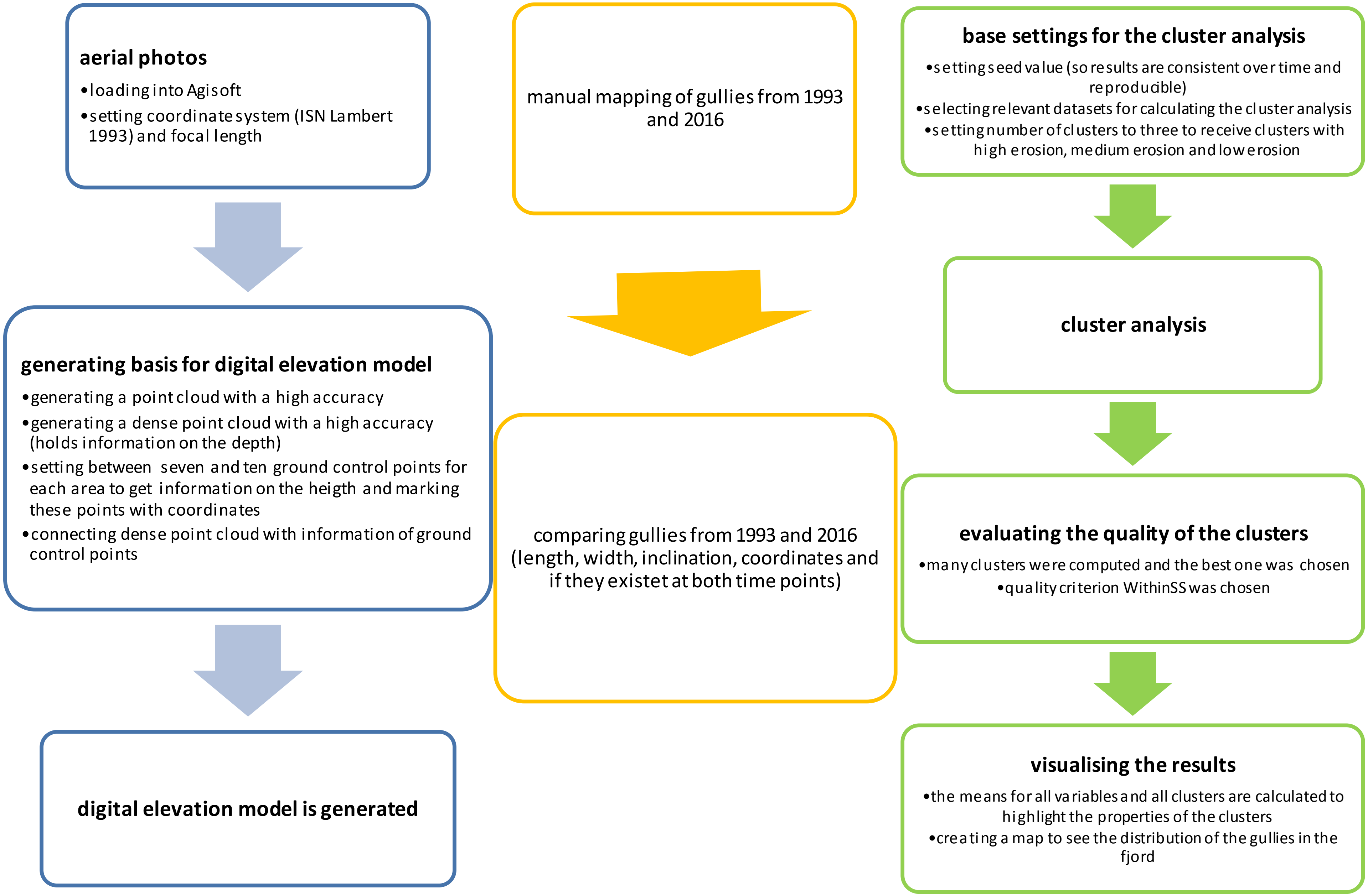

Figure 29: workflow diagram of the different methods

5.1 Generating digital elevation models

Digital elevation models are generated using aerial photos of 1993. This was done using the programme Agisoft, which is a software to generate point clouds, 3D-models and digital elevation models from aerial photos.

In a first step, after loading the aerial photos in the software, the coordinate system is set to know which geographic reference system the dataset should have. For Iceland the coordinate system ISN Lambert 1993 is used. After that the focal length is set. The pixel size, cannot be set, because it is not given in the metadata from the aerial photos.

After these first steps, a point cloud is generated with the command align photos. In order to receive a point cloud with a high accuracy, the highest accuracy in the settings is chosen. With the generated point cloud, a dense point cloud is generated. This dense point cloud holds information on the depth. Again, the highest accuracy is chosen in order to generate the dense point cloud.

Before generating the digital elevation model, ground control points had to be set to get information on the height and to mark these points with coordinates. Distinctive places like lakes, streets or rivers that are on the aerial photos and on the satellite images would be taken. Between seven and ten control points have been set for each area to receive a good result. It was made sure that the ground control points are distributed over the whole area. These control points are saved in a table with x and y coordinates and the height. This information was taken from the satellite image. The conditioned table was loaded into Agisoft to connect the dense point cloud with the information from the satellite image.

On the basis of the dense point cloud and the ground control points a digital elevation model could be generated. The generated digital elevation model is exported and loaded into ArcGIS. A hillshade was calculated; therefore the structure of the area could be seen.

To check that the generated digital elevation model is correct it was inspected manually. The generated digital elevation model from 1993 and the received digital elevation model from 2016 coincided and had no shift between them. Another criterion to see, whether the generated digital elevation model is correct, is the height. The height of distinctive points that showed in both digital elevation models, is visualised in ArcGIS. If the difference of the height of the distinctive points in both digital elevation models is not bigger than 5 meters, the generated digital elevation model was accepted as correct.

5.2 Mapping and measurement of eroded areas

On the satellite images and also on the hillshade of the digital elevation models lots of erosion gullies could be identified. These gullies are being mapped manually, on basis of the hillshade from 2016 and 1993 and on the Landsat and ASTER images. Not all of the fjord is mapped, because the digital elevation models from 1993 do not cover the whole fjord. Therefore, there are only those areas mapped, that are covered in the elevation models from 1993 and 2016.

In the process of mapping the erosion gullies attention was paid to only map erosion gullies and not river valleys or debris flows as well.

The mapping of the gullies was done following the definition of the Icelandic gullies of HARTMANN et al. 2003.

After mapping the gullies from 1993 and 2016 these gullies are compared in regard to their length, width, if they exist at both times, which slope is dominant in areas that gullies occur in, what the minimum and maximum height of the gullies is and additionally the coordinates of the gullies. This information is saved in an excel file for statistical analysis. This table can be found in appendix A.

The length of the gullies was calculated in ArcGIS. It is important that not the air-line distance is calculated, because this distance is shorter than the real length of the gullies. The real length of the gullies was calculated with the function Calculate Geometry for the year 1993 and 2016.

To detect the width of the gullies, the width was measured manually using a measuring tool for every gully, from margin to margin. This measurement was done at the beginning, in the middle and at the end of every gully. For very long gullies the width was measured on more than three points.

The inclination for every gully was computed in the program Excel. For this calculation the highest point, the lowest point and the real length of the gully were used. By using the arctangent the inclination was computed for 1993 and 2016 in radiant and degree. To validate that the formula is correct, the inclination is computed with test values $\Delta h = 1$ and $\Delta x = 1$. The result of this calculation was $\frac{\pi}{4}$ which corresponds to 45 degrees, which indicates the formula is correct. Table 11 shows the results of calculating in radiant and degree with different values.

The formula for calculating the inclination is:

$$\alpha = \arctan\left(\frac{\Delta h}{\Delta x}\right)$$

In this formula h denotes the height and x denotes the length. The result from this formula leads to a result in radiant. To receive a result in degrees, the result was multiplied with 180 and divided by PI.

Table 11: Results of calculating the inclination in radiant and degree with different values

length 2016	**height 2016**	$\mathbf{arctan}\left(\frac{\Delta \boldsymbol{h}}{\Delta \boldsymbol{x}}\right)$	$\mathbf{arctan}\left(\frac{\Delta \boldsymbol{h}}{\Delta \boldsymbol{x}}\right) * \mathbf{180}/\boldsymbol{\pi}$
1	1	$\frac{\pi}{4}$ = 0,79 rad	45°
1768	585	0.31 rad	18.31°
682	250	0.35 rad	20.21°
1658	535	0.31 rad	17.88°
2540	526	0.20 rad	11.70°

5.3 Cluster Analysis

The different information of the gullies measurement was analysed using a cluster analysis to identify regions in the fjord with similar erosion and with more or less erosion over the twenty tree years of observation and to see which factors support soil erosion and which factors decelerate soil erosion. To identify regions with more or less erosion, the coordinates, the length, the width and the inclination from the gullies which exists in 1993 and 2016 is taken, which can be seen in the list below. The inclination from 1993 is used, because this is the inclination of the slope which was given on the beginning of the period of research.

- coordinates of the gullies
- length difference (length 2016 minus length 1993)
- inclination from 1993
- difference of the width at the beginning (width at the beginning 2016 minus width at the beginning 1993)
- difference of the width at the middle (width at the middle 2016 minus width at the middle 1993)
- difference of the width at the end (width at the end 2016 minus width at the end 1993)

"Cluster analysis is a generic term for a wide range of numerical methods for examining multivariate data with a view to uncovering or discovering groups or clusters of observations that are homogeneous and separated from other groups" (EVERITT and HOTHORN 2010: 318).

There are different types of cluster analysis like hierarchical clustering, model based clustering, k-means clustering and maximum likelihood clustering. (EVERITT and HOTHORN 2010: 319-323) For this thesis the k-means cluster analysis was used. "The k-means clustering technique seeks to partition a set of data into a specified number of groups, k, by minimising some numerical criterion, low values of which are considered indicative of a 'good' solution" (EVERITT and HOTHORN 2010: 322). The reason for using the k-means cluster analysis is the simple structure of this analysis and good performance.

The k-means cluster analysis was calculated with the program R. In a first step a seed value was set, which serves as a starting value for the random process included in k-means. This way the results are consistent over time and reproducible. The relevant columns from the excel file with the datasets are selected to calculate the cluster analysis. These columns are the coordinates of the gullies, the difference of the length from 1993 and 2016, the inclination from 1993, the difference of the width at the beginning of the gully from 1993 and 2016, the difference of the width at the middle of the gully from 1993 and 2016 and the difference of the width at the end of the gully from 1993 and 2016. In 1993 the number of gullies is less than in 2016, so the cluster analysis was only calculated with the gullies, which exist at both time points. The parameter k (number of clusters) was set to three, with the idea to resemble high erosion, medium erosion and low erosion.

To evaluate the quality of the clustering, many clusterings were computed and the best one was chosen. To assess the quality of the assignment of the data points to the clusters, the criterion WithinSS was used. The criterion WithinSS is the sum of all squared distances from data points to the corresponding cluster centres. Low values of WithinSS indicate a good solution. (URL-U)

After calculating the cluster analysis the means for all variables and for each cluster were calculated to highlight the properties of the resulting clusters. With these results a map was created, to visualize the cluster distribution in the fjord.

The code, which the cluster analysis is based on, can be found in the appendix B.

5.4 Literature analysis about counteractive measures for preventing soil erosion

To get information about counteractive measures which should prevent or slow gully erosion in the Skagafjörður, different publications are analysed. The aim was to find literature about existing counteractive measures and how they perform and as well as for literature about future projects in preventing soil erosion.

When studying different types of literature, publications were found about protecting the soil in whole Iceland and publications about protecting soil in smaller regions, like the Skagafjörður. The main idea of these different publications is always the same, protecting the soil against erosion.

Some literature about land use and counteractive measures in Iceland is written by HARTMAN et al. 2017, DECAULNE et al. 2016, ARNALDS and BARKARSON 2003, ZUAZO et al. 2011, THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002, MARONSSON 2017, ÁSBJÖRNSSON 2015 and ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001.

While a few of the mentioned publications is older than a decade, most of them are very recent. This gives an impression that this topic is very relevant in Iceland and there are many new ideas and projects in preventing or decelerating soil erosion.

6 Results

6.1 Results from mapping

In figure 30 the results from mapping the gullies in 1993 and 2016 are shown. The hillshade of the digital elevation model from 1993 is behind the mapped gullies, to get a better overview of the form of the fjord surface. Behind these hillshade is the hillshade of the digital elevation model from 2016, because the older hillshade does not cover the entire fjord. Firstly it can be seen, that the number of gullies is increasing from 1993 to 2016. In the southern parts of the fjord there are a few long gullies in 1993. In 2016 in addition to the long gullies, there are also short gullies in the southern parts of the Skagafjörður. The number of gullies in the northern part of the fjord is also increasing in 2016 but not as much as in the southern area of the fjord.

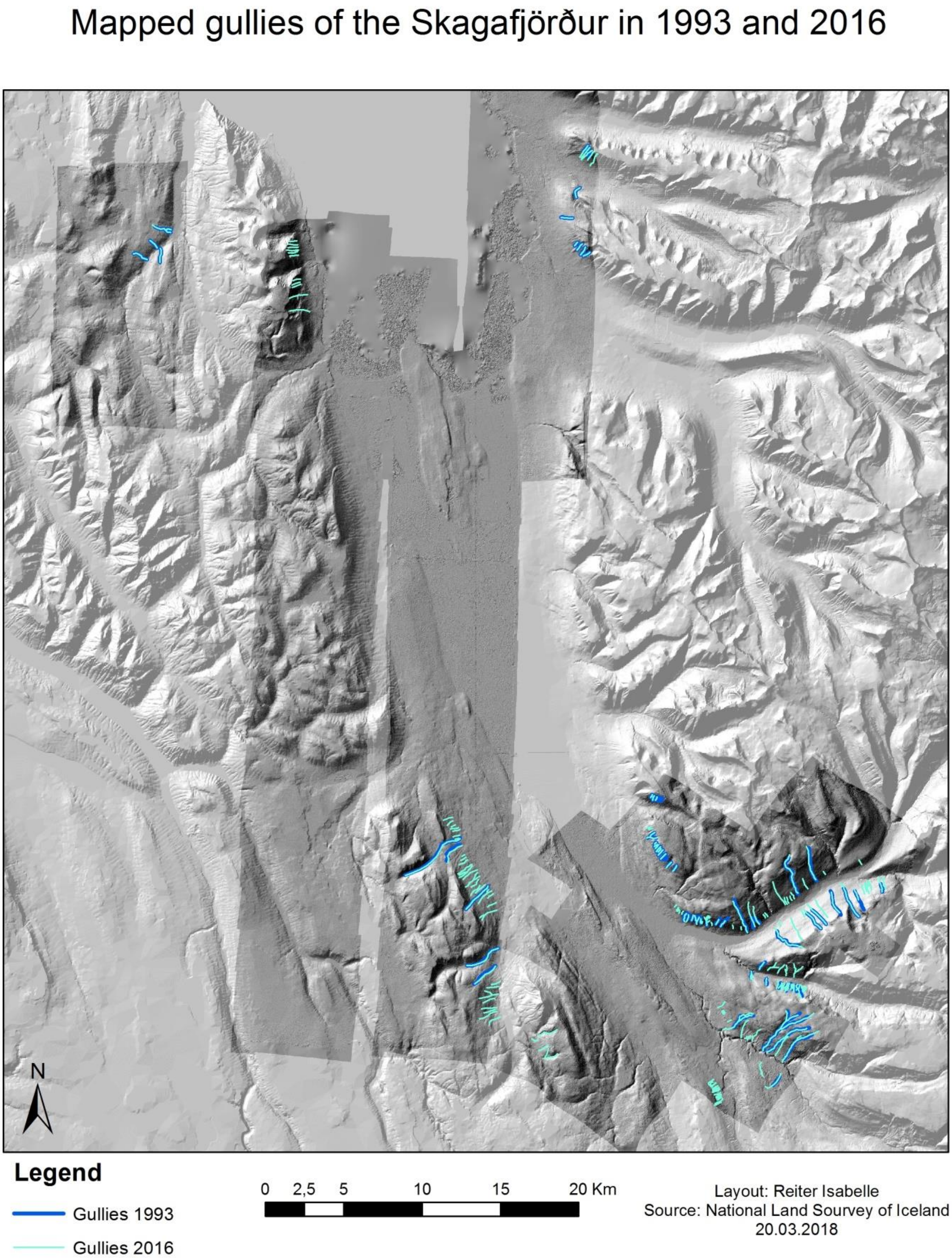

Figure 30: Mapped gullies of the Skagafjörður in 1993 and 2016 (Reference: REITER 2018)

The transformation of the gullies in the southern part of the fjord is better shown in figure 31. In 1993 there are less gullies in the fjord than in 2016. Some of the existing gullies are getting longer at the start of the gully as well as in the end of the gully. The exact results of how the gullies changed by length and width over the 23 years are shown in chapter 6.2 through the results of the cluster analysis. A few gullies have not changed in length during years. But many gullies newly formed from 1993 to 2016. The reason why there are so many new gullies, cannot be explained by looking only at the digital elevation models from 1993 and 2016. To answer this question satellite images and meteorological datasets had to be observed to identify changes in the land use and to know, if any extreme weather events happened in the last 23 years.

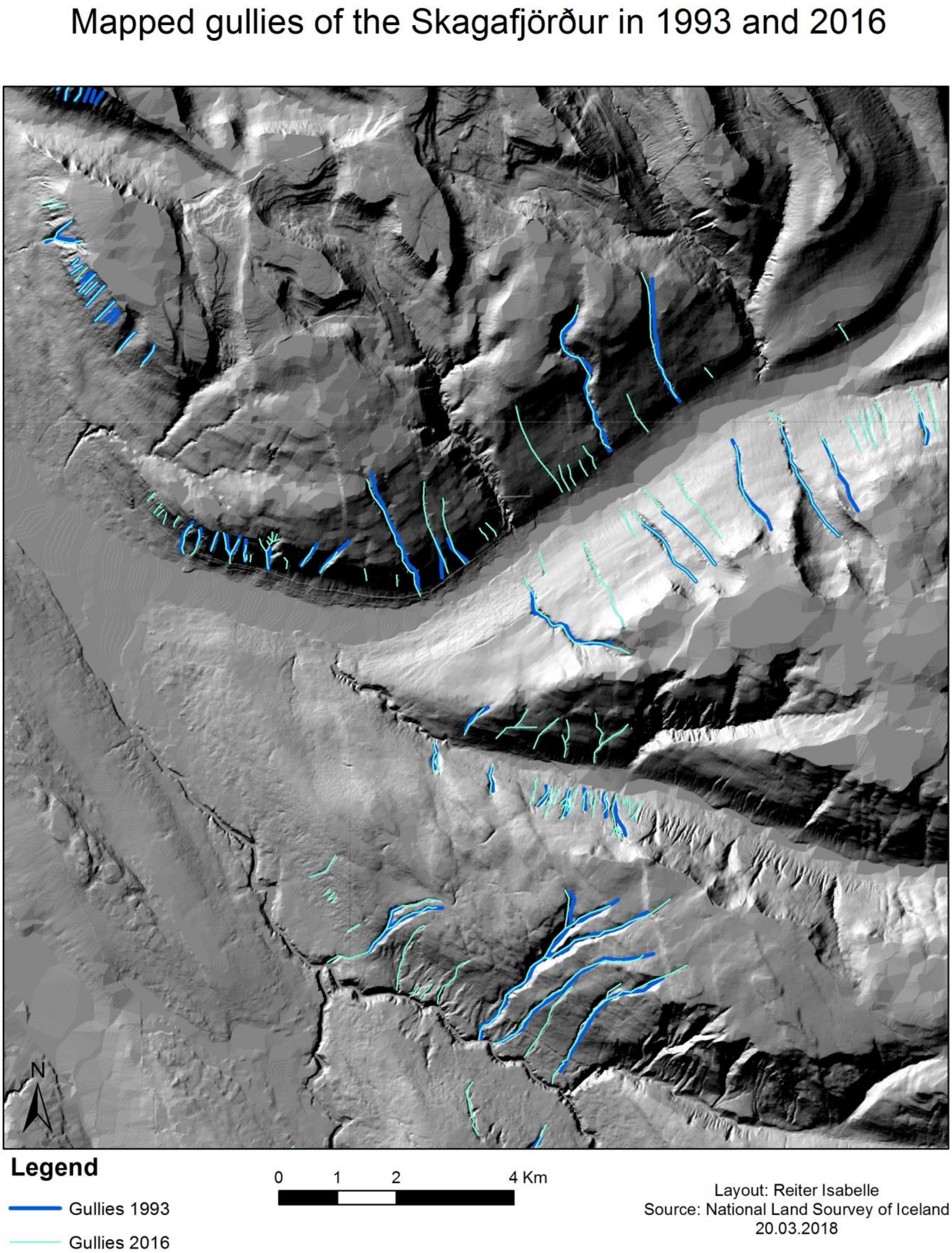

Figure 31: Mapped gullies of the Skagafjörður in 1993 and 2016 (Reference: REITER 2018)

In comparing the Landsat satellite image from 1995 and the ASTER satellite image from 2012 there can be an alluvial fan be seen. This alluvial fan is fresh in the Landsat image (figure 32) can also be seen in the ASTER image (figure 33) but here it is old. It can be seen that the alluvial fan have a dark colour. The gullies nearby this alluvial fan are similar in 1995 and 2012. But it can be said, that this alluvial fan has its origin in the big gully above which merged out of two single gullies. Therefore, a lot of melting water can run down from the mountains to the bottom of the fjord and erode soil, which can accumulate in an alluvial fan. No new alluvial fans can be seen in the ASTER satellite image. Therefore, a lot of snow must have melted in spring of 1995 or in the years before in order to create this alluvial fan. In October and December 2012 there were a few days with heavy snowfall in the north of Iceland. (URL-A and URL-B) Through melting, extreme water masses can erode much soil and create new alluvial fans. A weather event like this could be the reason for the alluvial fan in 1995, as there is not as much precipitation, and therefore alluvial fans could not arise as a result from heavy rainfall.

Figure 33: Alluvial fan (marked with red circle) of the Skagafjörður in the Landsat satellite image from 1995 (Reference: REITER 2017)

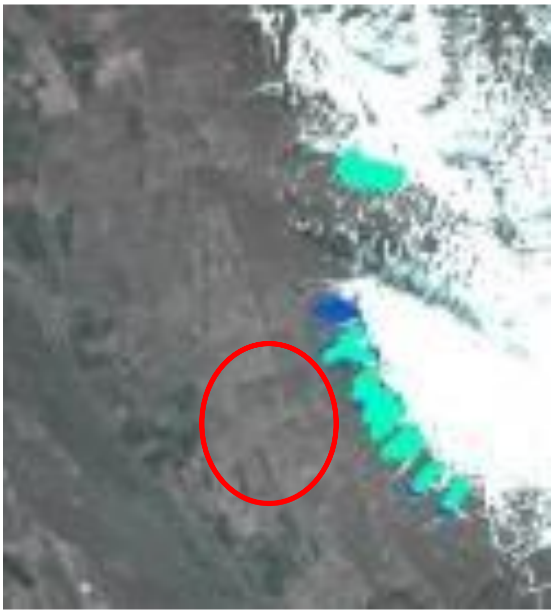

Figure 32: Alluvial fan (marked with red circle) of the Skagafjörður in the ASTER satellite image from 2012 (Reference: REITER 2017)

6.2 Results of the Cluster Analysis

To get a better overview about the change of the gullies in these 23 years, different statistical parameters are shown in the following graphics.

The change of the length difference of the gullies between 1993 and 2016 can be seen in figure 34. Most gullies are showing a gain in length from 1993 to 2016. But there are also gullies that are decreasing in length. A reason for this could be that the datasets have different resolutions, which can lead to an inaccuracy in mapping gullies. Another reason could be that there are changes in land use with the aim to minimize gully erosion. There are also gullies with a high difference in length. These are gullies, which build ramification over these 23 years which leads to a higher gain in length. The mean and the median of the length difference is 148 meters, which means that more than half of the gullies are increasing more than 100 meters in length.

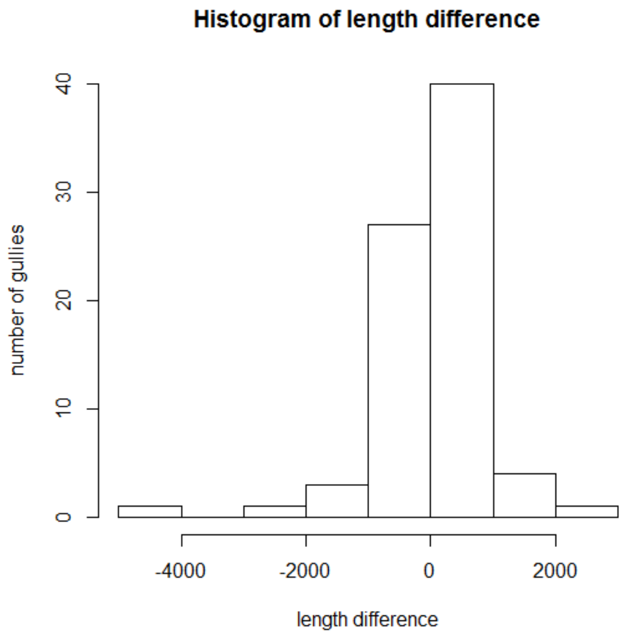

Figure 34: Histogram of the length difference of the gullies between 1993 and 2016

Following figure (figure 35) shows the distribution of the gullies with the inclination in 1993. There are two big groups of gullies. One group is located on hillsides with an inclination between ten and 15 and the other group is located on hillsides with an inclination between 30 and 40 degrees. The average of the inclination is 23 degree. Only less than five gullies are located on hillsides with an inclination over 40 degrees or under five degrees.

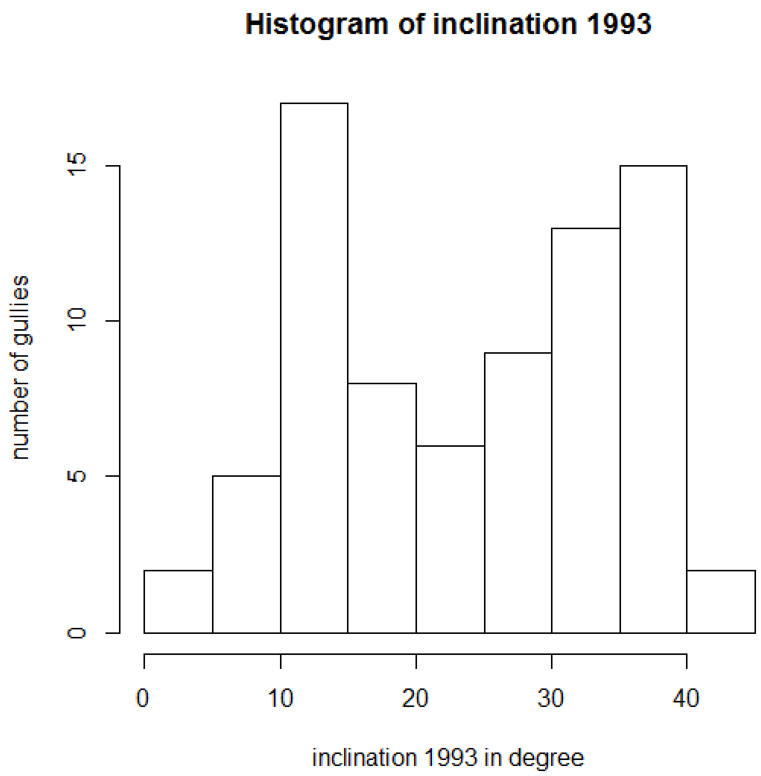

Figure 35: Histogram of the inclination of the gullies in 1993

The difference of the width at the beginning of the gullies between 1993 and 2016 can be seen in figure 36. At the beginning, main gullies are showing a change between minus ten and plus ten meters. Only a few gullies have greater changes in the width at the beginning. The mean change of the gully width at the beginning is +1,4. Which states (in combination with figure 36) that most gullies have only little changes of the width at the beginning.

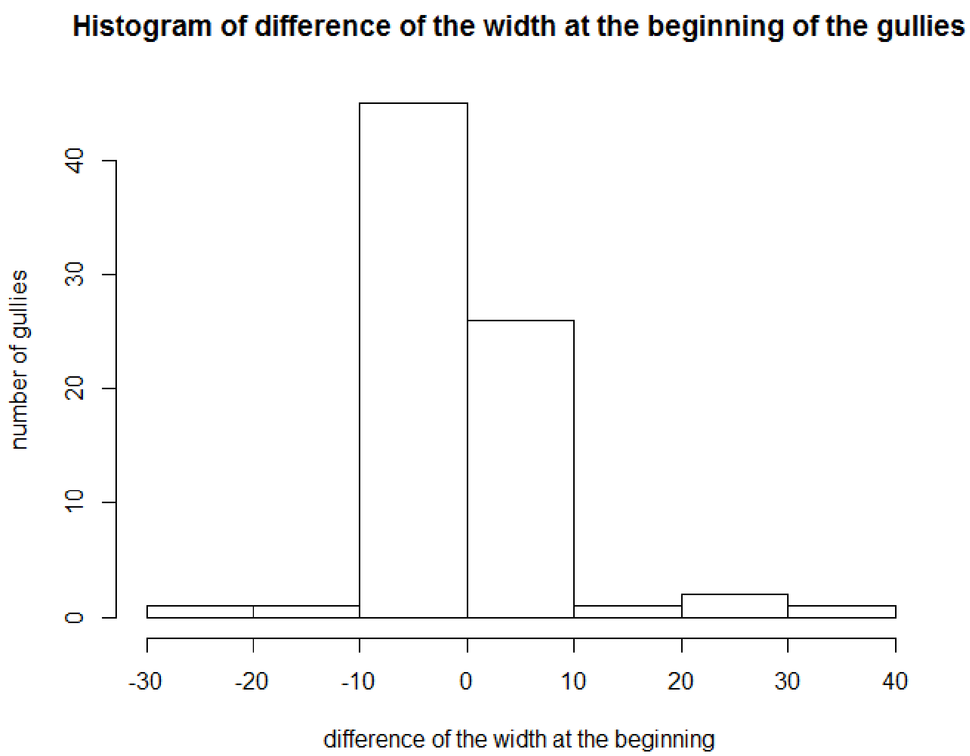

Figure 36: Histogram of the difference of the width at the beginning of the gullies between 1993 and 2016

Figure 37 shows the difference of the width at the middle of the gullies between 1993 and 2016. The variance of the width difference at the middle of the gullies is similar than at the beginning of the gullies. Most gullies have also a change in width between minus ten and plus ten. But the difference of the width change at the middle to the width change at the beginning is that more gullies have width changes that are greater than ten. The mean for the difference of the width at the middle of the gullies is 0,3, which says that on average there are no big changes over time in the width at the middle of the gully.

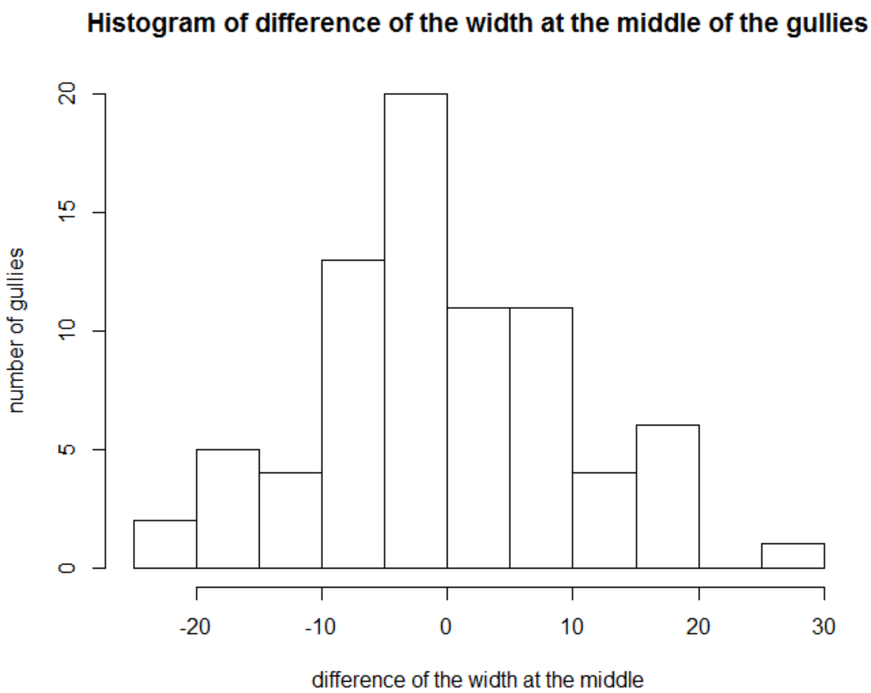

Figure 37: Histogram of the difference of the width at the middle of the gullies between 1993 and 2016

Following figure (figure 38) shows the difference of the width at the end of the gullies between 1993 and 2016. Again the variance is similar to the difference of the width at the middle of the gullies, but most gullies are showing positive values in a change in width at the end, which means that there are more gullies getting wider than getting smaller. The mean of the difference of the width at the end of the gullies is +3,3. So gullies on average have a greater change in the width at the end than at the middle. In the beginning there is also a change in width but in smaller size compared to the end.

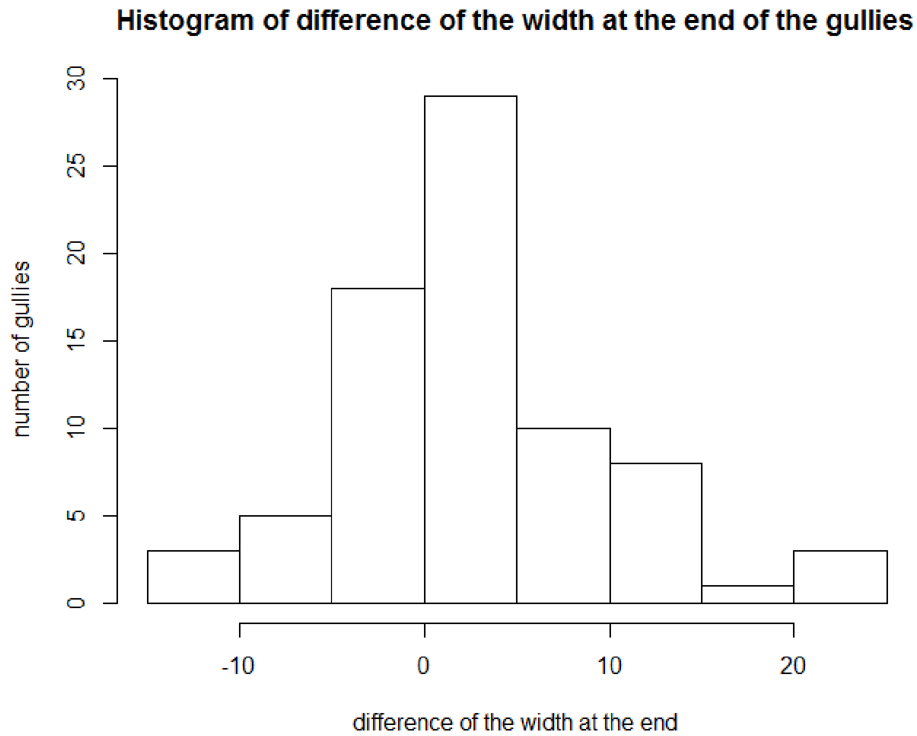

Figure 38: Histogram of the difference of the width at the end of the gullies between 1993 and 2016

The results of the cluster analysis are shown in table 12. It can be seen, that the length of the gullies is increasing on average in cluster one and two. The length is decreasing on average in cluster three as indicated by a negative value. Observing the average inclination of 1993 by cluster assignment also shows decreasing values from cluster one to three. The change of the width over time is different from the length difference and the inclination. Clusters one and three tend to grow in width while in cluster two the gullies tend to become narrower.

Cluster one shows the highest inclination and the highest gain in width. Cluster two shows the smallest changes in width with many data points having a loss in width. Cluster three also shows small changes in width. A first view at the data suggests that a high inclination leads to longer and wider gullies and a low inclination leads to gullies getting shorter with constant width. But in this analysis important variables such as vegetation and land use of the gully areas are not included. Therefore, there are more important factors that explain how the gullies are distinguished.

Table 12: Result cluster analysis (Reference: REITER 2017)

	Cluster 1	Cluster 2	Cluster 3
LengthDiff	578.1	320.5	-673.3
Inclination1993	32.3	25.8	10.9
WbDiff	5.5	-0.1	1.1
WmDiff	11.8	-4.0	-1.4
WeDiff	11.1	-0.9	5.3

Figure 39 shows the relation of the different variables. The red points stand for cluster one, the green points stand for cluster two and the blue points stand for cluster three. A high inclination seems to correlate with a great gain in length but shows no obvious correlation with change in width. Therefore, these gullies are growing longer, because of the high inclination. Those gullies with a low inclination are growing shorter. The reason for this could be a difference in data resolution or a change in land use over the 23 years of analysis. At the beginning of the gully, all clusters are showing a low width difference. Noticeably, the change of middle width and end width also has a high correlation. Also length difference and middle width change also show a positive correlation

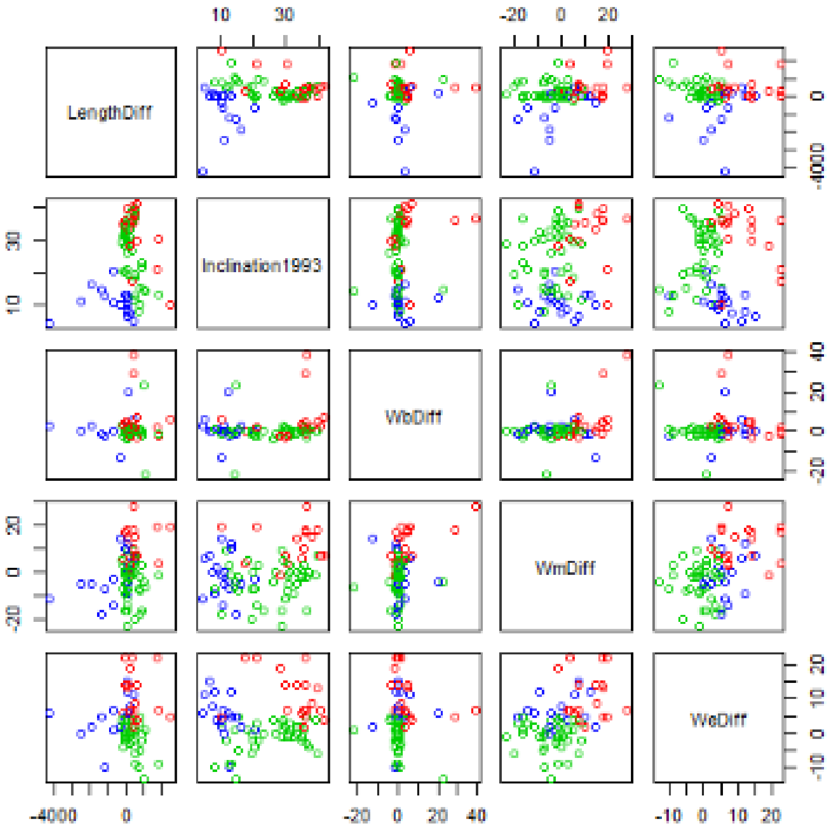

Figure 39: Relation of the variables (Reference: REITER 2017)

In figure 40 the underlying data points for the results of table 1 are shown. The gullies in cluster one (red) have the highest inclination and are getting wider and longer. Cluster two (green) also shows gullies with a higher inclination, but they vary from low to high inclination values. The gullies in this cluster are also getting longer but do not show a gain in width. Cluster three (blue) displays gullies that are of constant or decreasing length. It is the cluster with the slightest inclination and shows an increase of width at the end of the gullies.

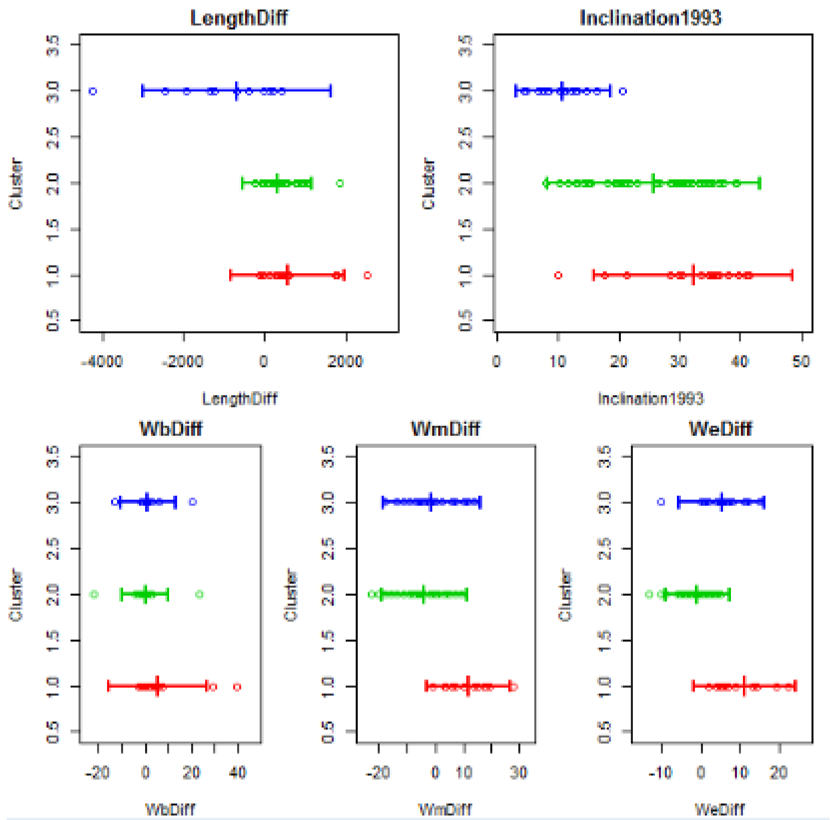

Figure 40: Confidence interval for each cluster at each variable (Reference: REITER 2017)

Figure 41 shows the spatial distribution of clusters in the fjord. The blue points stand for cluster 3 with low or regressive erosion. These are correctly assigned to the parts of the fjord with low inclination. Like the north-western part of the Skagafjörður and some southern parts. The red points, which are representing cluster 1 with high erosion, are lying in the areas with high inclination. These are located on the coast in the north and in the south-eastern part of the fjord. Most of the data points are assigned to cluster two, the green points, distributed in the fjord. On this basis can be said, that most parts of the Skagafjörður are affected by gullies that change slightly compared to the gullies from the other clusters. These gullies (green points) are also located in areas with a moderate inclination. How this area corresponds to the vegetation cover and the land use cannot be said looking at the clustering because these factors are not observed in the analysis.

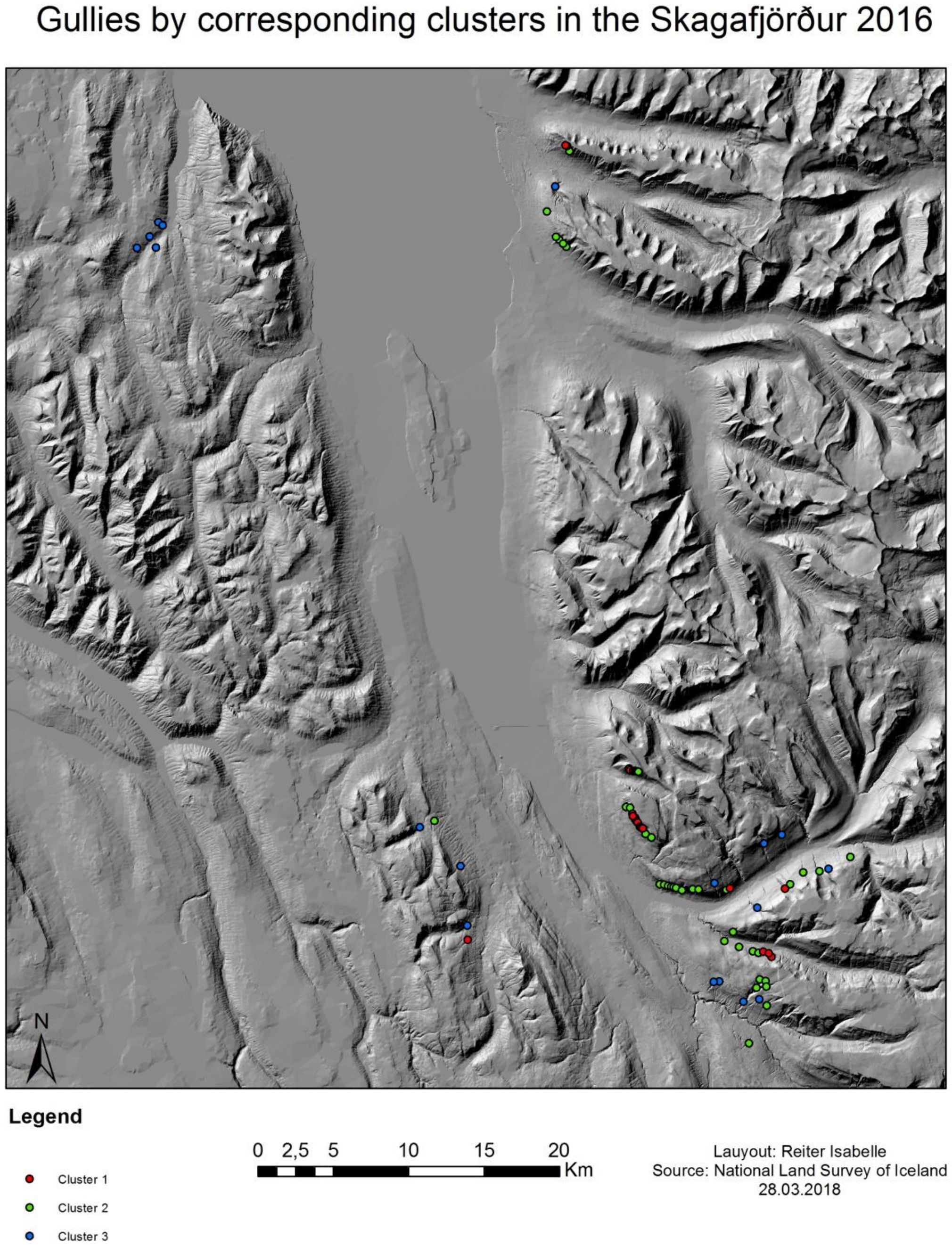

Figure 41: Gullies by corresponding clusters in the Skagafjörður (Reference: REITER 2018)

6.3 Results of the literature analysis about counteractive measures for preventing soil erosion

Through the late ninth century, Iceland was settled and many birches and willow woods covered the island. The livestock which was taken to Iceland through the settlers and the settlers themselves changed the landscape. A change in the vegetation and soil erosion are the results of the settlement of Iceland. (HARTMAN et al. 2017: 126) The livestock of the farmers changed over time. The number of sheep was increasing, while the number of pigs and goats decreased. Sheep are important for the Icelandic export to Europe, because of their wool. An increasing of sheep leads to a stronger soil erosion, because of the stronger pressure on the soil. The fjord bottom was not always a meadow. It was a peat bog, which was heavily drained to create space for farming and living. (DECAULNE et al. 2016: 1308) The sheep and horse farmers of the Skagafjörður took their animals to the highland in summer and the plants of the fjord bottom were used to produce winter fodder. These farming techniques are also common today. (STEINBERG et al. 2016: 391) “Most of the highlands are communal grazing areas, where each local community (hreppur) has grazing rights. The size of the commons is quite variable, ranging from <100 to >5000km^2” (ARNALDS and BARKARSON 2003: 107). Therefore, the human induced land changes are not only in areas that are settled and used for agriculture. Also the mountain areas and the highland were changed over time through the grazing livestock, which set a foundation for gully erosion long before today. The large amount of livestock removes too much vegetation which makes the soil unprotected against erodible processes. Through so many hooves on the ground, the unprotected soil can also easy erode. There are restrictions from the Icelandic Soil Conservation Service who are trying to handle overgrazing but these restrictions are not easy to perform. These restrictions for handling overgrazing are a good approach for protecting the soil, if the soil is intensely damaged from overgrazing. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 54)

To protect the pastures and soil against gully erosion, a solution for sustainable farming had to be found, to avoid that a rural area like the Skagafjörður is lost for agriculture. “Soil-erosion control measures include: to protect the soil productivity, improve or sustain crop yields, retain nutrients and chemicals in soils, improve water quality, and reduce hazards of eroding soil” (ZUAZO et al. 2011: 21). Therefore, it was important to use different management practices to protect the soil against water induced erosion. Such as, protecting the vegetation cover of the soil, supporting a good soil structure and using practices to control soil erosion processes. But it is also important to get the population involved in these management practices and spread awareness about protecting soil against erosional processes. (ZUAZO et al. 2011: 22) Another important factor in protecting the soil against erosion is the amount of livestock which is grazing on the pastures. “Livestock density should be regulated based on the carrying capacity of soils. The first priority should be to restore good grazing land in the lowlands, where sheep should be relocated. In the highlands, grazing should be prohibited in sensitive areas (as defined by SCS soil erosion categories) and in the volcanic belt above 500 metres, to allow natural recovery of vegetation” (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 54). With these approaches the farmers of Iceland had an orientation framework for responsible handling of grazing areas. But these approaches had to be implemented and accepted by the Icelandic government and the farmers to make sure that results are achieved.

“A Ministry for the Environment was established in 1990 and new laws related to nature conservation have been made and amended. Laws concerning grazing, vegetation and soil conservation have, however, not been changed since 1965, excluding minor amendments” (ARNALDS and BARKARSON 2003: 106). The Icelandic government presented a new guideline in

2002, that was supposed to support the farmers in sustainable land use. (ARNALDS and BARKARSON 2003: 106) This guideline is about sustainable land use for the farmers and how to protect the nature. The participation of farmers in these sustainable land use projects is increasing as well as the number of tree farms, which are a part of this project. This is an essential step for farming and preserving the land for future generations. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 17) "The Icelandic Soil Conservation Service has tried continuously to facilitate the protection of the desert commons from grazing. Grazing management practices on the commons, including length of grazing period and stocking density, are in the hands of district councils and vary between commons. The district councils have not offered incentives to achieve substantial changes to land use practices or to suggest protection from grazing. The grazing period for sheep on the commons generally ranges from late June to early September when the sheep are rounded up" (ARNALDS and BARKARSON 2003: 107). Therefore, it is a good solution to implement management practices to protect the mountain areas against soil erosion from farming, but it is also necessary that these management practices are similar throughout Iceland and that all farmers follow the same guidelines for minimizing and avoiding soil erosion. There is also a program which is supporting the planting of birch woods, to reclaim soil and land. This programme tries to reclaim land, to decelerate soil erosion and to provide usable land for the future. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 38)

The public is well informed about soil conservation projects and forestry. Therefore, they understand the great problem of soil erosion and have knowledge about soil conservation programmes and techniques. Vegetation which is robust is used to revegetate eroded areas and systematically conserve the soil. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46) "About 0.2% of the country is covered with natural birch woodland that is at least 5m tall, about 1% of the country is covered in birch thicket, while around 0.2% of the country has been planted with new forests, most of it in the past 10 years. It is estimated that about 30% of the country was covered by woodland at the time of the settlement. Overgrazing, especially during the winter, was a major reason why the birch woods could not recuperate after logging. Sheep grazing still halts the spread of birch in some areas" (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46). Hence, it is not easy to revegetate areas which are affected by overgrazing, because of the short growing season. Plants that are damaged through game animals have harder growing conditions in spring and summer than undisturbed plants. Therefore, it is important to regulate the number of grazing livestock on pastures so that the natural vegetation can recover in winter, to provide better growing conditions in spring and summer. The farmers get suggestions for land improvement projects. Hence, they can use even areas that are not suitable for grazing if they are involved in land improvement projects and practice responsible horse or sheep farming. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46) There are guidelines for horse and sheep farmers to ensure that they practice responsible farming.

The farm land of each horse farmer was evaluated from colleges of the soil conservation service of Iceland and the actual state of the land was captured. The land needs to conform to specific criteria in order to be accepted as land for sustainable land use and is controlled annually. During the controlling period, which starts on the 15th August and ends on the 15th November each year, the soil has to be free from snow. (MARONSSON 2017: 8) In case the condition of the land improves after three years, the controlling period is only held every two years. (MARONSSON 2017: 3) Horse farmers that are not owners of pastures but their horses are on pastures of other farmers, can make a request for evaluating this land. (MARONSSON 2017: 9) As a result, the farmers are making sure to take good care of their land and to therefore improve its quality. This is good for protecting the soil against erosion and for a better well-being of the horses. Because they have better pastures for grazing and the farmers can earn more money with better horses. The number of horse farmers involved in land improvement projects has doubled from 2000 to 2016. (MARONSSON 2017: 3) The horse farmers of the Skagafjörður are distributed over the whole fjord, hence there are many places in the fjord which are sustainably farmed. (MARONSSON 2017: 7)

The used farmlands are fertilized for more vegetation and better pastures. It is forbidden to take horses to freshly fertilized land in spring. Because during this time the vegetation is not full developed and the horses would decimate the fresh saplings, which would lead to a greater loss of soil because of the unprotected soil surface. After spring the vegetation is fully developed and can resist the grazing of horses, without loss of soil. If grazing is necessary in fertile areas, these areas have to be restored after grazing. These areas need to be protected against the grazing horses especially in spring and winter, because during these times, they are especially susceptible against soil erosion. Another important factor for protecting the soil against erosional effects is minimizing the number of grazing horses in an area. Because fewer horses mean less browsing and erosion, which is caused by many hooves on the ground. (MARONSSON 2017: 5-6)

As well as for the horse farmers, there is also a framework of conditions for responsible soil use of sheep farmers. (ÁSBJÖRNSSON 2015: 3) Most of the sheep farmers also have cows for dairy production, which means that they need more land for grazing and producing hay. (ARNALDS and BARKARSON 2003: 109) The number of participants in qualitative sheep farming is rising. In 2014 there were 1 750 participants in qualitative sheep farming. The farmland of sheep farmers is controlled regarding the state of the land in the past and they receive criteria about responsible land use for a better land care in the future and to prevent soil erosion. The condition of farm land is improving since 2013, there it has been proved that the actions sheep farmers take in sustainable land use have an impact. (ÁSBJÖRNSSON 2015: 4) But the horses and sheep are not only on pastures on the fjord bottom. In summer they are on pastures in mountain areas and in the highland. “Most of the communal grazing areas in the central highlands are not suitable for grazing by s heep because of poor condition” (ARNALDS and BARKARSON 2003: 105). 7% of the total number of sheep in Iceland is on pastures in the highland, which has poor grazing conditions. This is not a high percentage, but for the local conditions of soil erosion, the grazing of unsuitable land is i mportant. (ARNALDS and BARKARSON 2003: 112) Once an area in the highland cannot be used for grazing anymore, new grazing areas need to be found, which are possibly further away and taking their sheep to a grazing area could therefore cost the farmers more time and money. It is necessary to handle those areas that are sparsely vegetated with care. The soil of these areas is weaker protected against the hooves of the sheep and the horses because of the sparse vegetation. Areas of the mountains also have a higher slope than areas at the fjord bottom. Therefore, the energy of the melting water and rain discharge is higher and can erode more soil which is not protected with vegetation. Hence, it would be required to protect the mountain areas and highland against overgrazing, to prevent soil erosion and gully erosion in these areas. Therefore, there are some restrictions for farmers which use unsuitable grazing areas in the highland. “The farmers using commons not suited for grazing will not meet the criteria for quality management according to the subsidy agreement resulting in lower subsidies. The new subsidies agreement may therefore slowly turn a proportion of the sheep grazing off these unsuitable commons to other areas better suited for grazing by sheep” (ARNALDS and BARKARSON 2003: 112). The farming areas of the lowlands are well suited for grazing, which can be an alternative for an area which has a high portion of unsuited grazing areas like the highlands. (ARNALDS and BARKARSON 2003: 112)

“The Agricultural Research Institute, the Farmers Association of Iceland, the Soil Conservation Service (SCS) and the Ministry of Agriculture collaborate on a project called *Land for Use*. It is meant to be a comprehensive record of landholding in Iceland. Amongst other things, it will gather basic data on the size of individual properties in Iceland together with vegetation details and will provide a basis for assessing whether there is sufficient vegetation for grazing. The project improves the database that certification of sustainable utilization must be based on. *Better Estates* is a collaborative project of the Agricultural College, the Farmers Association of Iceland and the SCS on revegetation and land use in cooperation with farmers" (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47). Hence, there are ongoing projects to improve the land use and to avoid and minimize soil erosion. The Icelandic parliament determined a soil conservation project that runs for twelve years, which was the first long term strategy in soil protection strategies. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) "Emphasis is placed on curbing soil erosion, revegetation, monitoring of the condition of vegetation and soil, land use management, research and dissemination of information" (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47). Another aim of this strategy is to find congruent definitions of desertification and nature conservation. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) The policy also supports afforestation projects. All over Iceland there are regional forest projects and the farmers and land owners get support for their participation in afforestation. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47). The afforestation projects started in east Iceland, because the good climatic conditions, which lead from the Gulf Stream, support tree growth. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 54) An important point of the afforestation projects is the multiple use of the planted trees. Their sole purpose is not only to protect the soil against erosion, they provide also habitats for other organisms and are in special cases for timber production. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) The planted trees are not always domestic species. For example the Sitka Spruce is used in eroded areas to protect them and now this tree species is increasing in Iceland. To control the imported species, a regulation for the use of imported species was introduced in 2000, to protect the typical Icelandic flora. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 57) "It is important that the forests are maintained in harmony with the landscape and that afforestation will not disturb important habitats, natural phenomena or archaeological sites" (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47). Therefore, there are many ongoing projects which aim to minimize soil erosion and to conserve the usable land for farming and settling.

The Skagafjörður is a rural area with small villages and the biggest town Sauðárkrókur has about 4 400 inhabitants. (URL-E) In the past the fjord bottom was a peat bog, which was heavily drained for framing and living, by the first settlers. (DECAULNE et al. 2016: 1308) The turf from the peat bog was used to build houses, because timber is rare in Iceland. (STEINBERG et al. 2016: 391) Since the Landnám time the Skagafjörður was continuously and actively farmed, which leads soil erosion in the low lands, like the regions of Hegranes and Langholt. (CATLIN 2016: 17-18) Therefore, this area has been highly affected by human induced processes for a long time, which set the basis for soil erosion processes. But the first settlers need the drained peat bog for farming and the turf for living, because of the limited natural resources. As they did not have much choice regarding farming areas and building materials, areas that were suitable for farming and were near to the sea to practise fishing, provide them with a basis for survival. The vegetation of Iceland changes through the grazing livestock, which results in a reduced tree growth and the first settlers, needed the turf from the peat bog to build houses and stables. Nowadays agriculture and fishing are still important sectors of Iceland´s economy but in addition to that the tourism and the hospitality sector, as well as other industries play an important role in the Icelandic economy. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 91 and SCHUTZBACH 1985: 220-221)

One of Iceland´s most important export products are goods produced by the fishing industry. It makes more than 12% of Iceland´s gross domestic product. (URL-D) In addition to the fishing industry, agriculture is also an important economic factor of Iceland. Horses are also important export products and have cultural worth for the Icelandic population. (SCHUTZBACH 1985: 210)

For the past few years Iceland´s economy is growing and energy intensity is decreasing since 1990. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 19-20) There are new innovations for pollution management, such as the switch from oil to geothermal energy and also new ways of managing natural resources sustainably. These sustainable management plans contain long term planning for regional projects and land ownership rights. These are important steps for protecting the natural resources and to use them responsibly and protect the highland. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 19-20) Protecting the highland and mountain areas from intensive grazing of livestock is important. But it is also necessary to protect the highland for example from tourists, which are hiking aside of hiking paths. If a lot of people do this, it can lead to new rills on the ground, which can develop into gullies if the slope is high enough and the run off energy is also high enough. Therefore, it is relevant to make everyone attentive of the problem of soil erosion and that it is an irreversible problem for any country, especially for an island.

7 Discussion

To conduct research on the process of soil erosion and the factors which contribute to it, it is essential for every country that is susceptible to this geomorphological process.

“Soil is a natural resource that is not renewable in a historical time scale. It results from the interaction of aggradation and degradation processes, which lead to a progressive increase of soil thickness (i.e. pedogensis), or, in turn, to the removal of soil material and consequent thinning of the soil profile (i.e. morphogenesis)” (BINI and ZILIOLI 2011: 36). If the morphogenesis is more distinctive than the pedogenesis, soil erosion is given. (BINI and ZILIOLI 2011: 36)

The geomorphological form of gully erosion transfers surface water and sediments from the high mountain areas to the fjord bottom. Erosion gullies are connected to the permanent hydrological processes and have an impact on the evolution of the landscape. (BINI and ZILIOLI 2011: 41)

Satellite images and digital elevation models are in combination a good dataset to locate gully erosion and to see how the gullies have changed from 1993 to 2016 and to see which erosional processes are ongoing or happened in the past. But it is important that the data basis covers the same area of the fjord and that the datasets have a similar resolution, to see how the area has changed. The digital elevation models are good basis for mapping the gullies and to make decisions about how they changed in length and over time. A disadvantage for detailed results is the resolution of the digital elevation models. The digital elevation model from 2016 had a resolution of ten meters and the digital elevation model of 1993 had a resolution of five meters. Both digital elevation models can be used for identifying and mapping gullies but the result of this is afflicted with the error of different resolutions. Another disadvantage of the digital elevation models is that the model from 1993 does not cover the whole fjord. Therefore, there are areas that cannot be compared regarding their changes in gully erosion. But the south eastern part of the fjord, which is characterized through intense gully erosion, is covered by both digital elevation models. Therefore, statements can be made on how these areas have changed over the course of 23 years and which factors affect gully erosion. In order to get results on gully erosion for the whole fjord, it would have been necessary that the data base of the digital elevation models of different years had the same resolution and covered the whole fjord. In investigating gully erosion in the Skagafjörður, it is important to analyse digital elevation models and satellite images to see how this area has changed. But it is also important to look at different factors which can lead to gully erosion or factors which prevent gully erosion, to make decisions on the area´s degree of vulnerability for erosion and which practices are good for slowing or preventing gully erosion. The information of the digital elevation models can be analysed statistically to see how the different variables influence each other. The satellite images have a lesser resolution than the digital elevation models, so they are not suitable for identifying gully erosion. Satellite images are a good addition to the digital elevation models, to see how the land use has changed over time through comparing different satellite images and if the process of gully erosion is highly active or not, in comparing the deposits of gully erosion. If they are vegetated, the erosional processes are not active. Another important point for using satellite images is, to consider that the satellite images have a small cloud cover and are mainly free from snow, to see as much as possible from the satellite images. These satellite images are also a good dataset to calculate different indices, for example the NDVI (Normalized Differenced Vegetation Index), to identify the vegetated areas and to see how healthy the vegetation is. (NOURI et al. 2017: 12) Near infrared satellite images are good basis to see how densely the Skagafjörður is vegetated. To get better results about the ongoing gully erosion processes of the Skagafjörður, it would be good to verify the mapped gullies of the digital elevation models by mapping the gullies in the field. Thus, the ongoing erosion processes can be direct evaluated and evidence about the soil, vegetation cover and farming techniques can be taken.

By analysing the process of gully erosion in the Skagafjörður, it can be observed that there are different factors which support gully erosion. Gully erosion depends on the type of soil, if the soil is covered with vegetation and how dense the vegetation cover is, on the amount of precipitation, by the melting water in spring, the inclination of the slope and how the area of the Skagafjörður is used and formed by humans.

The main part of the Skagafjörður is covered with Andosols. This type of soil is a good soil for vegetation but it could easily lead to landslides. If the soil is saturated with water it can act like liquids. (ARNALDS 2008: 416) This could be the reason, why there are so many new gullies in 2016. During the snow melting the soil is highly saturated with water and can easily move away and build new gullies in sparsely vegetated areas. Existing gullies that are not intensely vegetated can grow longer and wider because of this phenomenon. Many gullies develop through melting water. Because of the flowing water, the soil surface and the cover of vegetation are washed away. (GUÐMUNDSSON 2007: 325)

By analysing the different factors, which can support gully erosion, statistically with a k-means cluster analysis, it is shown that a high inclination correlates with a gain in length. But a high inclination shows no correlation with a change in width. A low inclination seemingly leads to gullies which are growing shorter. This is an interesting point, because there must be something happening, that existing gullies are growing shorter. It could be that this is due to the different resolution of the digital elevation models. They have an inaccuracy of five meters, which does not make it easy to map weak pronounced gullies on shallow slopes correctly. To make sure that gullies with a low inclination are growing shorter, it needs digital elevation models with the same resolution so all gullies are mapped on the same data resolution and there could be no error from different resolutions. Another reason for the decrease in length could be, that the population had practiced counteractive measures over those 23 years to protect shallow slopes against progressive gully erosion. To answer this, literature about counteractive measures had to be studied, to make sure which different types of counteractive measures had been made in these 23 years in the Skagafjörður. The result of the literature studies is that only the fjord bottom is intensively protected against soil erosion. The mountain areas, in which the gullies are located, are used as pastures. It cannot be decided by literature study alone if the farmers, which practice responsible horse or sheep farming in the lowlands, also take care about the mountain areas. There are projects about revegetating and afforestation but it cannot be said if these projects take place at the same places where the gullies are located. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46) The satellite images of the Skagafjörður are showing no significant new vegetation in the gully areas. To answer this question, it would be necessary to investigate the vegetation of the gullies in the field to find out whether they are protected with vegetation and to talk to local farmers and land owners to know if the mountain areas are handled with care to decelerate gully erosion and which places of the Skagafjörður are revegetated through afforestation and revegetation projects.

Statistical analyses are a good tool to identify factors which correlate with gully erosion and to locate patterns of gully erosion in the fjord. Therefore, through these analyses different patterns are identified, which builds a basis for new studies. Further research on this should be done based on the findings of this thesis to treat the question why some gullies are decreasing in length.

The Skagafjörður is a rural area which has been cultivated for a long time by local farmers. (URL-E and DECAULNE et al. 2016: 1308) As a result of this long and intense farming, the fjord bottom and the highlands are highly affected by soil erosion. (CATLIN 2016: 17-18) The farmers took their sheep and horses in winter on pastures at the fjord bottom and in summer on pastures in the highland. (STEINBERG et al. 2016: 391) The highland areas are very sparsely vegetated and through the large amount of the grazing livestock highly vulnerable to soil erosion. (SCHUTZBACH 1985: 193) The erosion form of gully erosion is spread over the whole mountain areas of the Skagafjörður and the fastest growing gullies in length and width are in those areas which have a high inclination, which can be seen on the digital elevation models and is detected through the statistical analysis. Through the grazing livestock, the vegetation of the mountain flanks is minimized and the large amount of hooves on the ground sets the basis for gully erosion. If there is a lot of melting water in spring, the disturbed and unprotected soil is washed away and a new erosion gully is formed. (GUÐMUNDSSON 2007: 325) Therefore, it is important to protect the soil against erosional processes. The different projects for avoiding and minimizing soil erosion are about minimizing the amount of grazing livestock, land improvement projects, guidelines for the farmers about sustainable land use, revegetation of the sparsely vegetated highland and afforestation projects. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) It would be a good addition to evaluate not only the farmlands on the fjord bottom but also the parts of the highland and mountain areas, which are used as pastures. To see how these areas has changed over time and how changes in the number of livestock and revegetation affects gully erosional processes. Because most of the sustainable farming projects plan to protect the densely vegetated fjord bottom. (MARONSSON 2017: 8) Hence, it could be a good idea that the gully areas with a low slope are used as farmlands and are taken care of by the farmers to decrease gully erosion and to conserve as much pastures as possible. This could be also the reason, why gullies which are located on areas with a low slope are decreasing in length. It is a good idea to protect the farmlands on the fjord bottom against intense farming. But the mountain areas and highland are highly susceptible for soil erosion. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) Therefore, the highland and mountain areas should be better protected. In order to protect these areas against intensive farming and allowing the natural vegetation to recover, more plans and guidelines need to be issued. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 19-20) In addition to these projects it is also important to make sure that the population of Iceland as well as the tourists are well informed about the problem of soil erosion and how to prevent and minimize soil erosion. With this knowledge a basis for sustainable tourism in Iceland can be made, which could be ground-breaking for sustainable economy as well. It is also essential that the population learns from childhood on, that soil erosion is a great problem for an island and that the soil has to be handled with care to avoid that it is lost. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 22) Gully erosion is only a small part of soil erosion forms in Iceland, but the impact of gully erosion on agricultural areas and settlements should not be underestimated. Because erosion gullies cannot be undone and they have impacts on the transfer from surface water and sediments and they can change the hydrological processes and evolution of the landscape of the fjord. Therefore, it is important to know that gully erosion is also a great problem for a region, especially for a rural region that needs areas for farming. If the persistent farming areas are lost, the farmers need new areas that they can use as pastures. Therefore, they need more time and money to take their livestock to other pastures in other regions, which are maybe farther away. Hence, if there is not an action in trying to prevent and minimize gully erosion, a whole region could be lost for farming.

Therefore, the ministry for the environment in Iceland has different projects with different organisations about different themes to avoid soil erosion and minimize ongoing soil erosion processes to conserve the usable farming areas and to support sustainable farming, as well as to improve farming areas that are susceptible for soil erosion. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) Iceland has good techniques that are used to care for the soil and preserve it for future generations as well as to slow down the loss of soil and trying to reserve the damage that the first settlers have done to the island. Hence, the Skagafjörður and Iceland will be vegetated areas like they were, before the first settlers arrived. (HARTMAN et al. 2017: 126) With the vegetation and afforestation projects that are supported by the policy, Iceland is on a good way to slow and prevent the process of soil erosion with natural instruments which protect the soil for a long-lasting time. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46-47) But the different vegetation types need to be considered. Imported vegetation needs to be handled with care to avoid it spreading across the whole island, which would lead to new problems. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 57) Therefore, a well-informed population and tourists are required to guarantee sustainable land care and protect the soil cover against erosion.

8 Conclusions

The process of gully erosion is not easy to capture because there are different factors which are contributing to this process. Among these factors are the amount of precipitation or water which is available to erode soil, the inclination of the mountain flanks, if the soil is protected with vegetation and the type of the soil and also the influence of humans in the area.

Therefore, it needs a lot of research and analyses to get information about these different variables. Through literature study different information about the study area can be found, which is about the climate, geology, soil, land use, vegetation, population, historical development of the Skagafjörður and counteractive measures in preventing gully erosion and ongoing as well as future projects.

Through analysing satellite images and digital elevation models over the period of 23 years changes of the gullies can be detected and different parameters of the gullies can be received. On basis of the digital elevation models it can be seen that the gullies have changed but it cannot be said how much they have changed and which parameters support a change of the gullies. Therefore, a statistical analysis is a good tool to detect associations and to see which parameters have a high influence on gully erosion. These analyses give a good basis to understand the influencing factors of gully erosion. This knowledge is in combination with literature study about counteractive measures and future projects about decelerating soil erosion essential, to know the risk of gully erosion and which could be done to prevent areas from this process or to slow existing processes of gully erosion.

Through these different analyses the research questions and hypothesis could be answered by the following.

"How good can remote sensing with medium resolution satellite images and digital elevation models capture gully erosion processes in the study area?"

After analysing satellite images and digital elevation models many erosion gullies could be found in the Skagafjörður. The gully form is clearly visible on the older as well as on the newer digital elevation model but the resolution of the Landsat and ASTER satellite images is not suitable for mapping. These satellite images of Landsat and ASTER provide useful information about the land cover of the Skagafjörður and by looking at the vegetated areas, it can be decided, if deposits from erosion gullies are new or old. Old deposits are vegetated and new deposits are unvegetated. Therefore, the vegetation cover gives insights about the activity of gully erosional processes. Hence, digital elevation models and satellite images form a good combination and basis for capturing gully erosion processes.

"How has the area affected by erosion changed in the last twenty-three years?"

North Iceland has less precipitation than other parts of Iceland. Therefore, normal precipitation cannot be the reason why there are so many gullies in the Skagafjörður. In the twenty-three years, which are observed in this thesis, there were a few days with heavy snowfall in the north of Iceland. These extreme snow masses lead to enormous amounts of melting water in spring, which can easily erode the soil surface, which is unvegetated during this time. (URL-A and URL-B)

Comparing the gullies regarding their change over time, it can be seen, that some gullies have grown in size over these twenty-three years. Other gullies are showing no changes over this time. Many new gullies formed during these twenty-three years, which can be as a result of the enormous amounts of melting water, which was caused by heavy snowfall.

"Are there spatial patterns in soil erosion phenomena?"

By looking at the cluster analysis it can be said, that most parts of the Skagafjörður are affected by gullies that change marginally. These areas have a moderate inclination, which results in a marginal change in the existing gullies. Those areas of the fjord which have a higher inclination have gullies longer in size, which also show a growth in length over these years. The areas on the coast in the north and in the south eastern part of the Skagafjörður are areas with a high inclination. In these areas there are gullies which are higher eroded, than others. The areas with a slight inclination, which are in the north western parts of the fjord and the southern part, have shorter gullies which tend to become narrower.

"Which counteractive measures were taken?"

The number of horses and sheep was minimized to protect the ground against erosion. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 74) Based on the capacity of the soil, the number of livestock is regulated. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 54) There are projects for sustainable land use which provide guidelines for the farmers on how to care for the soil and protect it against soil erosion. They get also suggestions for land improvement projects and if the condition of the pastures for horses and sheep is better, the farmers can earn more money with better sheep or horses. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) The sparsely vegetated highland is used as grazing area for the livestock. (SCHUTZBACH 1985: 193) It is advised to primarily use grazing areas in the low land, because these areas are better vegetated and not as susceptible for erosional processes. (ARNALDS and BARKARSON 2003: 112) Robust vegetation is planted to cover eroded areas and make them unsusceptible to erosion. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 46) Iceland also has afforestation projects to protect the soil against erosion. These afforestation projects are supported by the policy, to motivate people to plant forests. (THE MINISTRY FOR THE ENVIRONMENT IN ICELAND 2002: 47) The Icelandic population is informed about the risks of soil erosion and soil protecting projects. (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2001: 22) Therefore, these are important steps to minimize soil erosion processes and to preserve the usable areas for agriculture and living.

In answering the research questions, the following hypothesis can be accepted.

"Soil erosion consumes agricultural areas in North Iceland. Spatio-temporal patterns of soil erosion can be captured with medium-resolution satellite imagery and digital elevation models."

This means that satellite imagery and digital elevation models are a good data foundation for capturing gully erosion. In combination with literature study, different information about the study area and counteractive measures could be found to understand this process in this area better and to how the different factors of gully erosion influence each other.

Therefore, this thesis gives a good overview about the process of gully erosion on an island and which problems results from that. Still there are not only negative effects of gully erosion, because it also offers the opportunity for creating new ideas for projects and research in protecting usable land in Iceland.

9 References

ARNALDS A. (2004): Approaches to landcare – A century of soil conservation in Iceland. – In: Land Degradation Development 16 (2005) 113 – 125.

ARNALDS Ó., THORARINSDOTTIR E. F., METUSALEMSSON S., JONSSON A., GRETARSSON E. and ARNASON A. (2001): Soil erosion in Iceland. – Gutenberg.

ARNALDS Ó. (2004): Volcanic soils of Iceland. – In: Catena 56 (2004) 3 – 20.

ARNALDS Ó. (2008): Soils of Iceland. – In: Jökull 58 (2008) 409 – 421.

ARNALDS Ó. and BARKARSON B. H. (2003): Soil erosion and land use policy in Iceland in relation to sheep grazing and government subsidies. – In: Environmental Science & Policy 6 (2003) 105 – 113.

ÁSBJÖRNSSON G. (2015): Gæðastýring í sauðfjárframleiðslu Landnýtingarþáttur 2014. - Landgræðsla ríkisins. – Hella. Online: http://land.is/gaedastyring-i-saudfjarraekt/ (02.04.2018)

BARSI J. A., LEE K., KVARAN G., MARKHAM B. L. and PEDELTY J. A. (2014): The Spectral Response of the Landsat-8 Operational Land Imager. In: Remote Sensing 6 (2014) 10232-10251. Online: www.mdpi.com/2072-4292/6/10/10232/pdf (02.04.2018)

BINI C. and ZILIOLI D. (2011): Soil erosion between geomorphological fragility and sustainable land use in mountain areas (Italy). – In: FOURNIER A. J. (2011): Soil erosion: causes, processes and effects. – New York, 35 – 68.

BLUME H. P., BRÜMMER G. W., HORN R., KANDELER E., KÖGEL-KNABNER I., KRETZSCHMAR R., STAHR K. and WILKE B. M. (2010): Scheffer/ Schachtschabel Lehrbuch der Bodenkunde. – Heidelberg.

BOARDMAN J., POESEN J. and EVANS R. (2003): Socio-economic factors in soil erosion and conservation. – In: Environmental Science & Policy 6 (2003) 1 – 6.

CATLIN K. A. (2016): Archaeology for the Anthropocene: Scale, soil and the settlement of Iceland. – In: Anthropocene 15 (2016) 13-21.

DECAULNE A., COSSART E., MERCIER D., FEUILLET T., COQUIN J. and JÓNSSON H. P. (2016): An early Holocene age for the Vatn landslide (Skagafjörður, central northern Iceland): Insights into the role of postglacial landsliding on slope development. – In: The Holocene 26:8 (2016) 134 – 1318.

DECAULNE A., SÆMUNDSSON Þ., JÓNSSON H. P. and SANDBERG O. (2007): Changes in deposition on a colluvial fan during the upper Holocene in the Tindastóll mountain, Skagafjörður district, north Iceland: preliminary results. – In: Geografiska Annaler. Series A, Physical Geography 89, No. 1 (2007) 51-63.

DUGMORE A. J., GISLADÓTTIR G., SIMPSON I. A. and NEWTON A. (2009): Conceptual Models of 1200 years of Icelandic Soil Erosion Reconstructed Using Tephrochronology. – In: Journal of the North Atlantic 2 (2009) 2 – 18.

EINARSSON M. Á. (1984): Climate of Iceland. – In: Van Loon H. (Ed): World Survey of Climatology 15. Climates of the Oceans. Amsterdam, 673-697.

EVANS R. (1980): Mechanics of Water Erosion and their Spatial and Temporal Controls: An Empirical Viewpoint. - In: KIRKBY M. J. and MORGAN R. P. C. (Ed): Soil Erosion. – Chichester, New York, Brisbane and Toronto, 17-56.

EVERITT B. S. and HOTHORN T. (2010): A handbook of statistical analyses using R. second edition. – Boca Raton.

FEUILLET T., MERCIER D., DECAULNE A. and COSSART E. (2011): Classification of sorted patterned ground areas based on their environmental characteristics (Skagafjörður, Northern Iceland). In: Geomorphology 139-140 (2012) 577-587.

FOULGER G. R., NATLAND J. H. and ANDERSON D. L. (2005): Genesis of the Iceland melt anomaly by plate tectonic processes. – In: FOULGER G.R., NATLAND J.H., PRESNALL D.C. and ANDERSON D.L. (Ed): Plates, plumes, and paradigms. – Geological Society of America. – Special Paper 388 (2005) 595 – 625.

FOURNIER A. J. (2011): Soil erosion: causes, processes and effects. – New York.

GEIRSDÓTTIR Á., MILLER G. H. and ANDREWS J. T. (2006): Glaciation, erosion, and landscape evolution of Iceland. – In: Journal of Geodynamics 43 (2007) 170 – 186.

GISLADÓTTIR G., ERLENDSSON E., LAL R. and BIGHAM J. (2009): Erosional effects on terrestrial resources over the last millennium in Reykjanes, southwest Iceland. – In: Quaternary Research 73 (2010) 20 – 32.

GISLADÓTTIR G., ERLENDSSON E. and LAL R. (2011): Soil evidence for historical human-induced land degradation in West Iceland. – In: Applied Geochemistry 26 (2011) 528 – 531.

GOESSLING M. (2017): CORDEX climate trends for Iceland in the 21st century. – Icelandic Meteorological Office.

GREIPSSON S. (2012): Catastrophic soil erosion in Iceland: Impact of long-term climate change, compounded natural disturbances and human driven land-use changes. – In: Catena 98 (2012) 41-54.

GUÐMUNDSSON A. T. (2007): Lebende Erde – Facetten der Geologie Islands. – Reykjavík.

HARTMAN S., OGILVIE A. E. J., INGIMUNDARSON J. H., DUGMORE A. J., HAMBRECHT G. and MCGOVERN T. H. (2017): Medieval Iceland, Greenland, and the New Human Condition: A case study in integrated environmental humanities. – In: Global and Planetary Change 156 (2017) 123-139.

HARTMANN W. K., THORSTEINSSON T. and SIGURDSSON F. (2003): Martian hillside gullies and Icelandic analogs. – In: Icarus 162 (2003) 259 – 277.

MARONSSON B. (2017): Gæðastýring í hrossarækt, landnýting. Ársskýrsla 2016. - Landgræðsla ríkisins. – Hella. Online: http://land.is/gaedastyring-hrossaraektar/ (30.11.2017)

MC GOVERN T. H., VÉSTEINSSON O., FRIDRIKSSON A., CHURCH M. J., LAWSON I. T., SIMPSON I. A., EINARSSON A., DUGMORE A. J., COOK G. T., PERDIKARIS S., EDWARDS K. J., THOMSON A. M., ADDERLEY W. P., NEWTON A. J., LUCAS G. and EDVARDSSON R., ALDRED O. and DUNBAR E. (2007): Landscapes of Settlement in Northern Iceland: Historical Ecology of Human Impact and Climate Fluctuation on the Millennial Scale. – In: American anthropologist 109 (2007) 27 – 51.

MITCHELL J. K. and BUBENZER G. D. (1980): Soil Loss Estimation. – In: KIRKBY M. J. and MORGAN R. P. C. (Ed): Soil Erosion. – Chichester, New York, Brisbane and Toronto, 17 – 56.

NOURI H., ANDERSON S., SUTTON P., BEECHAM S., NAGLER P., JARCHOW C. J. and ROBERTS D.A. (2017): NDVI, scale invariance and the modifiable areal unit problem: An assessment of vegetation in the Adelaide Parklands. – In: Science of the Total Environment 584-585 (2017) 11-18.

ÓLAFSDÓTTIR R. and GUÐMUNDSSON H. J. (2001): Holocene land degradation and climatic change in northeastern Iceland. – In: The Holocene 12 (2002) 159 – 167. Online: http://hol.sagepub.com/content/12/2/159 (02.04.2018)

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (2001): Environmental Performance Reviews. Iceland. – Paris.

PIMENTEL D., HARVEY C., RESOSUDARMO P., SINCLAIR K., KURZ D., MC NAIR M., CRIST S., SHPRITZ L., FITTON L., SAFFOURI R. and BLAIR R. (1995): Environmental and Economic Costs of Soil Erosion and Conservation Benefits. – In: Science 267 (1995) 1117 – 1123.

SAVRY C. and E. CAÑÓN-TAPIA (2014): Iceland structure and volcanism: An alternative vision based on the model of volcanic systems. – In: Tectonophysics 636 (2014) 201 – 215.

SCHUTZBACH W. (1985): Island. Feuerinsel am Polarkreis. – Bonn.

STEINBERG J. M., BOLENDER D. J. and DAMIATA B. N. (2016): The Viking Age settlement pattern of Langholt, North Iceland: Results of the Skagafjörður Archaeological Settlement Survey. – In: Journal of Field Archaeology 41:4 (2016) 389 – 412. Online: http://dx.doi.org/10.1080/00934690.2016.1203210 (02.04.2018)

STREETER R. and DUGMORE A. (2014): Late-Holocene land surface change in a coupled social-ecological system, southern Iceland: a cross-scale tephrochronology approach. – In: Quaternary Science Reviews 86 (2014) 99 – 114.

THE MINISTRY FOR THE ENVIRONMENT IN ICELAND (2002): Welfare for the Future. Iceland's National Strategy for Sustainable Development 2002–2020. – Reykjavik. Online: https://eng.umhverfisraduneyti.is/publications/nr/393 (28.11.2017)

THORDARSSON T. and HOSKULDSSON A. (2002): Classic Geology in Europe 3. – Iceland. – Harpenden.

TOY T. J., FOSTER G. R. and RENARD K. G. (2002): Soil Erosion: Processes, Prediction, Measurement, and Control. – New York.

VEÐURSTOFA ÍSLANDS (2017): Ársskýrsla 2016. – Reykjavik.

ZEPP H. (2014): Geomorphologie. Eine Einführung. – Paderborn.

ZUAZO V. H. D., TEJERO I. G., MARTINEZ J. R. F. and FERNANDEZ J. L. M. (2011): Soil erosion: causes, processes and effects. – In: FOURNIER A. J. (2011): Soil erosion: causes, processes and effects. – New York, 1 – 34.

10 Online References

NATIONAL LAND SURVEY OF ICELAND (2006): Online: http://www.lmi.is/en/okeypis-kort/ (02.04.2018)

NATIONAL LAND SURVEY OF ICELAND (2013): Online: http://www.lmi.is/en/okeypis-kort/ (02.04.2018)

URL-A: http://en.vedur.is/about-imo/news/nr/2567 (02.04.2018)

URL-B: http://en.vedur.is/about-imo/news/nr/2609 (02.04.2018)

URL-C: http://en.vedur.is/about-imo/news/2015 (02.04.2018)

URL-D: https://www.cia.gov/library/publications/the-world-factbook/geos/ic.html (02.04.2018)

URL-E: http://www.northwest.is/2saudarkrokur.asp (02.04.2018)

URL-F: http://www.rala.is/ando/1-1.htm (02.04.2018)

URL-G: http://www.rala.is/desert/2-1.html (02.04.2018)

URL-H: https://www.soils.org/discover-soils/soil-basics/soil-types/histosols (02.04.2018)

URL-I: https://www.cals.uidaho.edu/soilorders/histosols_04.htm (02.04.2018)

URL-J: www.umweltbundesamt.at/fileadmin/site/.../1.../corine/CORINE_Nomenklatur.pdf (02.04.2018)

URL-K: http://rbg-web2.rbge.org.uk/bbs/Resources/gallery/R.%20lanoginosum.JPG (02.04.2018)

URL-L: http://lichenportal.org/portal/taxa/index.php?taxon=63777 (02.04.2018)

URL-M: http://www.nhm2.uio.no/botanisk/lav/Photo_Gallery/Cetraria/islandica_G=Norway+Buskerud +Sigdal_D=20030702_O=Timdal_C=ET_I=1.jpg (02.04.2018)

URL-N: http://www.arcticatlas.org/photos/pltspecies/spp_enlargement.php?queryID=caly3&fileName =caly3_2.jpg (02.04.2018)

URL-O: https://science.nasa.gov/ems/08_nearinfraredwaves (02.04.2018)

URL-P: https://asterweb.jpl.nasa.gov (02.04.2018)

URL-Q: https://terra.nasa.gov/about/terra-instruments/aster (02.04.2018)

URL-R: https://landsat.usgs.gov/landsat-project-description (02.04.2018)

URL-S: https://landsat.gsfc.nasa.gov/about (02.04.2018)

URL-T: https://landsat.gsfc.nasa.gov/landsat-8/landsat-8-bands (02.04.2018)

URL-U: https://stat.ethz.ch/R-manual/R-devel/library/stats/html/kmeans.html (02.04.2018)

Appendix A

X= easting, Y= northing, length2016= length of the Gully 2016, length1993= length of the Gully 1993, LengthDiff= difference of the length 2016 and 1993, Zmin2016= minimum height 2016, Zmin1993= minimum height 1993, Zmax2016= maximum height 2016, Zmax1993= maximum height 1993, Z maxDiff= maximum height difference 1993 and 2016

FID	Id	X	Y	Length2016	Length1993	LengthDiff	Zmin2016	Zmin1993	ZminDiff	Zmax2016	Zmax1993	ZmaxDiff
0	0	501345	548890	1768	1263	505	220	390	-170	805	805	0
1	0	503888	549910	682	1346	-664	419	442	-23	669	945	-276
2	0	500981	548607	1658	1357	301	261	367	-106	796	796	0
3	0	503283	549755	2540	2101	438	260	346	-86	786	786	0
4	0	499776	540850	3288	2495	793	208	255	-47	1012	937	75
5	0	499295	541288	3121	3149	-28	162	206	-44	934	951	-17
6	0	498603	538363	1459	693	766	261	305	-44	455	431	24
7	0	459279	591083	923	924	-1	50	50	0	160	160	0
8	0	459441	592774	1329	1109	221	39	39	0	200	186	14
9	0	459723	592567	403	403	0	40	40	0	120	120	0
10	0	458856	591814	668	668	0	60	60	0	180	180	0
11	0	458000	591068	1046	1046	0	69	69	0	228	228	0
12	0	485749	595143	766	766	0	253	253	0	364	364	0
13	0	485204	593486	741	761	-20	208	208	0	483	483	0
14	0	486022	591618	518	518	0	231	231	0	514	514	0
15	0	485819	591806	273	275	-2	254	254	0	417	417	0
16	0	486489	591134	475	475	0	243	243	0	425	425	0
17	0	486277	591343	603	603	0	203	203	0	554	554	0
18	0	479466	550093	2065	2066	0	252	252	0	735	735	0
19	0	486710	597478	864	312	553	186	341	-155	713	597	116
20	0	486548	597805	890	329	562	181	430	-249	702	679	23
21	0	486432	597875	439	450	-11	697	376	321	1029	702	327

FID	Id	X	Y	Length2016	Length1993	LengthDiff	Zmin2016	Zmin1993	ZminDiff	Zmax2016	Zmax1993	ZmaxDiff
22	0	490470	554020	467	547	-80	658	630	28	909	1001	-92
23	0	491749	552230	438	377	60	743	704	39	998	909	89
24	0	492142	551986	544	344	201	137	794	-657	439	998	-559
25	0	492703	548907	465	570	-105	156	147	9	441	493	-52
26	0	492986	548878	341	288	54	271	253	18	536	466	70
27	0	493241	548799	557	267	290	277	303	-26	527	520	7
28	0	493458	548740	302	339	-37	196	286	-90	482	499	-17
29	0	493601	548718	273	360	-87	241	286	-45	434	521	-87
30	0	493756	548647	290	350	-60	215	241	-26	354	487	-133
31	0	494161	548512	370	367	3	344	211	133	583	391	192
32	0	494859	548572	460	456	3	296	351	-55	532	614	-82
33	0	495267	548562	1616	711	905	230	307	-77	687	608	79
34	0	497096	548514	1205	658	547	223	225	-2	578	458	120
35	0	497332	548636	2267	499	1768	340	232	108	851	426	425
36	0	500771	552181	957	2177	-1220	319	318	1	664	820	-156
37	0	505336	550718	1447	532	914	324	448	-124	715	660	55
38	0	502212	549690	2516	1726	790	226	300	-74	913	778	135
39	0	499157	547357	561	1918	-1357	319	320	-1	554	825	-271
40	0	497554	545739	461	563	-102	304	360	-56	548	568	-20

FID	Id	X	Y	Length2016	Length1993	LengthDiff	Zmin2016	Zmin1993	ZminDiff	Zmax2016	Zmax1993	ZmaxDiff
41	0	496981	545132	567	419	148	339	262	77	660	409	251
42	0	497946	544753	331	398	-67	349	315	34	547	531	16
43	0	498867	544461	721	382	339	308	367	-59	711	559	152
44	0	499224	544355	391	439	-48	316	361	-45	517	628	-111
45	0	499543	544418	982	351	631	324	332	-8	511	534	-23
46	0	500093	544089	2451	639	1812	130	370	-240	521	746	-225
47	0	499903	544316	674	400	274	663	344	319	837	560	277
48	0	496631	542457	871	1537	-666	663	240	423	918	524	394
49	0	496252	542424	611	460	152	546	315	231	663	414	249
50	0	499321	542579	2431	569	1862	546	690	-144	988	824	164
51	0	499710	542491	1897	902	995	152	690	-538	546	931	-385
52	0	499104	542030	1762	675	1087	358	518	-160	683	690	-7
53	0	499751	542126	2435	1879	556	541	518	23	328	952	-624
54	0	498230	541110	1600	1972	-371	260	158	102	507	518	-11
55	0	479939	545208	4401	1878	2523	271	358	-87	600	694	-94
56	0	479922	546154	2891	2451	440	332	328	4	917	541	376
57	0	477738	553104	2246	1503	743	181	286	-105	809	500	309

FID	Id	X	Y	Length2016	Length1993	LengthDiff	Zmin2016	Zmin1993	ZminDiff	Zmax2016	Zmax1993	ZmaxDiff
58	0	476775	552670	222	4472	-4250	914	269	645	1072	612	460
59	0	499599	551600	306	2765	-2458	834	337	497	1047	878	169
60	0	496306	548966	257	2175	-1918	871	212	659	1041	849	192
61	0	490631	556572	497	222	275	697	914	-217	1016	1072	-56
62	0	490721	556468	194	306	-112	600	834	-234	697	1047	-350
63	0	490939	556403	407	257	150	743	871	-128	1062	1041	21
64	0	491067	556402	285	239	46	807	906	-99	1014	1073	-59
65	0	491169	556377	454	195	260	720	930	-210	1055	1058	-3
66	0	491270	556348	463	211	252	706	921	-215	1041	1077	-36
67	0	490724	553954	150	391	-242	856	740	116	988	961	27
68	0	491055	553288	233	232	1	808	856	-48	1009	1049	-40
69	0	491062	553194	899	407	492	158	743	-585	688	1062	-374
70	0	491137	553107	727	285	442	233	807	-574	730	1014	-284
71	0	491210	552981	923	454	469	151	720	-569	665	1055	-390
72	0	491368	552717	422	463	-41	312	706	-394	619	1041	-422
73	0	491467	552659	589	269	319	274	814	-540	773	1007	-234
74	0	491550	552602	622	218	403	289	850	-561	734	1005	-271

FID	Id	X	Y	Length2016	Length1993	LengthDiff	Zmin2016	Zmin1993	ZminDiff	Zmax2016	Zmax1993	ZmaxDiff
75	0	490866	553560	719	150	569	289	856	-567	779	988	-209
76	0	490895	553421	692	233	459	289	808	-519	719	1009	-290

Inclination2016= inclination in 2016, Inclination1993= inclination in 1993, InclinationDiff= Difference of inclination from 1993 to 2016, E2016= exist in 2016, E1993= exist in 1993

FID	Id	X	Y	Inclination2016	Inclination1993	InclinationDiff	E2016	E1993
0	0	501345	548890	18,31	18,19	0,12	1	1
1	0	503888	549910	20,13	20,49	-0,36	1	1
2	0	500981	548607	17,89	17,55	0,34	1	1
3	0	503283	549755	11,7	11,83	-0,13	1	1
4	0	499776	540850	13,74	15,29	-1,55	1	1
5	0	499295	541288	13,89	13,31	0,58	1	1
6	0	498603	538363	7,57	10,3	-2,73	1	1
7	0	459279	591083	6,8	6,79	0,01	1	1
8	0	459441	592774	6,91	7,55	-0,64	1	1
9	0	459723	592567	11,23	11,23	0	1	1
10	0	458856	591814	10,19	10,19	0	1	1
11	0	458000	591068	8,64	8,64	0	1	1
12	0	485749	595143	8,25	8,25	0	1	1
13	0	485204	593486	20,35	19,86	0,49	1	1
14	0	486022	591618	28,64	28,64	0	1	1
15	0	485819	591806	30,85	30,64	0,21	1	1
16	0	486489	591134	20,95	20,95	0	1	1
17	0	486277	591343	30,2	30,2	0	1	1
18	0	479466	550093	13,16	13,16	0	1	1
19	0	486710	597478	31,37	39,4	-8,03	1	1

FID	Id	X	Y	Inclination2016	Inclination1993	InclinationDiff	E2016	E1993
20	0	486548	597805	30,33	37,14	-6,81	1	1
21	0	486432	597875	37,12	35,91	1,21	1	1
22	0	490470	554020	28,27	34,14	-5,87	1	1
23	0	491749	552230	30,23	28,52	1,71	1	1
24	0	492142	551986	29,02	30,7	-1,68	1	1
25	0	492703	548907	31,48	31,25	0,23	1	1
26	0	492986	548878	37,82	36,53	1,29	1	1
27	0	493241	548799	24,16	39,1	-14,94	1	1
28	0	493458	548740	43,46	32,17	11,29	1	1
29	0	493601	548718	35,27	33,13	2,14	1	1
30	0	493756	548647	25,64	35,1	-9,46	1	1
31	0	494161	548512	32,88	26,16	6,72	1	1
32	0	494859	548572	27,17	29,95	-2,78	1	1
33	0	495267	548562	15,79	22,95	-7,16	1	1
34	0	497096	548514	16,42	19,5	-3,08	1	1
35	0	497332	548636	12,7	21,23	-8,53	1	1
36	0	500771	552181	19,83	12,98	6,85	1	1
37	0	505336	550718	15,12	21,71	-6,59	1	1
38	0	502212	549690	15,27	15,48	-0,21	1	1
39	0	499157	547357	22,73	14,75	7,98	1	1

FID	Id	X	Y	Inclination2016	Inclination1993	InclinationDiff	E2016	E1993
40	0	497554	545739	27,89	20,27	7,62	1	1
41	0	496981	545132	29,53	19,33	10,2	1	1
42	0	497946	544753	30,87	28,5	2,37	1	1
43	0	498867	544461	29,19	26,67	2,52	1	1
44	0	499224	544355	27,22	31,3	-4,08	1	1
45	0	499543	544418	10,78	29,94	-19,16	1	1
46	0	500093	544089	9,06	30,48	-21,42	1	1
47	0	499903	544316	14,47	28,36	-13,89	1	1
48	0	496631	542457	16,32	10,47	5,85	1	1
49	0	496252	542424	10,84	12,15	-1,31	1	1
50	0	499321	542579	10,31	13,25	-2,94	1	1
51	0	499710	542491	11,73	14,96	-3,23	1	1
52	0	499104	542030	10,45	14,3	-3,85	1	1
53	0	499751	542126	-5	13	-18	1	1
54	0	498230	541110	8,77	10,35	-1,58	1	1
55	0	479939	545208	4,28	10,14	-5,86	1	1
56	0	479922	546154	11,44	4,97	6,47	1	1

FID	Id	X	Y	Inclination2016	Inclination1993	InclinationDiff	E2016	E1993
57	0	477738	553104	15,62	8,1	7,52	1	1
58	0	476775	552670	35,46	4,39	31,07	1	1
59	0	499599	551600	34,8	11,07	23,73	1	1
60	0	496306	548966	33,49	16,33	17,16	1	1
61	0	490631	556572	32,68	35,46	-2,78	1	1
62	0	490721	556468	26,55	34,8	-8,25	1	1
63	0	490939	556403	38,08	33,49	4,59	1	1
64	0	491067	556402	35,96	34,9	1,06	1	1
65	0	491169	556377	36,41	33,31	3,1	1	1
66	0	491270	556348	35,88	36,43	-0,55	1	1
67	0	490724	553954	41,41	29,46	11,95	1	1
68	0	491055	553288	40,78	39,77	1,01	1	1
69	0	491062	553194	30,52	38,08	-7,56	1	1
70	0	491137	553107	34,36	35,96	-1,6	1	1
71	0	491210	552981	29,11	36,41	-7,3	1	1
72	0	491368	552717	36,03	35,88	0,15	1	1
73	0	491467	552659	40,3	35,62	4,68	1	1

FID	Id	X	Y	Inclination2016	Inclination1993	InclinationDiff	E2016	E1993
74	0	491550	552602	35,59	35,35	0,24	1	1
75	0	490866	553560	34,28	41,41	-7,13	1	1
76	0	490895	553421	31,84	40,78	-8,94	1	1

Wb2016= width in beginning of the Gully 2016, Wb1993= width in beginning of the Gully in 1993, WbDiff= difference of the width in beginning from 1993 to 2016, Wm2016= width in the middle of the Gully 2016, Wm1993= width in the middle of the Gully 1993, WmDiff= difference of the width in middle from 1993 to 2016, We2016= width in the end of the Gully in 2016, We1993= width in the end of the Gully 1993, WeDiff= difference of the width in end from 1993 to 2016

FID	Id	X	Y	Wb2016	Wb1993	WbDiff	Wm2016	Wm1993	WmDiff	We2016	We1993	WeDiff
0	0	501345	548890	2	2	0	25	20	5	5	4	1
1	0	503888	549910	3	3	0	21	24	-3	7	6	1
2	0	500981	548607	1	1	0	30	26	4	25	3	22
3	0	503283	549755	3	3	0	35	26	9	7	9	-2
4	0	499776	540850	3	2	1	15	17	-2	8	3	5
5	0	499295	541288	2	3	-1	15	5	10	10	5	5
6	0	498603	538363	3	4	-1	7	25	-18	7	4	3
7	0	459279	591083	3	3	0	20	13	7	18	3	15
8	0	459441	592774	1	1	0	10	10	0	10	2	8
9	0	459723	592567	4	1	3	6	6	0	6	1	5
10	0	458856	591814	1	1	0	7	8	-1	6	2	4
11	0	458000	591068	3	2	1	8	6	2	8	4	4
12	0	485749	595143	3	2	1	25	34	-9	14	2	12
13	0	485204	593486	1	2	-1	10	10	0	4	6	-2
14	0	486022	591618	3	3	0	13	4	9	6	3	3

FID	Id	X	Y	Wb2016	Wb1993	WbDiff	Wm2016	Wm1993	WmDiff	We2016	We1993	WeDiff
15	0	485819	591806	1	2	-1	3	8	-5	3	3	0
16	0	486489	591134	3	2	1	6	20	-14	6	3	3
17	0	486277	591343	3	2	1	3	11	-8	3	4	-1
18	0	479466	550093	2	3	-1	19	7	12	17	5	12
19	0	486710	597478	2	2	0	13	6	7	2	8	-6
20	0	486548	597805	2	1	1	5	5	0	3	7	-4
21	0	486432	597875	2	3	-1	24	7	17	24	2	22
22	0	490470	554020	1	1	0	9	10	-1	5	3	2
23	0	491749	552230	1	1	0	5	28	-23	5	6	-1
24	0	492142	551986	3	2	1	12	13	-1	3	4	-1
25	0	492703	548907	1	3	-2	9	6	3	2	1	1
26	0	492986	548878	1	4	-3	9	25	-16	6	1	5
27	0	493241	548799	3	3	0	9	10	-1	6	2	4
28	0	493458	548740	2	2	0	8	17	-9	6	7	-1
29	0	493601	548718	3	4	-1	6	11	-5	6	4	2
30	0	493756	548647	2	2	0	6	5	1	4	5	-1
31	0	494161	548512	1	5	-4	7	11	-4	6	2	4
32	0	494859	548572	3	1	2	7	18	-11	5	3	2
33	0	495267	548562	2	2	0	13	29	-16	10	10	0
34	0	497096	548514	2	2	0	8	28	-20	4	10	-6
35	0	497332	548636	3	1	2	24	5	19	25	3	22
36	0	500771	552181	3	5	-2	9	16	-7	6	16	-10

FID	Id	X	Y	Wb2016	Wb1993	WbDiff	Wm2016	Wm1993	WmDiff	We2016	We1993	WeDiff
37	0	505336	550718	2	4	-2	23	20	3	13	15	-2
38	0	502212	549690	3	3	0	19	27	-8	6	11	-5
39	0	499157	547357	3	4	-1	14	32	-18	14	9	5
40	0	497554	545739	1	3	-2	11	18	-7	3	7	-4
41	0	496981	545132	1	2	-1	9	16	-7	4	4	0
42	0	497946	544753	2	3	-1	10	26	-16	8	7	1
43	0	498867	544461	3	4	-1	19	19	0	7	7	0
44	0	499224	544355	3	4	-1	13	13	0	11	8	3
45	0	499543	544418	2	5	-3	20	13	7	23	9	14
46	0	500093	544089	2	4	-2	24	20	4	13	6	7
47	0	499903	544316	2	4	-2	26	27	-1	28	9	19
48	0	496631	542457	3	3	0	12	26	-14	14	7	7
49	0	496252	542424	23	3	20	25	29	-4	24	18	6
50	0	499321	542579	2	3	-1	12	13	-1	14	23	-9
51	0	499710	542491	26	3	23	26	30	-4	17	30	-13
52	0	499104	542030	2	24	-22	20	26	-6	14	13	1
53	0	499751	542126	3	3	0	24	21	3	17	26	-9

FID	Id	X	Y	Wb2016	Wb1993	WbDiff	Wm2016	Wm1993	WmDiff	We2016	We1993	WeDiff
54	0	498230	541110	8	21	-13	38	24	14	18	16	2
55	0	479939	545208	7	1	6	36	17	19	8	3	5
56	0	479922	546154	7	1	6	20	14	6	19	8	11
57	0	477738	553104	4	3	1	22	29	-7	13	23	-10
58	0	476775	552670	6	3	3	14	25	-11	13	7	6
59	0	499599	551600	3	3	0	11	16	-5	10	10	0
60	0	496306	548966	5	2	3	9	14	-5	9	7	2
61	0	490631	556572	3	1	2	10	7	3	10	3	7
62	0	490721	556468	5	1	4	11	5	6	9	3	6
63	0	490939	556403	2	2	0	20	6	14	16	2	14
64	0	491067	556402	2	2	0	5	7	-2	4	6	-2
65	0	491169	556377	2	2	0	8	8	0	8	8	0
66	0	491270	556348	3	1	2	8	10	-2	7	10	-3
67	0	490724	553954	4	1	3	7	2	5	7	3	4
68	0	491055	553288	6	1	5	20	2	18	15	2	13
69	0	491062	553194	3	1	2	18	3	15	11	2	9
70	0	491137	553107	30	1	29	20	2	18	7	2	5

FID	Id	X	Y	Wb2016	Wb1993	WbDiff	Wm2016	Wm1993	WmDiff	We2016	We1993	WeDiff
71	0	491210	552981	40	1	39	31	3	28	9	2	7
72	0	491368	552717	6	1	5	20	3	17	16	2	14
73	0	491467	552659	3	1	2	9	6	3	7	6	1
74	0	491550	552602	4	1	3	14	4	10	6	4	2
75	0	490866	553560	8	1	7	9	2	7	6	2	4
76	0	490895	553421	4	1	3	10	3	7	10	3	7

Appendix B

```
setwd("C:/Users/Isa/Documents/Master_Geo/Masterarbeit")
erosion <- read.csv2("GullyforR.csv")

set.seed(5)     #setting random numbers to receive results that are not random and to receive always the same result

clusterdata <- erosion[,c(5,13,19,22,25)+2]  #selection of the relevant columns
head(clusterdata)

clusterdata <- clusterdata[!is.na(clusterdata[,2]),]  #deletes rows with NA values in the inclination coulmn
clusterdata_scale <- scale(clusterdata)

clusterres <- kmeans(x=clusterdata_scale, centers=3, iter.max = 100, nstart = 10)          #cluster analysis
clusterres$cluster[clusterres$cluster==2] <- 4
clusterres$cluster[clusterres$cluster==3] <- 2
clusterres$cluster[clusterres$cluster==4] <- 3

pairs(clusterdata,col=clusterres$cluster+1)  #merging of the clusterdata pairwise, clusters should marked with colours

#### comparing the results of the clusters ####

for(i in 1:10){
assign(paste0("c",i),kmeans(x=clusterdata_scale, centers=3, iter.max = 100, nstart = 1))}

#generating 10 cluster subdivisions

c1$tot.withinss
c2$tot.withinss
c3$tot.withinss
c4$tot.withinss
c5$tot.withinss
c6$tot.withinss
c7$tot.withinss
c8$tot.withinss
c9$tot.withinss
c10$tot.withinss
```

```
#### creating a map with the cluster distribution (red=cluster1, green=cluster2, blue=cluster3)
par(mar=c(4,4,2,1))
plot(erosion[,3],erosion[,4],col=clusterres$cluster+1,xlab="East",xaxt="n",yaxt="n",ylab="North",main="Gullies by corresponding clusters")


#### mean ####

means <- matrix(NA,nrow=5,ncol=3) #creates a blank matrix for the results from the loop
rownames(means) <- names(clusterdata)    #determining the column and row names
colnames(means) <- paste("Cluster",1:3)

#### loop for calculating the mean, for each variable and for each cluster to see the results better####

for(i in 1:5){
        means[i,] <- tapply(clusterdata[,i],clusterres$cluster,mean)
}
means <- round(means,1)      #rounds the result to one decimal place
means #showing table means


#### variance ####

vars <- matrix(NA,nrow=5,ncol=3)     #creates a blank matrix for the results from the loop
rownames(vars) <- names(clusterdata)       #determining the column and row names
colnames(vars) <- paste("Cluster",1:3)

#### loop for calculating the variance, for each variable and for each cluster to see the results better ####

for(i in 1:5){
        vars[i,] <- tapply(clusterdata[,i],clusterres$cluster,var)
}
vars <- round(vars,1)  #rounds the result to one decimal place
vars     #showing table vars


layout(matrix(c(1,1,1,2,2,2,3,3,4,4,5,5),nrow=2,byrow=T))  # selects distribution of plots within plot window
par(mar=c(4,4,2,1))                                        # cuts boarder between plot andmargin
```

```
for(i in 1:5){               # runs over all variables
        plot(0,0,type="n",xlim=range(clusterdata[,i])*c(1,1.2)-
c(3,0),ylim=c(0.5,3.5),main=rownames(means)[i],
                xlab=rownames(means)[i],ylab="Cluster")            # produces empty plot
        for(j in 1:3){               # runs over all cluster
                lines(x=c(means[i,j]-1.95*sqrt(vars[i,j]),means[i,j]+1.95*sqrt(vars[i,j])),y=c(j,j),
                        col=j+1,lwd=2)                          # lines for confidence interval
                lines(x=rep(means[i,j]-1.95*sqrt(vars[i,j]),2),y=j+c(-1,1)*0.06,col=j+1,lwd=2)       #
line for lower end CI
                lines(x=rep(means[i,j]+1.95*sqrt(vars[i,j]),2),y=j+c(-1,1)*0.06,col=j+1,lwd=2)       #
line for upper end CI
                lines(x=rep(means[i,j]                    ,2),y=j+c(-1,1)*0.10,col=j+1,lwd=2)# line for
mean

        points(x=clusterdata[clusterres$cluster==j,i],y=rep(j,times=sum(clusterres$cluster==j)),
                        col=j+1)                             # adds points to the plot
}}
```

histograms, mean and creating table for the figure about the location of the clusters in the Skagafjörður

```
summary(clusterdata)

hist(clusterdata$LengthDiff, xlab = "length difference", ylab = "number of gullies", main =
"Histogram of length difference")

hist(clusterdata$Inclination1993, xlab = "inclination 1993 in degree", ylab = "number of gullies",
main = "Histogram of inclination 1993")

hist(clusterdata$WbDiff, xlab = "difference of the width at the beginning", ylab = "number of
gullies", main = "Histogram of difference of the width at the beginning of the gullies")

hist(clusterdata$WmDiff, xlab = "difference of the width at the middle", ylab = "number of
gullies", main = "Histogram of difference of the width at the middle of the gullies")

hist(clusterdata$WeDiff, xlab = "difference of the width at the end", ylab = "number of gullies",
main = "Histogram of difference of the width at the end of the gullies")

write.table(x=cbind(erosion[1:77,],
clusterres$cluster),file="clusterdatagis.csv",row.names=F,dec=",",sep=";")
```

Curriculum Vitae

Personal data

Name	**Isabelle Reiter**
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Adress	Mühlhofstraße 4/5/68
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	eMail: isabelle.reiter@univie.ac.at
Date of birth/ place	29.11.1990 in Krems an der Donau
Citicenship	Austria

Education

10/2015 – 2018	**Master Geography** (University of Vienna) title of the master thesis: „Gully erosion in the Skagafjörður (North Iceland) in the period 1993 – 2016"
10/2011 – 04/2015	**Bachelor Geography** (University of Vienna) title of the bachelor thesis: „Geomorphologische Veränderungen in einem deregulierten Flussabschnitt der Donau in Hainburg nach dem Hochwasserereignis 2013. Eine Erhebung mittels Kartierung im Gelände und GIS-Analysen."
09/2010 – 06/2011	**MTF-Schule** in St. Pölten (Medizinisch Technische Fachschule)
09/2009 – 06/2010	**general qualification for university entrance** on the Erzbischöfliches Realgymnasium in Hollabrunn
09/2005 – 06/2009	**Landwirtschaftliche Fachschule** Tullnerbach/Edelhof

Internships

08-09/2016 and 07/2015	**via Donau** in Vienna GIS department of Hydrography and Hydrology handling databases (INSPIRE), collaboration on the EU-Project PROMINENT, GIS analysis, field crew reference: DI Johannes Hubmann (+43 5043212435)
07/2013	**Joanneum Research** on the Institute for Geophysics and Geothermal energy in Leoben Groundwater exploration, archaeological investigations, block glacier investigations
07/2012	**Österreichische Post AG** in Krems an der Donau delivery service
07/2007 – 06/2008	**Islandpferdehof Gut Pöllndorf** in Weistrach, NÖ riding lessons

Jobs

03/2017 – 08/2017	**Tutor** for „Field methods in the physical geography“
03/2016 – 07/2016	**Tutor** for „Geomorphology“
03/2015 – 07/2015	**Tutor** for „Geomorphology”

Language skills

German	native speaker
English	good knowledge

Computer Skills

Excellent knowledge	ArcGIS, QGIS, Word, Excel, Powerpoint
Basic knowledge	R, SQL, Python, Agisoft, JabPlot, OPALS, RiSCAN

Interests and hobbies

Horse riding, running, hiking, climbing, geocaching