# *The disappearing past:*
# Coastal archaeology, shoreline erosion and contributing factors along the coast of Skagafjörður, Northern Iceland

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Title photo: A drone photo of the archaeological remains at Naustavík on the Hegranes peninsula, Northern Iceland. Photo: Guðný Zoëga.

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## Abstract

Coastal erosion is affecting archaeological sites in many parts of Iceland. In the region of Skagafjörður, Northern Iceland, a recent survey of coastal archaeology revealed that erosion is occurring along extensive parts of the coastline and many archaeological sites have already been affected by erosion. The aim of this study is to explore the extent and shoreline change rates along the eastern coast of Skagafjörður and to assess which factors affect shoreline changes. The results will be used to evaluate the risks posed by coastal erosion to multiple archaeological sites located within the study area. The shoreline was mapped from aerial photographs dating from between 1999 and 2017 and shoreline change rates were calculated for the same time-period. A linear regression analysis was used to assess the degree of relationship between shoreline change and several ecological and environmental variables. The selected variables, *geology*, *aspect*, *vegetation*, *elevation*, *slope* and the *presence of beach*, where based on existing theory. Data for the variables were derived from a digital elevation model and GIS analysis but also gathered through field work at three study sites, each covering a 3 km long stretch of shoreline. The results showed that erosion was widespread in the study area and that the extent of erosion and erosion rates are likely controlled by a combination of factors. For the surveyed coastline, 24% was found to be either stable or showing accretion, while 76% showed signs of erosion. The mean rate of shoreline change for study area was -0.11 m/a. A significant relationship was found between shoreline change and *geology* and *coastal aspect*. A significant relationship was, however, not found between shoreline change and the *presence of beach*, *slope* or *coastal elevation*. Based on the erosion rates demonstrated by the study, it seems highly probable that even more archaeological sites will be affected by erosion in the near future. The results presented in this study, can help in choosing which areas are most likely to be subjected to coastal erosion in the future. This would help prioritize which coastal heritage sites are most in need of further research, conservation or protection.

Keywords: GIS, Coastal Erosion, Rocky Coastlines, Coastal Archaeology, Linear regression

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# 1. Introduction

Coastal erosion is a global problem, and the number of coastal areas facing problems of land loss due to erosion is growing (Adamo et al., 2014; Özyurt & Ergin, 2009). It has been estimated that at least 70% of sandy beaches around the world are in recession (Bird, 1985). Coastline changes brought about by erosion or deposition are natural processes that occur over a range of time scales (Armah, 2011). The effects of these processes become a problem when they start threatening social and economic activities like human occupations, agricultural or forested land and constructions (e.g., buildings and roads) as well as significant cultural or historical sites (Bird, 2016; Hampton et al., 2004). Rates of coastal erosion are expected to rise globally due to climate change factors such as sea level rise and increased storminess (Zhang et al., 2004) further enhancing the problems resulting from erosion.

The mechanisms that affect the evolution of coasts, including coastal erosion, take place within the coastal zone. Coastal zones (or coastal areas) are highly dynamic and complex multifunctional systems that are subject to influences from both coastal and marine ecosystems (Sunamura, 1992; Trenhaile, 1987, Ramieri et al., 2011; Siry, 2007). They are historically important as centres of economic activity and settlement (Denner et al., 2015) and Masselink (2017, pp. 584) goes as far as arguing that coastal environments are "…the most important and intensely used of all areas settled by humans." Coastal zones are exposed to a range of coastal hazards, both of manmade and natural origin, e.g. intensive development, pollution, climate change and coastal erosion (Neumann et. al, 2015).

Arctic coasts are likely to become one of the environments most impacted by coastal erosion and the arctic coastline is rapidly changing (Lantuit et al., 2012; Frederick et al. 2016;). There has, for example, been a doubling in arctic coastal erosion rates in the United States since the middle of the 20$^{th}$ century and the trend seems to be accelerating (Mars & Houseknecht, 2007). Iceland lies in the subarctic just outside the southern fringe of the Arctic circle, making it an important area to study coastal erosion.

Throughout history, humans have settled in coastal areas because of the abundance of natural resources (Fitton et al., 2016). This has also been the case in Iceland where fishing has undoubtedly been practiced since settlement times (late 9th to early 10$^{th}$ century) (Arnórsdóttir, 2008). Coastal archaeological sites contain invaluable information on, for example, the history of coastal settlements and fisheries and Erlandson (2012) argues that the consequences of global warming will most likely increase the destruction of these sites. Despite this potential threat, destruction of cultural heritage on the coastline has only been addressed to a limited degree (Erlandson, 2008).

It has become evident, in recent years, that coastal erosion is affecting archaeological sites in several parts of Iceland. Three large rescue excavations on important coastal archaeological sites, that have been damaged by erosion, have been undertaken in recent years with the intention of salvaging information on the sites before they disappear completely (Lárusdóttir et al., 2012; Pálsdóttir, 2015; Traustadóttir and Svensson, 2012). Coastal archaeological survey projects have been undertaken in the Skagafjörður region in Northern Iceland, the Snæfellsnes peninsula in Western Iceland and Dýrafjörður fjord located in the Westfjords. The survey results show that archaeological sites have already been or are likely to be affected, in the near future, by coastal erosion (Edvardsson, 2017a, 2017b; Zoëga, 2012-2016).

Limited research exists on coastal erosion in Iceland. The few research projects that have been undertaken in recent years, have been preliminary coastal vulnerability assessments for the Westfjords, the town of Ísafjörður and the island of Viðey (Davies, 2012; Vilhelmsson, 2013; Meidinger, 2011).

A coastal survey of archaeology in the region of Skagafjörður, previously undertaken by the author of this study, revealed that erosion is detectable along extensive parts of the region's coastline (Zoëga, 2017). Numerous archaeological sites, located at different coastal types (cliffs (high/low) bluffs, loose sediments), have already been affected by erosion. Skagafjörður fjord is one of the largest fjords in Iceland and has relatively varied coastal landscapes. It is one of few areas in Iceland that has specifically been surveyed for coastal archaeology, and these factors combined, make the area well suited for this study.

The focus of coastal erosion studies has, primarily been on sandy and dune backed beaches but there has recently been a growing interest in studies on rocky coasts according to Naylor et al. (2010), who also emphasize that further work is still needed. Dornbusch (2005) argues that while cliff retreat on a large scale is generally linked to the lithology of the rock, the variability on smaller scales is likely to be influenced by other factors.

Coastal erosion is a current threat to coastal archaeology and is expected to be exacerbated by rising sea levels and increased storminess among other climatic changes. More knowledge and information on coastal susceptibility to erosion is, therefore, needed. Better understanding of the factors relating to the coasts susceptibility to erosion may be of use in the planning of coastal areas in general. The information could also be important with regard to management of coastal archaeological sites or for the identification of vulnerable sites.

The first objective of this project is to explore the extent of shoreline erosion and shoreline changes, along the predominantly rocky coast of Skagafjörður. The second objective is to identify and assess the relationship between shoreline change and a number of -relatively easily attainable - ecological and environmental variables, as well as to estimate their contribution to coastal change along the fjord's coastline. The third objective is to use the information to assess future risks from coastal erosion at archaeological sites located at the chosen study sites.

The aims of the study will be met by answering the following research questions:

1. What is the extent of shoreline erosion along the coast of Skagafjörður?
2. What are the rates for shoreline change in Skagafjörður?
3. To what degree does a relationship between shoreline change and the ecological and environmental variables slope, elevation, aspect, geology, vegetation and the presence of beach exist, along the coast of Skagafjörður?
4. Which archaeological sites are most likely to be at risk due to coastal erosion?

The thesis is organized as follows. The theoretical framework of the study is reviewed in chapter two. Chapter three presents the study area, the data and methods used in the study. Results are presented in chapter four followed by discussions in chapter five. Chapter six features the conclusions.

# 2. Theoretical framework

## 2. 1. The coastal zone

There is no uniform definition of what constitutes a coastal zone, but it is generally referred to as the broader transitional region between the terrestrial and the marine environment (Fig. 1) (Neumann et al., 2015). A coast (also called a shore) is defined as the broad area of land that borders the sea (Encyclopædia Britannica, 2019). A shoreline (also coastline or seaboard) can be defined as the line where a body of water and the shore meet (common term), and as the line that forms the boundary between the coast and the shore, e.g. the foot of a cliff or dune (technical term) (Mangor et al., 2017. The processes that affect the evolution of a coastline take place in the foreshore and the nearshore zones and will be further explained in the subsequent sub-chapters.

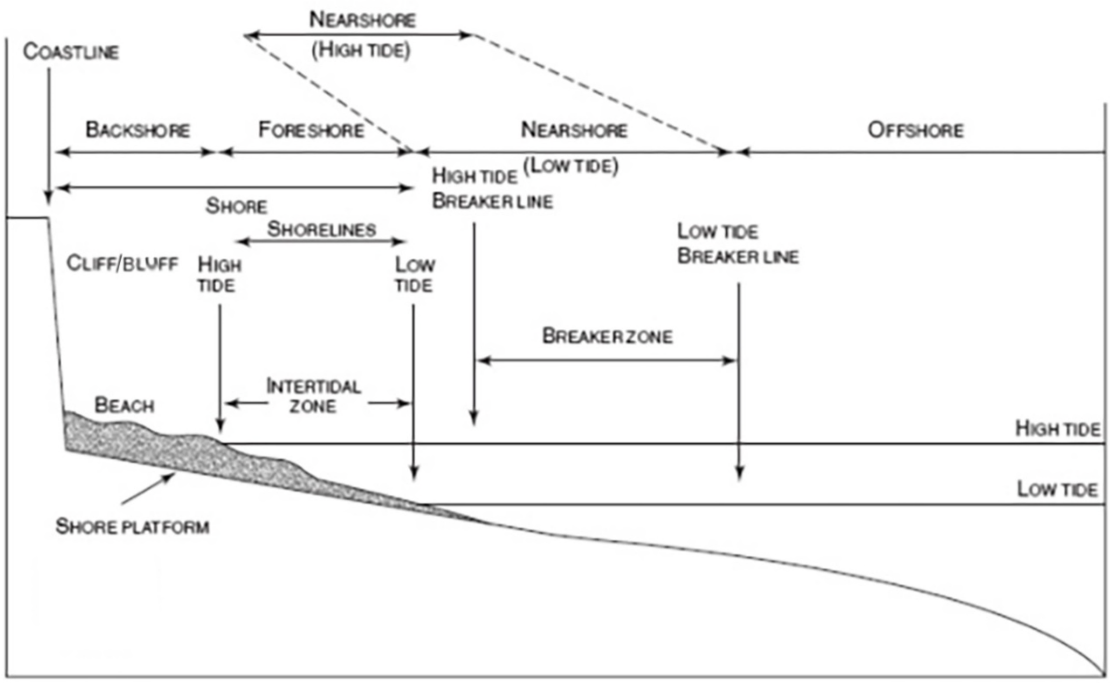


*Fig. 1. Spatial boundaries of the coastal zone. Adapted from: Bird, 2000.*

## 2.2 Coastal changes

Over the past 6000 years most coastlines have shown change to some degree, either in the form of an advance or a retreat. A coastline retreats where erosion exceeds deposition, when there is a rise in sea-level or when there is submergence due to land subsidence. It advances where sediment deposition exceeds the rate of erosion, either with a fall in sea-levels or where there is emergence due to uplift of land (Bird, 2000). Some coastlines have changed very little, and others alternate between advance and retreat. Coasts in recession exceed those that are advancing, and it is estimated that about 70% of sandy beaches in the world are in recession and only about 10% are advancing (Bird, 1985). Coastal erosion can be defined as the removal of material from the coast, either offshore or along the coastline, resulting in a net loss of sediment or rock (Davis jr. and Fitzgerald, 2004). The process can be divided into acute and chronic erosion. Acute erosion takes place at the foot of a cliff or a dune, mainly during strong winds, high tides and high waves or under storm surge conditions. Chronic erosion occurs when drift export is greater than the supply of material which results in decrease in beach or shoreface (Mangor et al., 2017).

### 2.2.1 Coastal landforms

Current coastal landforms have mostly been shaped in the past 6000 years when sea level remained close to its present level (Bird, 2000). Coastal landforms are the result of a combination of subaerial, biological and marine processes that influence the sediments and rock present in the coastal zone (Kennedy et al., 2014). These processes will be further explained in the subsequent chapters. The present-day coastal landforms are, therefore, dependent on the balance between the erosional processes and the resisting forces of the bedrock (Kennedy et al., 2014). Coasts are highly diverse in their morphology and sedimentary compositions which can largely be explained by geology and sedimentation as well as changes in sea-level (Anthony, 2014; Switzer, 2014). Coastal landforms can, at the most basic level, be divided into clastic (mud, sand, gravel) or rocky coasts. The former type of landforms is depositional while the latter are erosional. Erosion and deposition are the two factors that cause changes in coastal morphology (Masselink, 2017).

A recent study by Young and Carilli (2018) suggests that coastal cliffs occur along 52% of the world's coastlines. The term, coastal cliff, refers to steeply sloping surfaces where elevated land meets the coastline of both oceans and lakes (commonly called lake bluffs). The terms cliffs and bluffs are often used interchangeably but the term bluff can also refer to escarpments eroded into unlithified material, such as glacial till (Hampton et al, 2004). Rocky coasts are termed erosional since they are constantly being cut back by the sea with the consequence of permanent retreat which is an irreversible process (Masselink, 2017, Sunamura, 1992). They have traditionally been thought to have slow rates of erosion and therefore be relatively resilient to climate change. But recent studies have shown that rocks can also erode fairly quickly (Naylor et al., 2010). Depositional coastal environments, on the other hand, undergo a reversible change, that can entail both accretion or erosion (Sunamura, 1992) and they can change dramatically in a short time, for instance during storms (Davis jr. and

Fitzgerald, 2004). Depositional coastal environments, particularly those unaffected by humans, have, up to a certain point, the capacity (resilience) to counteract sea-level rise with ecological buffers such as coral reefs, salt marshes as well as morphological protection such as sand and gravel beaches and barriers (Masselink, 2017). Table 1 lists some of the most common erosional coastal landforms.

*Table 1. An overview of erosional coastal landforms. This is not an exhaustive enumeration of all coastal landforms but rather an example of some of the most common ones (adapted from Masselink, 2017 and Bird, 2000).*

| **Erosional** |
|---|
| |
| **Erosive coasts (rocky coasts)** |
| Sloping shore platform (erosional features: notch, arch, stack, cave, headlands, bays) |
| Sub-horizontal shore platform (erosional features: notch, arch, stack, cave, headlands, bays) |
| Plunging cliff/bluff |

### 2.2.2 Hydro- and aerodynamic processes

*Winds* (aerodynamic), *waves*, *tides* and *currents* (hydrodynamic) are processes that are at work in coastal waters and together they provide the energy that shapes and alters a coastline by transporting, eroding and depositing sediments (Bird, 2000). Waves are the most dominant of these processes and together with tides they provide the energy for essentially all changes in coastal geomorphology (Masselink, 2017; Conley, 2014). Waves, tides and currents interact, either by augmenting or diminishing the effect they have on one another (Bird, 2000). Waves can be described as undulations on a water surface produced by wind action and the size of a wave is controlled by wind strength (Bird, 2000; Masselink, 2017). In addition to wind strength, wave dimension is also determined by wind speed, wind duration and fetch (the distance travelled by wind or waves across open water) (Sunamura, 1992). *Currents* are generated in various ways and some of them are of multiple origin. They have the capacity to transport sediments (sand or even gravel) that are already in movement, either from the beach into sea or deposited, by the sea, at the beach (Bird, 2008). Nearshore currents and sediment transport in the surf zone (also called breaking zone, Fig. 1) are generated by energy released during wave breaking. The intensity of these currents increases with increasing wave energy level and therefore the strongest currents are encountered during storms (Masselink, 2017). Other significant processes (coastal hazards) that can alter coastal morphology are *storm surges* and *tsunamis* which, together with tides, are represented by changes in water level and are meaningful controlling factors affecting both the magnitude and position of the incoming waves (Bird, 2000; Sunamura, 1992).

### 2.2.3 Erosional processes

Masselink (2017) groups the erosional processes affecting rocky coasts into three main types, based on their function in controlling rocky coast morphology:

- mass movements,
- rock-breakdown processes,
- marine rock-removal.

Mass movements depend on the lithology and structure of the rock and include landslides, rockfalls and flows. They are episodic in nature and commonly happen during the winter months due to increase in rainfall and undercutting of the cliff base.

Rock-breakdown processes are characterised by physical, chemical and biological processes that weaken and loosen the rock material. They are principally controlled by wave energy levels, climate and rock type. Mechanical wave action (abrasion and hydraulic) is the most common erosional agent in swell and storm-wave environments. Physical (frost, wetting/drying, salt crystals) and chemical (most significant in hot, wet climates) weathering is possibly the most common erosive agent in sheltered areas and on especially susceptible rocks. Bio-erosion relates to the removal of rock by organisms and is most common in tropical regions.

Rock material is produced by mass movements and weathering and is moved around marine processes (transportation). The efficiency of the sediment transport depends on the size of the waves (Masselink, 2017).

Bird (2000) also lists runoff after heavy rain or melting of snow. Fig. 2 depicts some of the forces that drive rocky cliff erosion.

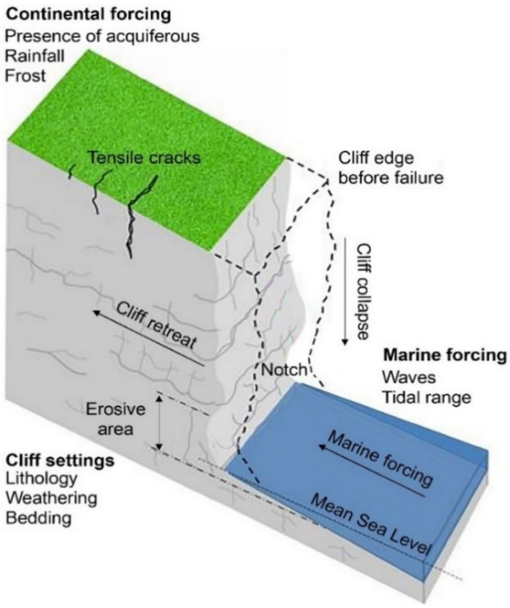


*Fig. 2. A Schematic profile of a cliff shore and rocky cliff erosion drivers where influential factors are grouped into three main classes (marked in bold) as reported by Prémaillon et al. (2018). Adapted from Gong et al. (2018).*

### 2.2.4 Rates of coastal erosion

Rates of recession on rocky coastlines varies with elevation, rock resistance, geological structure and incident wave energy (Bird, 1985). A recent study by Prémaillon et al. (2018) concluded that lithology most clearly governs cliff retreat while marine and climate forcing, apart from the effect on frost on weak rocks, exhibit a weak relationship with cliff recession rates. Erosion rates are lower if the type of rock is resistant and higher if the rock type is less resistant. Rock lithology can vary from very hard formations such as granites or metamorphic rocks to softer types such as chalk, shale or clay (Bird, 2016). Internal weaknesses like joints and faults, presence of groundwater as well as the degree of weathering, also affect the resistance of the material to wave action and slope failure (Griggs and Patsch, 2004; Prémaillon et al., 2018). Cliff retreat is also related to the slope of a cliff or a bluff, since steeper slopes are, in general, more likely to fail, than less steep slopes (Hapke and Plant, 2010). Coastal aspect affects wave energy which is stronger on exposed sectors than on sheltered coasts. Moreover, shorelines facing the open sea or prevalent wind directions are likely to be more susceptible to erosion (Bird, 2016). The presence of beaches, in front of cliffs are known to protect against wave driven erosion (Lee, 2008). However, a recent study by Young (2017), suggests that the presence of a beach is not sufficient where cliffs are weak and sand supply is sufficient. Everts (1991) examined the relationship between beach width and rates of cliff erosion, in California, and found out that erosion rate decreases as a beach becomes wider. His results showed that a marked decrease happened when beach width exceeded 20 m and ceased altogether at a beach width of 60 m. Another study by Dornbusch et. al (2008) showed that, on the East Sussex coast of England, a beach width of over 70 m was needed to prevent storm waves from reaching the cliff.

The density and type of vegetation cover can aid in reducing erosion by dissipating wave energy reaching sheltered shores, binding the soil in the littoral zone or by encouraging the accumulation of organic and inorganic sediment. However, the roots of trees and grasses are generally too shallow to reduce erosion from large storm waves (Morton, 2003).

Rate of erosion and coastline retreat are often used synonymously, the former is correctly expressed in volume/length/time ($m^3$/m/year) but the latter in m/year (Mangor et al., 2017). Although, cliff recession is usually expressed as an average in meters per year, the actual retreat tends to be is episodic, both spatially and temporally (Bird, 2016; Hapke, 2004, Masselink, 2017). A recent study by Prémaillon et al. (2018), that calculated recession rates on a global scale, reported that average rates of cliff recession can range from less than 10 cm $yr^{-1}$ (on hard rocks) up to 85 cm $yr^{-1}$ (on weak rocks). The median erosion rates for hard rocks are 2.9 cm $yr^{-1}$, 10 cm $yr^{-1}$ for medium rocks and 23 cm $yr^{-1}$ for weak rocks. Sunamura (1992), calculated the recession rates for granite (<0.001 m $yr^{-1}$), shale (<0.001-0.1 m $yr^{-1}$) and glacially deposited materials (1-10 m $yr^{-1}$), which clearly shows the difference in rates based upon the hardness of the rock. A third study, by Lim et al. (2010) on high (34-90m), hard rock coasts (mudstone and shale) in northern England, reported recession rates of 0.065 m/$a^{-1}$ for their study area as a whole with, variations from 0.009-0.128 m/$a^{-1}$ for the five different sites (different types of rock) inspected in the study.

### 2.2.5 Coastal erosion and climate change

The rate of coastal erosion is expected to rise in this century, due to climate change (Zhang et al., 2004; Ramieri et al., 2011). It is also expected that the main impacts of climate change in the coastal zones will be associated with sea level rise and other meteorological changes (Ramieri et al., 2011). The IPCC (Wong et al., 2014) estimate that the future rates of global mean sea level will exceed 2.0 mm $yr^{-1}$ in the $21^{st}$ century, although with regional and local variations. Increased water depths reduce wave attenuation rates which leads to greater expenditure of wave energy at the cliff foot (Naylor et. al., 2010). Climatic changes include potential changes in storm frequency both in terms of event magnitudes and recurrence intervals (Lim et al., 2010). In the Arctic regions, other challenges due to climate change are flood levels, wind erosion, tree re-growth and decreasing permafrost (Blankholm, 2009). In Iceland, climatic factors like increase in sea-level are expected to be about 30-40% of mean global sea-level rise and storm surges are generally expected to become more frequent (Björnsson et al., 2018).

## 2.3 Mapping coastal change

### 2.3.1 Geographical Information Systems

Geographical Information System (from now on termed GIS) is a widely used system across a diverse user community and has become a fundamental part of geographical research (Fig. 3) (Johnson, 2005; Couclelis, 2005). The term GIS, according to Longley et al. (2011) fundamentally refers to the use of digital data to represent space and time. Heywood et al. (2011) add that data is the core of any GIS. Tomlinson (2007, pp. 1) argues that the term GIS tends to withstand any simplistic definition due to its "wide-ranging applications across the industrial and intellectual landscape". Holden (2017, pp. 745) defines GIS as: "A system of hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modelling and display of spatially referenced geographical data for solving complex planning and management problems.". This is not a complete definition according to Walford (2016) who states that any definition of GIS needs to include people. According to Unwin (1994) it is spatial data manipulation and the ability to manage spatial data spatially that differentiates GIS from any other database management system.

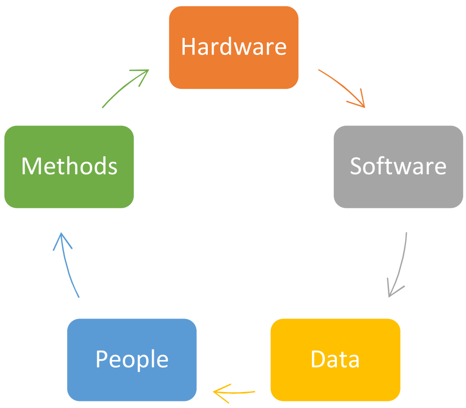


*Fig. 3. The components of a GIS.*

The term Environmental GIS refers to the use of GIS in environmental sciences and management and GIS can be used as a tool for managing as well as researching environmental change (Gillespie, 2016). Longley et al. (2011, pp. 66) state that it was "the environment", or the need for policies and environmental control, that drove some of the development and earliest applications of GIS in the mid 1960's. GIS and other geographic information technologies such as, remote sensing and the Global Positioning System (GPS) have for some time been widely used in all areas of environmental science (Longley et al., 2011). The focus of Environmental GIS is on the collection, analysis and visualization of environmental data and Gillespie (2016) states that the strength of GIS is that you can formulate and test theories. This can be done over different temporal (past, present and future) and spatial scales (local, regional and global) resulting in real world products that can be of use to scientists, decision makers and the general public.

GIS is commonly used in coastal research as well as a tool for coastal planning, coastal management and coastal monitoring (e.g. Bartlett and Smith, 2005). GIS has been used to detect, measure and predict coastal changes (e.g. Irrgang et al., 2018, Ford, 2013, Smith and Cromley, 2012 and Alberico, et al., 2012) as well as to define the causes and effects of coastal erosion (e.g. Senevirathna, 2017 and Armah, 2011). GIS is also commonly used in coastal vulnerability assessments (CVI) (e.g: Thieler and Hammer-Klose, 1999; Diez et al., 2007 and Palmer et al., 2011) and to assess risks and vulnerability and management of archaeological sites (e.g. Solsten and Aitken, 2006; Daire et al., 2012; Dawson, 2010). It can also be used for modelling and visualization (e.g. Brown et al., 2005, Addo et al., 2008, Panzeri et al., 2012; Fitton et al., 2016).

### 2.3.2 Shoreline mapping

Coastal zones are dynamic in nature and changes within them occur over many time scales. Quantification of shoreline retreat becomes important, for many reasons, when it happens on a human time scale (Moore, 2000). Information on past, present and predicted future shoreline positions is of fundamental importance to diverse actors such as coastal scientists, coastal engineers and coastal managers. Shoreline mapping has improved with advances in computer technology such as image capture, processing and analysis (Moore, 2000; Boak and Turner, 2005). This includes digital imagery and the use of GIS. Likewise, cliff mapping has improved with airborne LiDAR surveys that provide unprecedented detail of both volumetric and cliff changes (Young, 2017; Earlie et al., 2015).

A variety of possible data sources are available for shoreline detection. The choice of data is generally dependent on availability (Boak and Turner, 2005). When available, aerial photographs are the most widely used data source in shoreline mapping and monitoring (Moore, 2000; Addo et al. 2011; Boak & Turner, 2005). Other common data sources are coastal maps, historical maps, field surveys, remote sensing, Multispectral/Hyperspectral Imaging, Airborne Light Detection and Ranging Technology (LIDAR), Microwave Sensors and Video Imaging (Boak and Turner, 2005, Moore, 2000; Hapke, 2004). Earlie et al. (2015) point out that, in regard, to cliff erosion, aerial photographs do not wholly capture the detail in processes and failures occurring across the cliff face.

Moore (2000) has compiled a list of recommendations for successful shoreline mapping (adapted version). Each point will be discussed in more detail, below:

1. Select a mapping technique most suitable for the project.
2. Use the highest quality vertical aerial photographs available.
3. Use photographs of the largest scale possible and avoid using a scale smaller than 1:20.000.
4. When possible, use the top edge of a bluff, cliff, or dune as a proxy for shoreline position.
5. Perform an overall error assessment and quantify total error.

Several factors need to be considered before choosing a **mapping method**. These include: the accuracy required, the characteristics of data inputs, the necessary output and monetary and time constraints (Moore, 2000).

**Scale and resolution** have for a long time been core issues in geography (Lam & Quattrochi, 1992). The concept of scale is central to geography and spatial phenomena is often dealt with on various scales (e.g., from local to international) (Lam & Quattrochi, 1992). The concept of scale can be problematic since it has at least three meanings in science. The first meaning is the representative fraction, or the ratio between distance on the map and the corresponding distance on the ground. Second, is the extent of a study area and the third is the resolution. (Goodchild, 2011; Lam & Quattrochi, 1992). Resolution can be defined as the ability of a system to separate a scene into constituent parts, either spatial, temporal or spectral (Holden, 2017).

**A shoreline indicator** is a feature that is used as a proxy for the shoreline position (Boak and Turner, 2005) (Fig. 4). Shoreline indicators can generally be divided into two groups: the visually discernible indicators or a tidal datum-based shoreline indicators. Moore (2000) emphasizes that erosion rates can only be as accurate as the data from which they are derived, and the methods used for

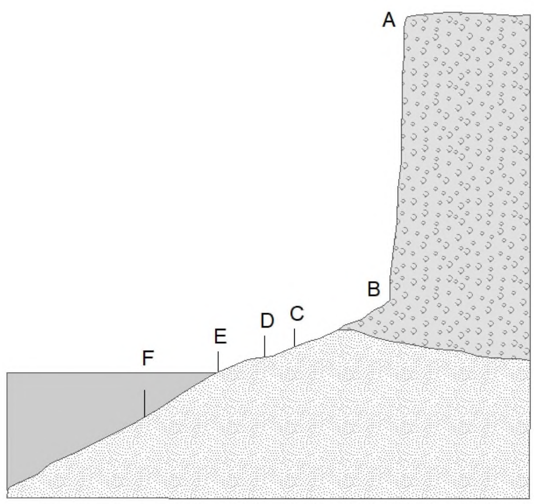


*Fig. 4. A diagram showing the spatial relationship between some commonly used shoreline indicators. A. Bluff top/cliff top. B. Base of bluff/cliff. C. Mean high water. D. Wet/dry line. E. Instantaneous water line. F. Mean lower water line. Adapted from: Boak and Turner, 2005.*

calculating them. She divides possible **error** in shoreline mapping into two categories: those that are introduced by the data sources, e.g., aerial photographs, and those introduced by the measurement methods, for example the interpretation process.

# 3. Materials and methods

## 3.1 Study area

The study area is the coastline of Skagafjörður fjord in Northern Iceland (Fig. 5). The area was chosen based on the findings of an archaeological survey that revealed the presence of coastal erosion along large parts of the region's coastline (Zoëga, 2016).

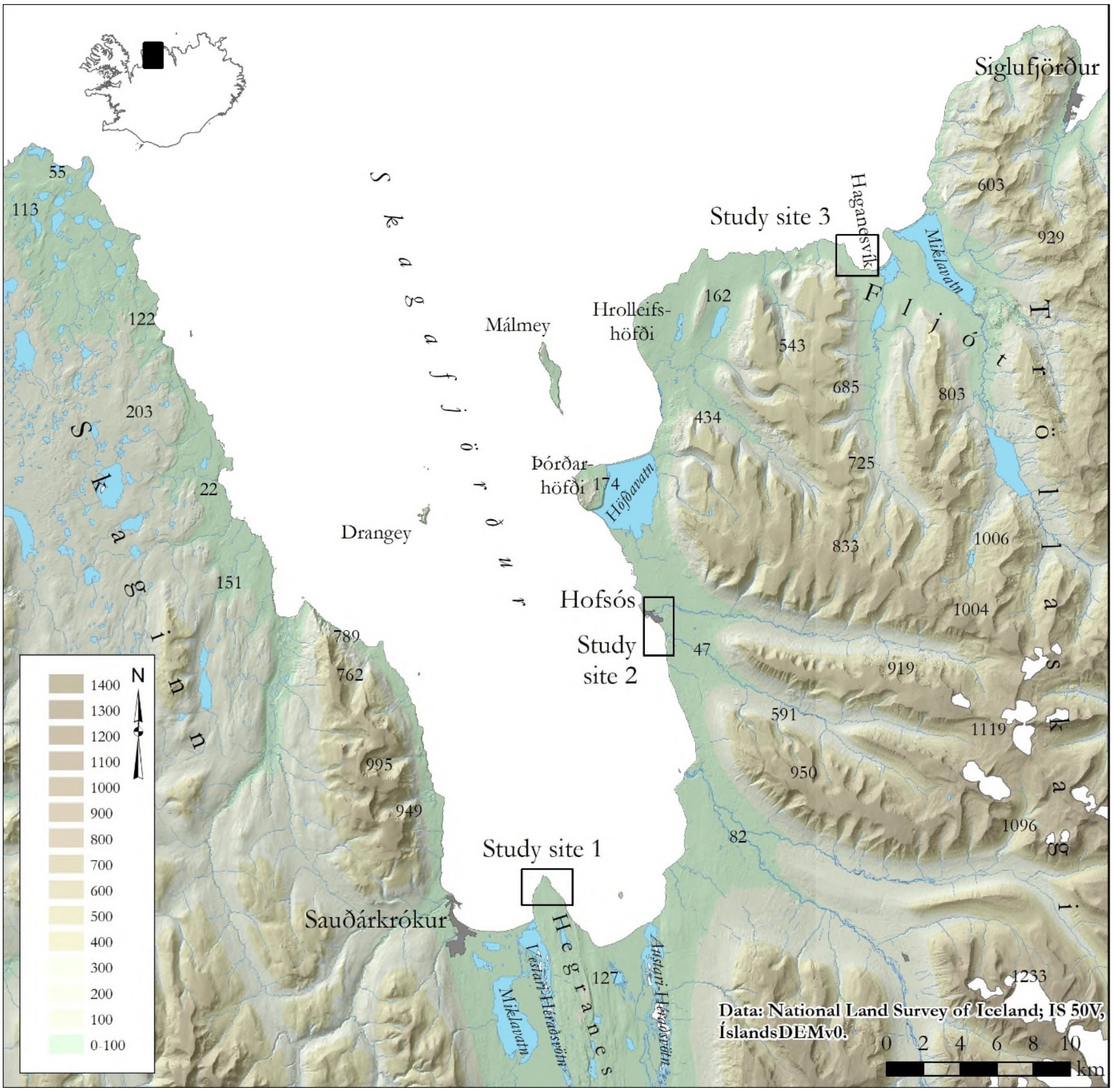


*Fig. 5. A map of the study area, study sites are marked with black rectangles. The inset map, in the upper left corner, shows the location of the study area within Iceland.*

The fjord lies in a north-south direction between two peninsulas, Tröllaskagi peninsula to the east and Skaginn peninsula to the west. Tröllaskagi is an extensive peninsula with, up to 1500 m, high mountain peaks, scattered with small glaciers and several inland valleys. It shelters large parts of Skagafjörður from north-easterly and easterly winds. Skaginn is much smaller in area, but it also has high mountains (up to 1000m) towards the south, while the northern part is low and characterised with hills and lakes. The coastline of Skagafjörður consists of a variety of coastal landscapes, like coves, smaller inlets and two large promontories (Hrolleifshöfði and Þórðarhöfði). The coastline is just over 150 km long and the mouth of the fjord opens to the north, towards the North Atlantic Ocean. The coast is mostly rocky, with a mixture of basaltic cliffs and bluffs made up of looser glacial sediments. The bottom of the fjord, being an exception, with long stretches of sandy beaches with dunes.

The geological history of the area spans over 11 million years (Hjartarson, 2016). The main bedrock of the area is basaltic and intermediate extrusive rocks and sediments from the lower Pleistocene to the middle Miocene, with a stretch of basaltic and intermediate interglacial and supraglacial lavas and sediments (Jarðfræðikort ÍSOR). The oldest formations are found on the northeast coast of the fjord. In general, they get younger as you go further inland (Hjartarson, 2016).

Iceland lies just south of the Arctic circle, on the border between the Polar and the Temperate climate zones resulting in maritime climate with cool summers and mild winters, (Björnsson et al., 2018). The interaction between the warm and moist air from the south and the cold and dry air from the north results in changeable weather conditions and often high wind speeds (Einarsson, 1984).

Skagafjörður is one of the driest regions in Iceland with average annual precipitation of less than 500 mm per year, apart from the area Fljót (study site 3) in the northeast where average annual precipitation almost doubles and reaches 965 mm a year (Auðunsdóttir, 1998). There is some variation in temperatures between the coast and the inland and also between the inner and outer parts of the fjord. The summers are usually warmer inland and conversely, winters are usually warmer by the coast. Annual mean temperature in lowland Skagafjörður is 2,5-3°C. July and August are usually the warmest months, with mean temperatures ranging from 8° degrees, at the mouth of the fjord to 10°C from the middle of the fjord and inwards. December and January are the coldest months with mean temperatures above -2 at the coast and below -2 inland (Lendis, 2009).

Due to the orientation of the fjord, the most common wind directions in the Skagafjörður area, are northerly and southerly (Lendis, 2009; Auðunsdóttir, 1998). But near the mouth of the fjord, northeasterly winds become prevailing, as can be observed from the area's Windatlas (The Icelandic Met Office, 2019). Northerly winds are more common in the summer months while southerly winds are more common during the winter (Lendis, 2009; Auðunsdóttir, 1998).

**Coastal archaeology**

The coastline of the study area was surveyed for archaeology between 2012 and 2016 (Zoëga, 2013a; 2013b; 2014; 2015; 2016; 2017). In Iceland, archaeological sites are defined as any kind of human settlements, whether on land, in sea, water or in a glacier, that are man-made and older than 100 years. This includes, for example, cultural landscapes, remains of old farms and fishing stations. All sites older than 100 years old are automatically protected (Minjastofnun Íslands, n.d).

A diversity of archaeological remains, from different time periods, have been surveyed along the coast of Skagafjörður fjord. The bulk of the sites are related to fishing (fishing stations (verbúð/sjóbúð), boathouses (naust) and farming (sheephouses (fjárhús), weaning folds (stekkur) boundary walls (garðar). There are also several small farm sites (11$^{th}$-20$^{th}$ century), remnants of a trading place (verslunarstaður) at Grafarós, old routes and at least two heathen grave sites (Zoëga, 2015). The oldest farm site dates at least back to the 11$^{th}$ century (Zoëga et al., 2016) but some archaeological features are even older, e.g. the heathen graves (pre 1000). Many of the archaeological sites have already been affected by erosion and written sources mention sites that have completely eroded away (Zoëga, 2015).

### 3.1.1 Study sites

Due to the size of the area, three smaller study sites were chosen for further investigation. Study site 1 is at the bottom of the fjord, study site 2 is along the eastern coast and study site 3, is further out on the eastern coast, close to the mouth of the fjord (Fig. 5). Each study site is about 3 km long. The three sites were chosen based on differences in geology and their location (bottom, middle and outer part of fjord). The choice of study sites was limited by the availability of aerial photographs in an acceptable scale.

**Study site - 1**

*Fig. 6. A drone photo from study site 1. The photo shows the coastline from survey point 14 to point 28 (see chapter 3.2.1 for details about survey points). The small inlet in the middle is called Naustavík (fig. 7). Perched on the coast of Naustavík are several archaeological features: the remnants of a small farm and fishing booths. Photo: Guðný Zoëga.*

Study site 1 is located at the northern tip of the Hegranes peninsula which is located at the bottom of Skagafjörður fjord (Fig. 6). The study site faces, west, north, northeast and east (Fig. 7).

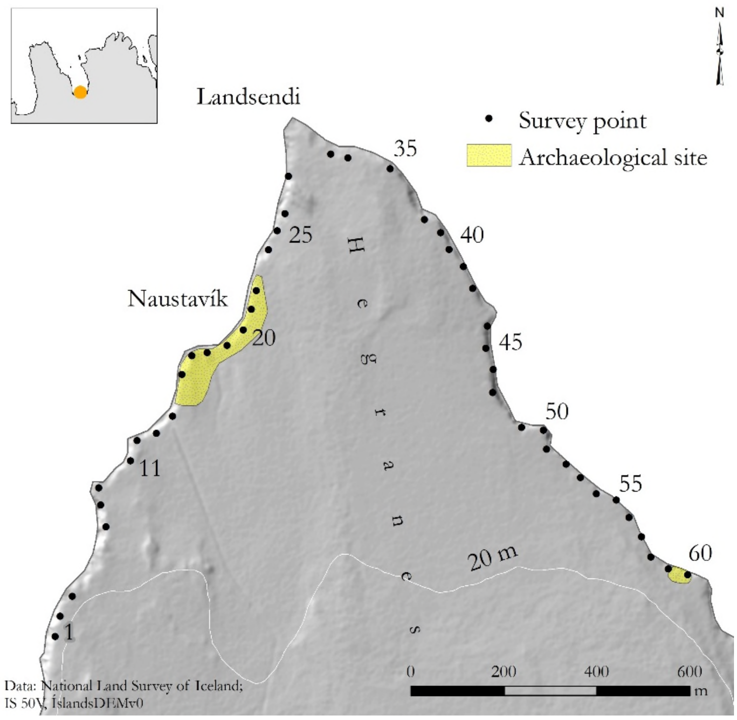


*Fig. 7. An overview of study site 1. The inset map shows the location of the study site within Skagafjörður fjord. The black dots mark the survey points where data was collected (survey points are explained in chapter 3.2.1)*

The peninsula protrudes into the fjord and divides the fjord's bottom into two. On each side of the peninsula are low lying sands that are formed by the deposits of two large glacial rivers, Austari – and Vestari-Héraðsvötn. The coast is characterized by cliffs, mixed with a few lower lying areas, mostly made up of loose sediments. Most of the shoreline is fronted with narrow rocky (cliff debris) beaches. The bedrock is either covered with loose sediments with soil on top or just soil. The tip of the peninsula is an exception as it consists of bare rock. The bedrock is basaltic and dates to the late Miocene (about 5,6-11 million years old) (Hjartarson, 2016). The windrose from study site 1 (Fig. 8), shows that the prevailing wind directions are from the south (offshore breeze) and north (seaward wind).

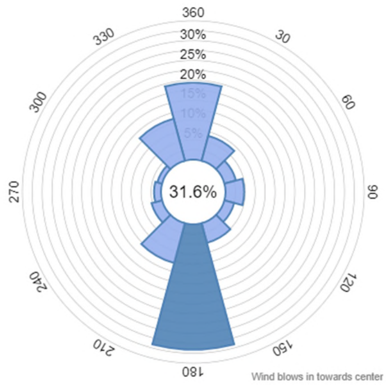


*Fig. 8 The windrose shows the average wind directions from 1995-2008 at study site 1. Wind is measured at 10 m height. Source: http://en.vindatlas.vedur.is/.*

There are two archaeological sites located within the perimeters of study site 1. There are the remnants of a fishing station, a small farm and relating outhouses from the 19-20th century and older ruins of unknown origin in Naustavík on the west coast of the peninsula. At least three of the archaeological features in Naustavík have already been affected by coastal erosion. On the east side there are visible evidence of a seal hunting site, which, still remain unaffected by erosion (Zoëga, 2017).

**Study site - 2**

*Fig. 9. A drone photo of the northern half of study site 2. The coastline faces west in the middle of the picture. The coastline in this area is characterized by high bluffs, dating from the late glacial period. Photo: Guðný Zoëga.*

Study site 2 is located along the shoreline of the small town of Hofsós and reaches about 2 km south of the town (Fig. 9 and 10). The coastline of the study site mostly faces southwest and west. The bedrock in the area is basalt and dates to the middle and upper Pleistocene (younger than 0,8 million years), it is by far the geologically youngest of all three study sites (Jarðfræðikort ÍSOR). The bedrock is mostly low and only visible in few places. An exception is a rock protrusion made up of basaltic columns, below the town itself (Staðabjarnarvík). The coast is otherwise characterized by high, relatively stable, bluffs consisting of loose sediments from the late glacial period (Pétursson, 2006). The bluffs alternate between being vegetated and non-vegetated. The shoreline is alternately fronted by a rocky beach, low basalt rocks or a mixture of both. The wind rose (Fig. 11) shows that the

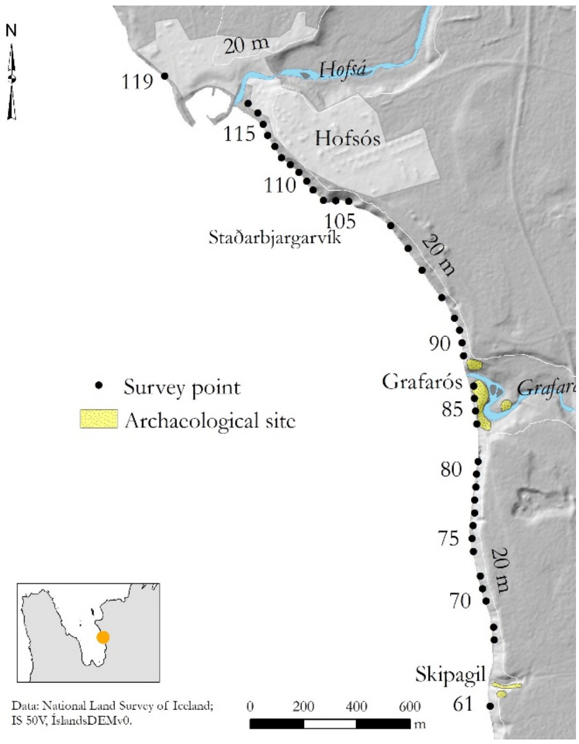


*Fig. 10. An overview of Study site 2. The inset map in the lower left corner shows the location of the study site within Skagafjörður fjord. The black dots mark the survey points where data was collected (survey points are explained in chapter 3.2.1)*

prevailing wind directions – about 1 km off coast – are from the south.

There are few archaeological sites located at the study site. The trading site at Grafarós is placed just south of the estuary of the river Grafará. The trading place was operational from 1835-1915. Prior to that, the only trading place in the region of Skagafjörður was located at Hofsós (13 km northwest of Grafarós). There are several ruins in Grafarós, remnants of the trading place; dwellings, stores, warehouses and icehouses. The sea reaches the ruins closest to the shore during storms and also the bottom of the hill, which, the trading place is built on. On the other (north) side of the rivers are old kitchen gardens from an abandoned farm located east of Grafarós. The other archaeological site is in and above Skipagil (*Skip* means ship and *gil* is a canyon), at the south end of the study site, where there are remnants of a boathouse and perched at the edge of the bluff are ruins of unknown origin (Zoëga, 2013). The sea most likely only reaches the ruins in Skipagil during storms but the ruins on top of the bluff are unaffected.

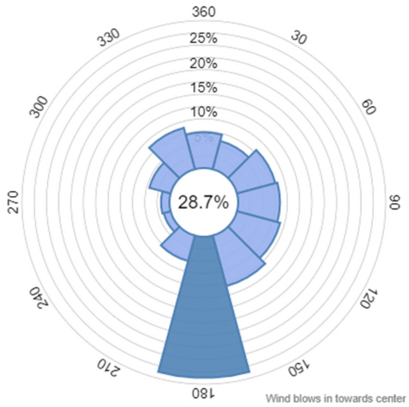


*Fig. 11. The windrose shows the average wind directions from 1995-2008 at study site 2. Wind is measured at 10 m height. Source: http://en.vindatlas.vedur.is/.*

*Fig. 12. A drone photo of study site 3. The coastline faces north. It is worth noting the different layers of coastal materials and how they have responded to coastal erosion. The bottom layer of the rock is undercut (notch) and the looser soil on top is also eroded. There is a small ruin (marked by an arrow) by the nearer edge of the small point at the bottom the photo. Photo: Guðný Zoëga.*

### Study site - 3

Study site 3 (Fig. 13) is located furthest north of the three study sites, at the mouth of the fjord and the northwest edge of an area called Fljót. It runs along the west side and towards the bottom of a small bay called Haganesvík. The coastline of the study site faces north, northeast and to a lesser extent east. This is geologically the oldest of the three areas, the bedrock being basalt dating from the middle of Miocene (more than 11 million years old) (Jarðfræðikort ÍSOR). The coast is mostly made of loose sediments with few, mostly low, cliffs. The bedrock is only visible in few places and often has a layer of loose sediments on top, topped with a layer of soil and vegetation (Fig. 12).

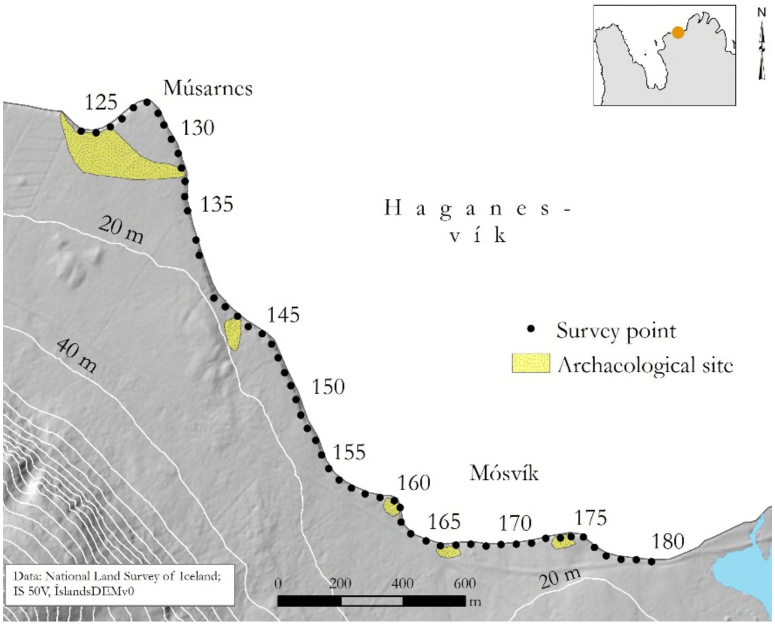


*Fig. 13. An overview of study site 3. The inset map, top right, shows the location of the study site within Skagafjörður fjord. The black dots mark the survey points where data was collected (survey points are explained in chapter 3.2.1)*

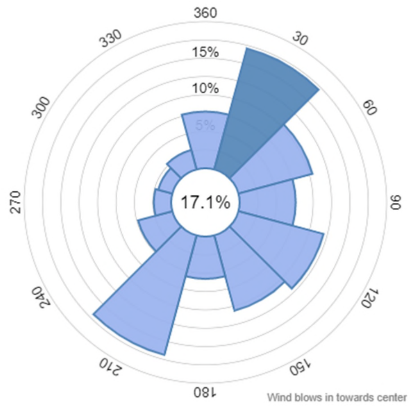


*Fig. 14. The windrose shows the prevailing wind directions from 1995-2008 at study site 3. Wind is measured at 10 m height. Source: http://en.vindatlas.vedur.is/.*

The prevailing wind directions are from the northeast and southwest and differ in that way from the other two study sites, where northerly and southerly winds are prevailing (Fig. 14). There are several archaeological sites at study site 3. The most extensive site is at Músarnes where there are several ruins from different time periods. The youngest is a sheephouse and the older are most likely the remnants of a fishing station. At least three of the ruins have been affected by erosion. There is also a concentration of ruins, from different time periods, above Stekkjarvík and one of them has been affected by erosion. Furthermore, are several ruins scattered along the coast, most of them associated with fishing, and all of them have been affected by erosion.

### 3.2 Overview of methods

Fig. 15 describes the main features of the methodological progress and the materials used in this study. A more detailed description is presented in the following chapters. The following chapter (3.2.1) explains methods of data acquisitions followed by an introduction and description of variables used for modelling (3.2.2). Chapter 3.3 describes the fieldwork methods and chapter (3.4) is an overview of the secondary data, aerial photographs and a DEM used for analysis. Chapter 3.5 describes the methods of extraction of data. It incorporates description of shoreline digitalization, calculation of shoreline change, the quantification of shoreline position uncertainty and finally the methods used to extract data on elevation, aspect and slope. The final chapter describes the statistical methods applied in this study.

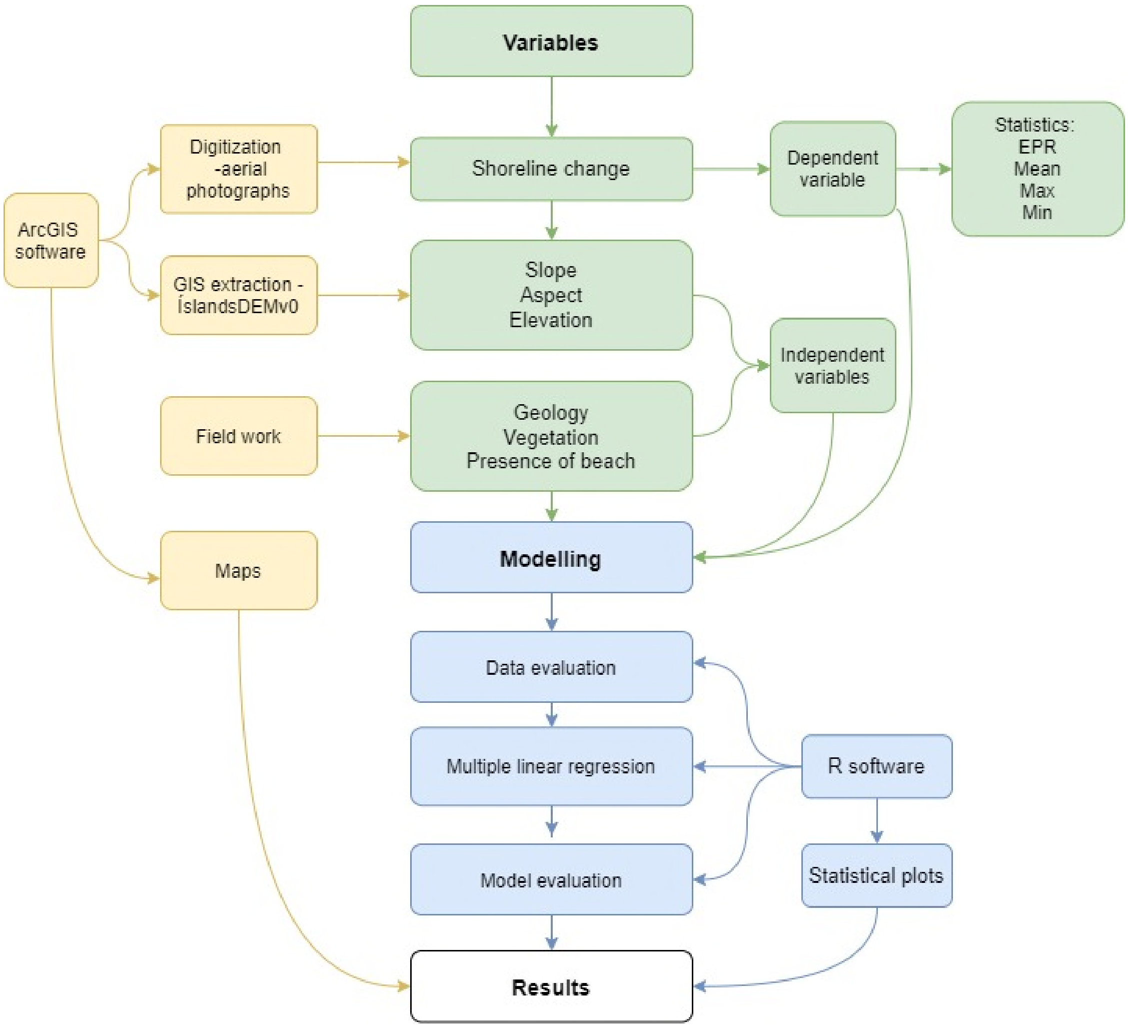


*Fig. 15. An overview of the methods and data used in the study. The yellow colour represents data acquisition and analysis, the green colour the variables and related statistics used in the study and the blue colour the modelling and output.*

### 3.2.1 Data acquisition

Data, for each variable used in this study (chapter 3.2.2), were collected at 50 m intervals along the coastline of all three study sites (Fig. 16).

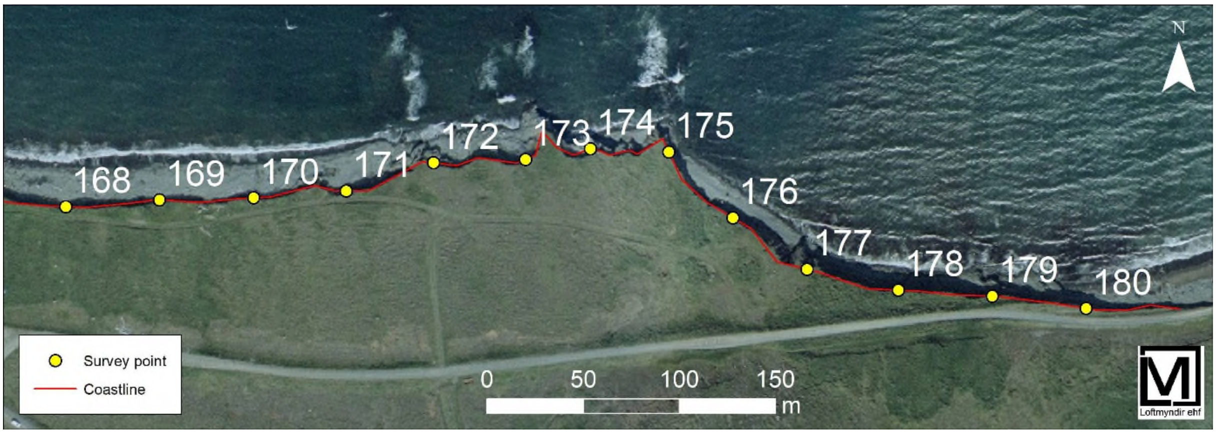


*Fig. 16. Survey points at study site 3.*

Points were constructed along the coastline on aerial photographs (from now on called survey points) (Fig. 16). This was done by using the Construct points in the Editor tool in ArcGIS 10.6. An equal interval of 50 m between points, on a 3 km long shoreline resulted in 60 points in each study site, 180 points in total for all three areas (n=180). Each point was then numbered from 1-180.

At study site 2, some of the points had been constructed at the top of a high bluff, when they should have been constructed at the bottom. Those points had to be adjusted in the field, that is, moved from the top to the bottom of the bluff. The results of this adjustment meant that, due to differences in the landscape at the top and the bottom, the intervals between those points either increased or decreased by few meters. These re-adjusted points were 19 in total.

Two of the points at study site 2, were located outside the margins of the available DEM and were, therefore, omitted from the data set (nr. 62 and 104). Further three points (nr. 82, 83 and 88) were discarded after the extraction process (explained in chapter 3.5.3), because their aspect values deviated from neighbouring values, for unknown reasons, in otherwise homogeneous surroundings. Further 34 points were eliminated due to possible inaccuracies (explained chapter 3.5.2) (nr. 4, 5, 6, 10, 15, 23, 27, 29, 30, 31, 34, 36, 37, 43, 48, 63, 64, 65, 66, 69, 73, 93, 95, 96, 98, 100, 102, 103, 118, 120, 121, 136, 139, 140) (15 from study site 1, 14 from study site 2 and 5 for study site 3). After the elimination process the dataset comprises 141 elements (n=141).

### 3.2.2 Variables

The variables used in this study have been selected in accordance with previous studies (Table 2). The choice of variables was dependent on the availability of data, but also, as stated in the introduction, the ease of access of data. The variables represent the current coastline, and it was therefore assumed, that the former coastline looked approximately the same. The reason is due to lack of data, in an acceptable scale, representing the former coastline.

*Table 2. An overview of the variables used in this study as well as the rationale for the choice of variables. Shoreline change is a dependent variable (DV) and the other variables listed are independent variables (IV).*

| No. | Variable | Rationale | Previously used in the literature |
|---|---|---|---|
| **1** | Shoreline change (DV) | The dependent variable of the model. The trends of shoreline changes, accretion (positive) or erosion (negative) are calculated. | |
| **2** | Elevation (IV) | Due to the proximity to coastal processes, like wave attack and inundation, low lying areas are more susceptible to coastal erosion than higher elevations (Fitton et al., 2016). | Fitton et al, 2016; Bryan et al., 2001. |
| **2** | Slope (IV) | Steep coastlines are more susceptible to erosion than more sloping coastlines (Hapke and Plant, 2010) while the latter are more susceptible to inundation which is related to sea level rise and increased storminess (K. Nageswara Rao et. al., 2008). | Hapke and Plant, 2010; Bryan et al., 2001. |
| **4** | Aspect (IV) | Wave energy is stronger on exposed coasts than sheltered ones (Bird, 2016). | Mc Laughlin and Cooper, 2010, Dornbusch and Robinson, 2005. Bryan et al., 2001. |
| **5** | Vegetation (IV) | The presence of vegetation can support the dissipation of wave energy as well as help reduce erosion by binding the soil in the littoral zone (Morton, 2003). | Denner et al., 2015: Palmer et al. 2011. |
| **6** | Geology (IV) | The effects of coastal erosion are influenced by the geology of a coast which affects the rates of erosion (Bird, 2016). | McLaughlin and Cooper, 2010; Hapke and Plant, 2010. |
| **7** | Beach (IV) | The presence of a beach can protect coasts from wave induced erosion (Lee, 2008). | Dornbusch and Robinson, 2005. |

Table 3 lists all variables with information on data source, type of variable and collection methods.

*Table 3. Overview of the variables used in this study, abbreviation, type, data source and collection method.*

| No. | Full name | Variable name | Type of variable | Reference level | Unit | Collection method |
|---|---|---|---|---|---|---|
| **1** | Shoreline change | s | Continuous | - | Number (m) | Digitized and calculated in ArcMap 10.7 from various sets of Aerial photographs |
| **2** | Elevation (m) | El | Continuous | - | Number (m) | Calculated in ArcMap 10.7 using a DEM (2019) at 2 m res. and by using the Zonal statistics as table tool. |
| **3** | Slope (in degrees) | Sd | Continuous | - | Number (degrees) | Calculated in ArcMap 10.7 using a DEM (2019) at 2 m res. and by using the Zonal statistics as table tool. |
| **4** | Aspect | a | Ordinal | Northeast | 10 classes | Calculated in ArcMap 10.7 using a DEM (2019) at 2 m res. and by using the Zonal statistics as table tool. |
| **5** | Vegetation | v | Nominal | Rock | 15 | Collected through field work |
| **6** | Presence of beach | b | Binary | Yes | 2 classes | Collected from Aerial and Drone photographs |
| **7** | Geology | H | Nominal | Weak | 3 classes | Collected through field work |

## 3.3 Field work

The data for the variable's vegetation, geology and presence of beach, were obtained through fieldwork which was performed in July 2019. The field work took seven days in total, each working day was about 8-12 hrs. In four of seven days, there were 2 people collecting the field data, so all in all, the field work took about 11 man-days.

The survey points were transferred to a handheld Trimble GEO7X Gps which was used to navigate to each point for data collection. The accuracy of this method was usually within 2 m from the original point. Information collected were noted down and pictures, for future references, taken at every point.

The *Presence of beach* was registered at every survey point, where it was visible. In those instances where it was not visible from the coast, drone photos were used.

*Vegetation* was mapped and classified using a habitat type classification system that has recently been adopted in Iceland. It is based on the pan-European EUNIS habitat type classification system, but it has been modified to fit Icelandic geological and ecological conditions. 64 terrestrial habitat types have been defined for Iceland. They have been grouped into 14 main categories or habitat type classes (Fig. 17) (Ottósson, et al., 2016). Those 14 classes were chosen for the mapping process since more detailed classification was not needed for the purpose of this project. A 15th class, called bare rock, was added for those areas where the cliffs were too high for the sea to reach the vegetated areas and vegetation would therefore not have any effect.

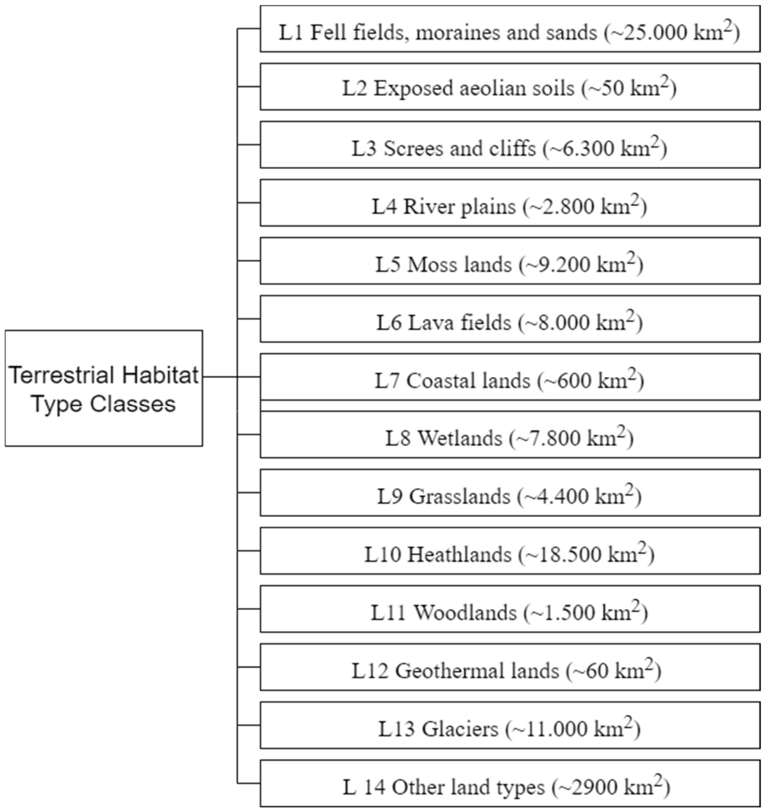


*Fig. 17. Habitat Type Classes (from Ottósson et al., 2016).*

In the field, a 5 x 5 m grid was laid out at every sample point. Habitat types within the grid were registered and a picture taken of each grid plot, for later verification purposes.

The data collected on *geology* was based on the strength of the rock as recommended by Prémaillon et al. (2018). The method chosen for estimating rock strength in the field is based on an aggregated version of field estimates of uniaxial compressive strength from Hoek and Brown (1998). Hoek and Brown (1998) describe seven grades of rock resistance, from extremely weak to extremely strong. Due to homogeneity in the geology of the area it was decided to use an aggregated version from Hoek and Brown (1998), proposed by Prémaillion et al. (2018), who combine the seven categories into three: hard, medium and weak (Table 4).

*Table 4. Aggregated categories of Hoek and Brown's (1997) field estimates of strength, as proposed by Prémaillon et al. (2018). Examples of rock types are adjusted to Iceland's geology.*

| Field estimate of strength | Term | Examples |
|---|---|---|
| 1. Specimen can only be chipped with a geo-logical hammer.<br>2. Specimen requires many blows of a geological hammer.<br>3. Specimen requires more than one blow of a geological hammer to fracture it. | **Hard** | Basalt, conglomerate, intermediate rocks, lavas, mudstone, plutonic rock, sandstone, shale, siltstone, volcanic rock, volcano-sedimentary |
| Cannot be scraped or peeled with a pocketknife, specimen can be fractured with a single blow from a geological hammer. | **Medium** | Claystone, volcanic tuff, sandstone, shale, siltstone, basalt, consolidated clay |
| 1. Can be peeled with a pocketknife with difficulty, shallow indentation made by a firm blow with the point of a geological hammer.<br>2. Crumbles under firm blows with the point of geological hammer, can be peeled by a pocketknife.<br>3. Indented by thumbnail. | **Weak** | Aeolianite, basalt, clay, conglomerate, dune deposits, fluvial deposits, glacial deposits, glaciofluvial gravel, loess, silt, sand, sandstone, slag, till, tuff |

The strength test was performed at beach level, below each survey points, and only measures the strength of the exposed rock which limits the predictive value of the variable, since it cannot be assumed that the whole rock face has the same strength. It should also be noted that this method only measures the current strength of the rock since it does not account for the thickness of weathered rock faces.

The strength test in the field was performed with a geological hammer. The flat head of the hammer was used to fracture the rock. Where the rocks were either broken or crumbled, the chisel end of the hammer or a trowel was used to pry it apart. Where the coastal materials were soft, a pin was used to estimate strength. In several instances the cliff or the bluff proved to be unreachable, usually due to steepness or the height of the cliff. In, those cases, the hardness was visually estimated. That method is not as reliable as the hammer test. To reduce the likelihood of errors, visual estimation was practiced in areas that were accessible and with similar geological features.

In many instances the rocks and cliffs were stratified or built up of layers of different rock types or layers of rock and softer materials like glacial till (Fig. 12 from study site 3). This made it difficult to evaluate the strength of the entire rock profile, since one profile could have up to several levels of rock strength. Where this was the case, the estimation of rock strength was based on the height of the coast. On high cliffs, the strength of the lower half of the cliff was estimated, since that part of the rock is more exposed to erosive forces like wave action.

On lower cliffs, which are more frequently exposed to waves, the weakest part of the cliff was used for estimation.

## 3.4 Secondary data

Table 5 gives an overview of the secondary data used in this study.

*Table 5. Overview of secondary data used in this study. It also lists, the source/provider of the data, resolution, how the data was processed and how and for what the data was used.*

| Data | Processing | Resolution | Data provider/ source | Use |
|---|---|---|---|---|
| **Aerial photographs (raster: 7 sets)[1]** | Pre-processed by Loftmyndir ehf. | Various > see table 3 | Loftmyndir ehf. | For digitalisation of shorelines, vegetation mapping and interpretation purposes |
| **ÍslandsDEMv0 (raster TIFF)** | Pre-processed by the National Land Survey of Iceland | 2 x 2 m | National Land Survey of Iceland | For extraction of elevation data and derivation of slope and aspect raster's |
| **Aspect (raster)** | ArcMap 10.7 > DEM > Aspect tool | 2 x 2 m | Generated from ÍslandsDEMvO | For calculation of mean aspect |
| **Slope (raster)** | ArcMap 10.7 > DEM > Slope tool | 2 x 2 m | Generated from ÍslandsDEMv0 | For calculation of mean slope |

*Notes: 1) See further information on aerial photographs in table 3.*

The ÍslandsDEMv0, from now on referred to as DEM, used in this study was downloaded (open source) from the homepage of The National Land Survey of Iceland (http://atlas.lmi.is/mapview/?application=DEM). The data is derived from multitemporal images from 2008-2019 (mostly 2012-2019) with some additional drone and lidar data from other sources. Horizontal accuracy is 3 m and the vertical accuracy is better than 1 m (Lýsigagnagátt, 2020). The DEM was used for deriving slope and aspect raster and further extraction of data for the variables *elevation*, *slope* and *aspect*, as well as a Hillshade for cartographic purposes.

Several sets of aerial photographs were used in this study (Table 6). They were mainly used for shoreline digitalisation, digitization of vegetation and for visual analysis and identification of areas of erosion or accretion. There is limited availability of aerial photographs of Skagafjörður, at a scale of 1:20.000 or larger (as recommended by Moore, 2000) which affected the choice of study sites.

Data preparation and analysis were done in the GIS software program Esri® ArcMap™ 10.7.0.10450 with the Spatial Analyst extension. The same software was used for producing the maps presented in this thesis. The co-ordinate system used was the ISN93 - Lambert 1993, Datum: Islands Net 1993, EPSG:3057, CRS: ISN93.

*Table 6. Overview of the aerial photographs used in this study with information on date of acquisition, altitude, scale, spatial resolution and the years between datasets. *Date of acquisition is unknown.*

| Study site | Date | Altitude (m) | Scale | Spatial resolution (m) | Years between datasets |
|---|---|---|---|---|---|
| **Fljót (study site 3)** | July and August 2016 | Ca. 3000 | 1:500 | 0.25 | 17 |
| **Hegranes (study site 1)** | August 8th 2016 | Ca. 3050 | 1:1000 | 0.5 | 13 |
| **Hofsós (study site 2)** | August 8th 2016 | Ca. 3000 | 1:1000 | 0,5 | 13 |
| **Hofsós (study site 2)** | August 18th 2015 | Ca. 1490 | unknown | 0,1 | 12 |
| **Hegranes (study site 1)** | 2003* | Ca. 2060 | 1:1000 | 0.5 | 13 |
| **Hofsós (study site 2)** | 2003* | Ca. 1455 | 1:300 | 0.15 | 12, 13 |
| **Fljót (study site 3)** | 1999* | Ca. 2145 | 1:500 | 0.25 | 17 |

All aerial photographs were obtained from Loftmyndir ehf. They were all digital and georeferenced. The more recent set 2015-2016, were made available through a contract with the Municipality of Skagafjörður and the older photos were bought from Loftmyndir for use in this research project. The photo from 2015, from study site 2, did not cover the whole area, so a photo from 2016 was used for the southernmost part. The choice of the photo from 2015 over the one from 2016, was due to a better quality.

## 3.5 GIS Extraction of data

### 3.5.1 Shoreline digitalisation

Shoreline change was chosen as the dependent variable for the statistical model. Shoreline change implies both erosion (negative) and accretion (positive) changes. For the purpose of this study, accretion is defined as the seaward movement of the shoreline (that is the proxy line for the shoreline) and erosion is defined as the landward movement. The shoreline change calculated was relatively short-term (the longest being from 1999-2016). Aerial photographs were used to map shoreline positions in each of the three study sites. Georeferenced aerial photographs (Table 6) for two different time periods, were used to map the extent of erosion or accretion.

Shorelines were manually digitized, in ArcMap 10.7, at the zoom level equivalent to the scale of 1:800. Two lines were digitized for each study site representing the former (older set of photos) and the more current shoreline (younger set of photos). This is a commonly used method (see e.g. Ford, 2013; Irrgang, 2018), although the choice of scale varies. To minimize possible errors in the digitization process, all shorelines were digitized by the same operator (see more on errors and uncertainty in chapter 3.5.3). The pairs of aerial photographs were taken 12-18 years apart. The quality between photos varied which can affect the interpretation of the shoreline in the digitization process. Difference in the colour of some of the photos as well as shadows and distortions along some of the high cliffs made the interpretation process challenging. In those instances, aerial photos from other time periods (viewed at www.map.is and www.ja.is) were used to support the interpretation.

A set of shoreline indicators, or proxies, were chosen to represent the shoreline (as explained in chapter 2.3.2). Due to differences in the landscape, three different proxies were used to map the shoreline: the vegetation line, top of a cliff /bluff or the bottom of a high bluff, were the bluff top was too far from the coast to be affected by waves (Fig. 18).


*Fig. 18. Shoreline indicators. The figure to the left shows the proxy line drawn at the bottom of a bluff. On the figure to the right, the proxy line is drawn at the vegetation line/edge of a bluff/cliff.*

Table 7 is based on an adapted overview from Boak and Turner (2005) showing different types of shoreline indicators. It incorporates the three proxies used in this study with a positional description and information about the pros and cons of each proxy.

*Table 7. A summary of the shoreline indicators used in this study. An aggregated and adapted version from Boak and Turner, 2005.*

| Shoreline indicator | Identification of feature (adapted) | Pros and cons (from Boak and Turner, 2005) |
|---|---|---|
| **Bluff top/cliff top** | Landward edge of the bluff top or cliff top | Good erosion indicator; morphology specific (hard coasts) |
| **Base of bluff/cliff** | Base of bluff or cliff; used when it was not easy to determine the landward edge or when the base of bluff was considered more relevant (e.g. due to height of bluff) | Not clearly defined; base position may be distorted due to rubble, etc; morphology specific (hard coasts) |
| **Vegetation line** | Distinct edge in image based on tonal and colour differences between the vegetated and non-vegetated beach areas. | Good erosion indicator, but may not show accretion or it will show it with a significant time lag |

In this study, vegetation was the most commonly used proxy line because it usually made the most easily identifiable line in the photos. In case vegetation was lacking or not discernible, the top of a cliff/bluff was used. The vegetation and top of a cliff proxies, coincide where vegetation reaches the edge of a cliff. The bottom of a bluff was used as a proxy line when it was visible, and/or the bluff was too high for the sea to affect the top directly. For consistency, the same type of proxy line was used for the same stretch of coastline for both time periods. There were two interruptions along the shoreline at study site 2, one at the mouth of Hofsá river and the harbour at Hofsós and the second one at the mouth of Grafará river. Those areas were excluded from the analysis.

### 3.5.2 Calculation of shoreline change

Shoreline change was calculated by measuring the distance between the former and the current digitized shorelines. First step was to construct points at 1 m intervals along the current digitized shoreline. Next, lines were drawn perpendicular from those points to the other digitized shoreline. ArcMap 10.7 was then used to calculate the length of the line between the two shorelines. This method did not distinguish between erosion or accretion so, in areas of erosion, points were (manually) given negative values afterwards. To account for possible extreme values of shoreline change, the average of all lines within a 5m buffer of each survey point was calculated. This calculation was done in several steps, some automatically computed while others were done manually. The whole workflow for shoreline change is further explained in Fig. 19.

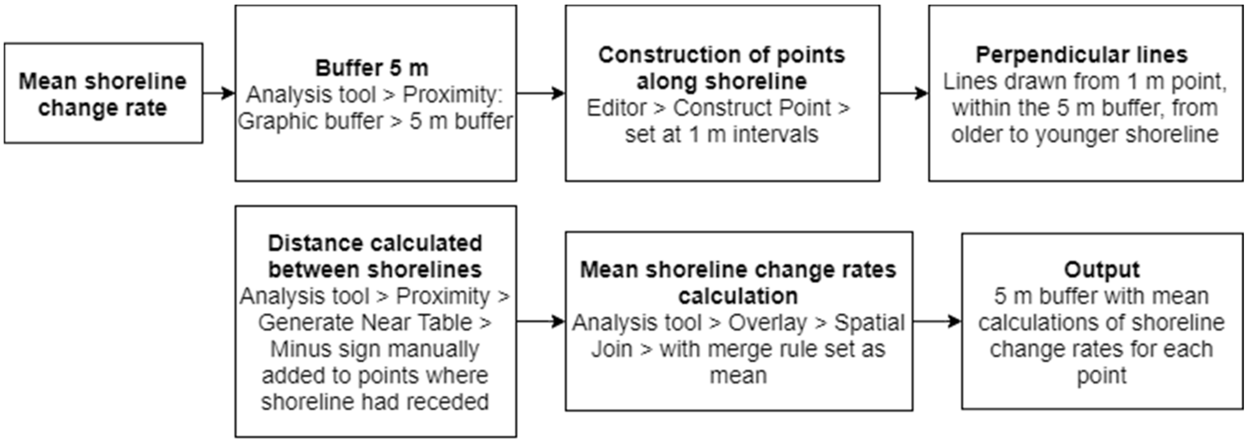


*Fig. 19. The workflow of calculating mean shoreline change rate.*

After the calculation process, 17 survey point (at study site 1 and 3) located on a cliff top had positive values for mean length, indicating cliff accretion. Cliffs are by nature erosional features so all positive values, indicating accretion, were assumed to result from digitizing errors. These 17 values were set to 0, indicating *stability,* that is neither accretion or erosion and implies that the shoreline is currently stable (the average value was 0.39 m).

Signs of erosion, were registered in the field at each survey point. This was done to further reduce potential error caused by the digitalisation process. Of 175 points, 107 showed visible signs of erosion whereas 68 showed no signs of erosion. The results were compared to the results of the shoreline change calculation, which led to 34 points (chapter 3.2.1) being eliminated from the data set because of the contradictory results of the two methods. Short-term rates of shoreline change were calculated for each survey point using an end-point rate. End point rates is calculated as the difference in shoreline position between the two shoreline years (Table 6) divided by the time between photo acquisition.

### 3.5.3 Shoreline position uncertainty

Several steps were taken to account for shoreline position uncertainty (U) and the shoreline position uncertainties at every survey point ($U_R$). To be able to calculate U and $U_R$, certain information is needed: the error caused by the digitization process ($E_d$), the errors resulting from georeferencing of aerial photos ($E_a$), the ground resolution of the aerial photographs and the time-period between datasets of aerial photographs.

In order to quantify $E_d$, a 200 m stretch of coastline was digitized 3 times in a row (1:800), and the variance between the lines was calculated (Irrgang et al., 2018 mention a similar method). This was done for each dataset, that is for, both the older and the younger set of photos. The 200 m stretches chosen for the accuracy test, were the ones, where the coastline was most unclear on the photos. The error is therefore likely to represent the maximum digitization error for the area at the given point in time. To calculate variance between lines at a given time, 20 points were randomly distributed along one of the three digitized lines. Lines were then drawn, perpendicular, from a point to the line furthest away. The sum of the length of lines was then added together and the mean length calculated. The results are presented in Table 8.

*Table 8. The results from the quantification of errors related to the process of digitizing shorelines ($E_d$). These numbers should represent the maximum errors in the calculation process as a result of the method used to calculate them.*

| **Study site 1 2003 (m)** | **Study site 1 2017 (m)** | **Study site 2 2003 (m)** | **Study site 2 2015 (m)** | **Study site 3 1999 (m)** | **Study site 3 2016 (m)** |
|---|---|---|---|---|---|
| 0.56 | 0.48 | 0.89 | 0.47 | 0.45 | 0.37 |

All aerial photos used in this study were already georeferenced, but the root-mean-square positional error (RMSE) was not known. ArcGis 10.6 was used to evaluate the positional internal differences between datasets ($E_a$), as these differences will introduce measurement errors in the calculation process of the shoreline change. To evaluate $E_a$, 6 control points were marked, on the younger set of aerial photos at easily discernible landmarks, like big rocks, roads or buildings. The points were placed as close to the coastline as possible. The same was done for the older set of photos and the distance between those points was calculated, using the measurement tool in ArcGIS. The same process was repeated for each study site. Results are presented in Table 9.

*Table 9. Results from the calculation of the errors resulting from the georeferencing of the aerial photographs used in the study ($E_a$).*

| **Study site 1- 2003/2017** | **Study site 2- 2003/2015** | **Study site 2- 2003/2016** | **Study site 3- 1999/2016** |
|---|---|---|---|
| 0.26 | 0.87 | 0.26 | 0.82 |

The uncertainty of each shoreline position (U) was then calculated as shown in the equation below (adapted from Ruggiero et al. 2012 and Irrgang et al., 2018):

$$U = \sqrt{E_g^2 + E_d^2 + E_a^2} \qquad (1)$$

where $E_g$ represents the ground resolution of the aerial images (Table 6). The results for each study site are presented in Table 10.

*Table 10. Results from calculations of shoreline position uncertainty (U).*

| Study site 1 2003 | Study site 1 2017 | Study site 2 2003 | Study site 2 2015 | Study site 2 2016 | Study site 3 1999 | Study site 3 2016 |
|---|---|---|---|---|---|---|
| 0.79 | 0.74 | 1.25 | 0.99 | 1.05 | 0.97 | 0.93 |

The average uncertainty (U) of shoreline positions for the whole study area is 1.01 m. It is 0.77 m for study site 1, 1.1 m for study site 2 and 0.95 for study site 3. The uncertainty for shoreline change rates at individual survey points ($U_R$) was calculated thus (adapted from Ruggiero et al. 2013):

$$U_R = \sqrt{\frac{U_1^2 + U_1^2}{year_2 - year_1}} \qquad (2)$$

where $U_1$ and $U_1$ are the shoreline position uncertainties of the first (year 1) and second (year 2) shorelines. The results are presented in Table 11.

*Table 11. Results from calculations of the uncertainty of shoreline positions ($U_R$) for each survey point in the study. The $U_R$ for study site 2 is calculated for the dataset 2003/2015 (points 61-70) and 2003/2016 (points 71-120).*

| Study site 1 (m) Point 1-60 | Study site 2 (m) Points 61-70 | Study site 2 (m) Points 71-120 | Study site 3 (m) Points 121-180 |
|---|---|---|---|
| 0.81 | 1.28 | 1.28 | 0.97 |

The average uncertainty ($U_R$) of shoreline change rates for the whole study area is 1.1 m.

### 3.5.4 GIS extraction: elevation, aspect and coastal slope

Values for elevation, aspect and coastal slope were all extracted from a DEM using ArcMap 10.7 as mentioned in Table 5. Values on elevation were extracted from the DEM with the Extract Multi Values to Points tool. Elevation values are given in orthometric height, which equals height above sea level, and is measured in meters. Slope and aspect rasters were derived from the DEM using the Surface Analyst tool in ArcGIS.

Slope can be defined as the vertical change in the elevation of the land surface, determined over a given horizontal distance while aspect is the downslope direction of the maximum vertical change in the surface determined over a given horizontal distance (Kimerling et al., 2016). In ArcGIS, the slope tool calculates the maximum rate of change from each cell to its eight neighbours. The lower the value of the slope, the flatter the terrain and vice versa (ESRI, 2020b). Values for slope were calculated in degrees. Aspect values indicate the compass direction that the surface faces at that location and is measured clockwise in degrees from 0 to 360 degrees, -1 indicates flat terrain (Table 7) (ESRI, 2020a).

As with shoreline change, mean values were calculated for slope and elevation, to smooth out possible extreme values. The workflow for calculations of the mean values for slope and elevation is shown in Fig. 20.

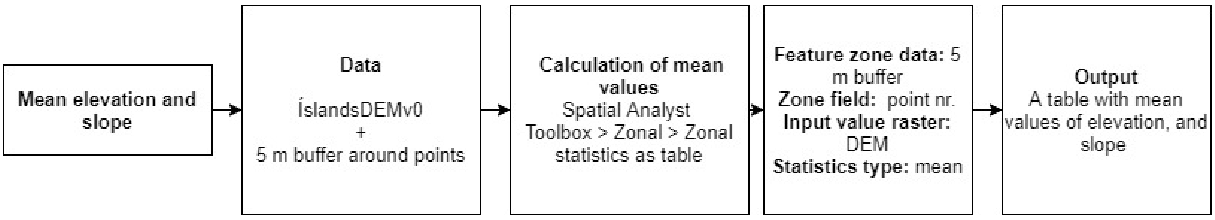


*Fig. 20. Workflow showing calculations of mean slope and elevation.*

Because aspect values are measured in a circle, from 0-360 degrees, it is not possible to calculate mean aspect in the same way as with slope and elevation. Instead of using mean as a statistic term the majority of values within the raster cells was calculated. The calculation was done with the Zonal tool (Fig. 21). The values extracted are given in numbers from 0-360, as explained above. To calculate majority, these values had to be reclassified into cardinal and intercardinal directions as can be seen in Table 12.

*Table 12. An overview Reclassification table from slope angle range to slope direction.*

| Code value | Slope direction (categories) | Slope angle range ° |
|---|---|---|
| -1 | Flat | -1 |
| 2 | North | 0-22.5 |
| 3 | Northeast | 22.5-67.5 |
| 4 | East | 67.5-112.5 |
| 5 | Southeast | 112.5-157.5 |
| 6 | South | 157.5-202.5 |
| 7 | Southwest | 202.5-247.5 |
| 8 | West | 247.5-292.5 |
| 9 | Northwest | 292.5-337.5 |
| 10 | North | 337.5-360 |

Fig. 21 shows the workflow of both the reclassification process and the extraction of mean aspect values.

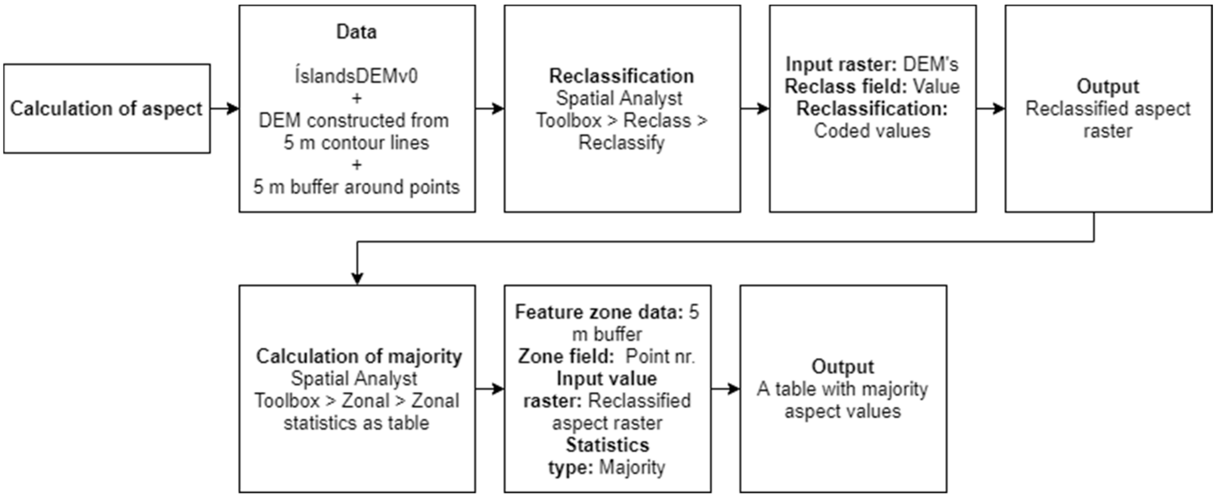


*Fig. 21. A workflow showing reclassification of aspect raster and calculation of majority of aspect values.*

## 3.6 Statistics

Descriptive statistics (mean and median) were calculated to describe the mean and median shoreline changes and the annual rates of change. Inferential statistics were used to assess the relationship between the dependent variable (DV) *shoreline change* and the six independent variables (IV), introduced in chapter 3.2.2, *slope, elevation*, *aspect*, *geology, vegetation and presence of beach*. For the inferential statistics the significance level was set at $p = .05$. The free software environment R and associated packages was used for all statistical analysis and graphics in this study (R Core Team, 2014). Two independent variables were transformed to normalise skewed distributions. *Log* transformation was applied on the variable *elevation* and *square root* transformation on the variable *slope* (Mangiafico, 2016).

*Multiple linear regression,* an extension of the simple linear model which accommodates multiple predictors, was used to model the association between the DV and the IV variables (James et al., 2013). Three linear models (LM) were produced for the study, all with shoreline change as DV. The original model (Model 0) incorporated all the variables described in chapter 3.2.2 (for summary of model 0 see Appendix II). The variable *vegetation* was later discarded from the model due to multicollinearity as explained later in this chapter. Discarding vegetation resulted in Model 1 includes the variables: *slope, elevation, aspect, geology* and *the presence of beach* (for summary of model 1 see Appendix III). A third model, Model 2 includes *aspect* and *geology* only and resulted from the best subset selection of variables as explained below.

Diagnostics plots examining the distribution of residuals errors and statistical tests were used to evaluate regression assumptions (Table 13): linearity of the data, normality of residuals, homogeneity of residuals variance and independence of residuals error terms (James et al., 2013).

*Table 13. An overview of the methods used to evaluate regression assumptions and the associated R packages.*

| Data exploration | Diagnostic plot | Statistical test | R package |
|---|---|---|---|
| **Outliers and high leverage points** | Residuals vs Leverage | | |
| **Normal distribution** | Normal Q-Q | | |
| **Homogeneity of variance (homoscedasticity)** | Scale-Location, Residuals vs. Fitted | + Breusch-Pagan | Lmtest |
| **Linearity** | Residuals vs. Fitted | | |
| **Multicollinearity** | | VIF – variance inflation factor | car |
| **Correlation** | Scatterplot Matrix | Spearman's ρ, Kruskal Wallis | |
| **Spatial autocorrelation** | Variogram | Moran's I | Dharma |

The, non-parametric *Spearman's ρ* was used to assess correlation between continuous variables and *Pearson's Chi-squared test* between continuous and categorical variables (two levels) (details in Appendix IV). *Variance inflation factor* (VIF: package: car, ver. 3.0-10) was used to measure the correlation among the independent variables (Fox and Weisberg, 2019). *Breusch-Pagan test* (package: Lmtest, ver. 0.9-38) was used to test for heteroskedasticity in the linear model in addition to the diagnostic plots (Zeileis and Hothorn, 2002). Spatial autocorrelation (SAC) is a common geographical phenomenon and refers to the correlation of a variable with itself through space and it breaches the assumption of independence of observations. The *Moran's I correlation coefficient* (package: Dharma, ver. 0.3.3.0) was used to measure spatial autocorrelation in the model residuals and variograms (package: nlme, ver. 3.1-142) were drawn to visually explore the correlation (Hartig, 2021; Pinheiro et al., 2021).

The diagnostic plots showed the standardized residuals to be normally distributed and linear but showed possible occurrence of heteroskedasticity which was confirmed with a follow up test (Breusch-Pagan: BP = 28.06, df=15, $p$ = .02). Outliers can have an effect on regression coefficients and even change the direction of coefficient signs (Burt and Barber, 1996). The residual plots identified five outliers (points: 22, 87, 117, 127, 180) which were all investigated for possible errors. All but point nr. 22 had relatively high shoreline change values, but all were seemingly correct and therefore, all outliers were kept in the model. The results from the calculations of the *Variance inflation factor* showed vegetation and geology (to be highly correlated, 20.1 and 12.7 respectively) but little correlation was found between the other independent variables (all under 5) in the model. The decision was made to remove one of the correlated variables. Vegetation was then removed on the grounds that geology is expected to have a greater significance on erosion than vegetation. The results from the *Moran's I correlation coefficient* demonstrated a significant SAC in the model residuals (observed = 0.13, expected = -0.007, sd = 0.003, $p < .001$). Measures were taken to counteract the SAC as explained later in the chapter.

*Best subset selection* (package: leaps, ver. 3.1) was performed for selecting the most successful independent variables (Lumley and Miller, 2020). The subset selection method consists of testing all possible combination of the predictor variables and is considered simple and feasible when p is relatively low (James et al., 2013). The results of the Best Subset selection were overall consistent across selection criteria and only included the categorical variables *aspect* and *geology* (model 2). Although, there were some variation in which of the categories of these variables were significant. Model 2 was the best model and is the one that will be presented in the results (chapter 3.4.1).

The diagnostic plots and statistical tests were re-evaluated after the Best subset selection and removal of the non-significant IV's. The standardized residuals were normally distributed, linear and no heteroscedasticity was detected. The latter was again, checked with the Breusch-Pagan test which had a *p*-value of .75 thus I failed to reject the null hypothesis of homoscedasticity. Removing the non-significant variables had also removed the heteroscedasticity. Spatial autocorrelation was still present in the model (observed = 0.1359, expected = -0.007 sd = 0.027, $p < .001$). Adding x and y co-ordinates as spatial variables did lower the p-value ($p = .003$) but did not remove SAC.

Since SAC was detected in the model residuals, a *Generalize Least Squares* (GLS) (Model 5) was chosen to replace the linear regression model. A GLS model (package: nlme) accounts for spatial autocorrelation and can be used for linear models of normally distributed data (Pinheiro et al, 2021; Dormann et al., 2007). Adding a correlation structure to the model, improved the AIC but did still not remove the SAC. The results of the LM and the GLS model were very similar and thus the decision was made to use the LM model.

# 4. Results

The following chapter contains the results of the present study. It is organized, much in the same way as the research questions proposed in chapter 1. Chapter 4.1 and 4.2 answer the questions on the extent and shoreline change rates along the coast of Skagafjörður, for the study site as a whole as well as for the individual sites. The condition of archaeological sites within each study site (research question 4) is reported in chapter 4.1. Chapter 4.4 presents the results of the regression model.

## 4.1 Shoreline changes along the coast of Skagafjörður and status of coastal archaeology

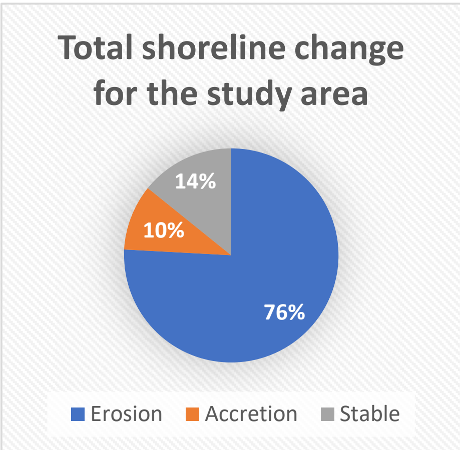


*Fig. 22. The pie chart shows the percentage of total shoreline change for the study area.*

The results provide the extent of shoreline change for the whole study area as well as the individual study sites. Calculation of shoreline change revealed coastal erosion along the coast at all three study sites, whereas accretion was only found at study site 2. The accretion was due to accretion in vegetation cover (proxy line) and not actual accretion of land. Coastal erosion was measured at 107 of 141 survey points. Visible signs of erosion were observed, at all these survey points. Accretion was measured at 14 of 141 points and 20 survey points were registered as being stable (Fig. 22).

The extent of shoreline change varies between the three study sites (Fig. 23).

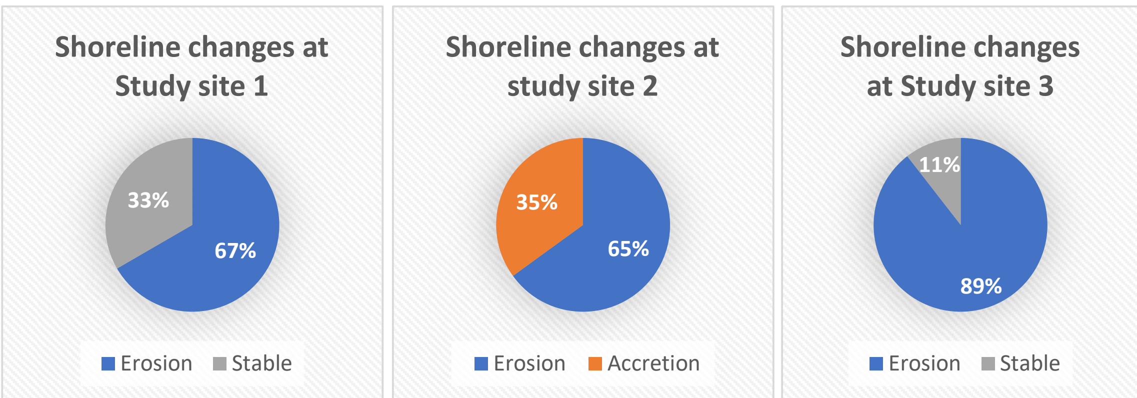


*Fig. 23. The pie charts show the comparison of shoreline change (%) between the individual study sites.*

**Study site 3** had the most widespread erosion, measured at 51 out of 56 survey points, whereas 5 survey points were stable (Fig. 24). Erosion was spread along, the majority, of the coastline at study site 3, apart from the area just south of the Músarnes promontory. That stretch of coastline is fronted with cliffs flanked by a relatively narrow stretch of rocky beach. The fifth survey point, which was stable, is located at the west side of the Mósvík inlet. The coast there is fronted by a low cliff. All, of the archaeological sites at study site 3, are located along an actively eroding coastline. The archaeological sites are placed at different coastal types, weak, medium and hard.

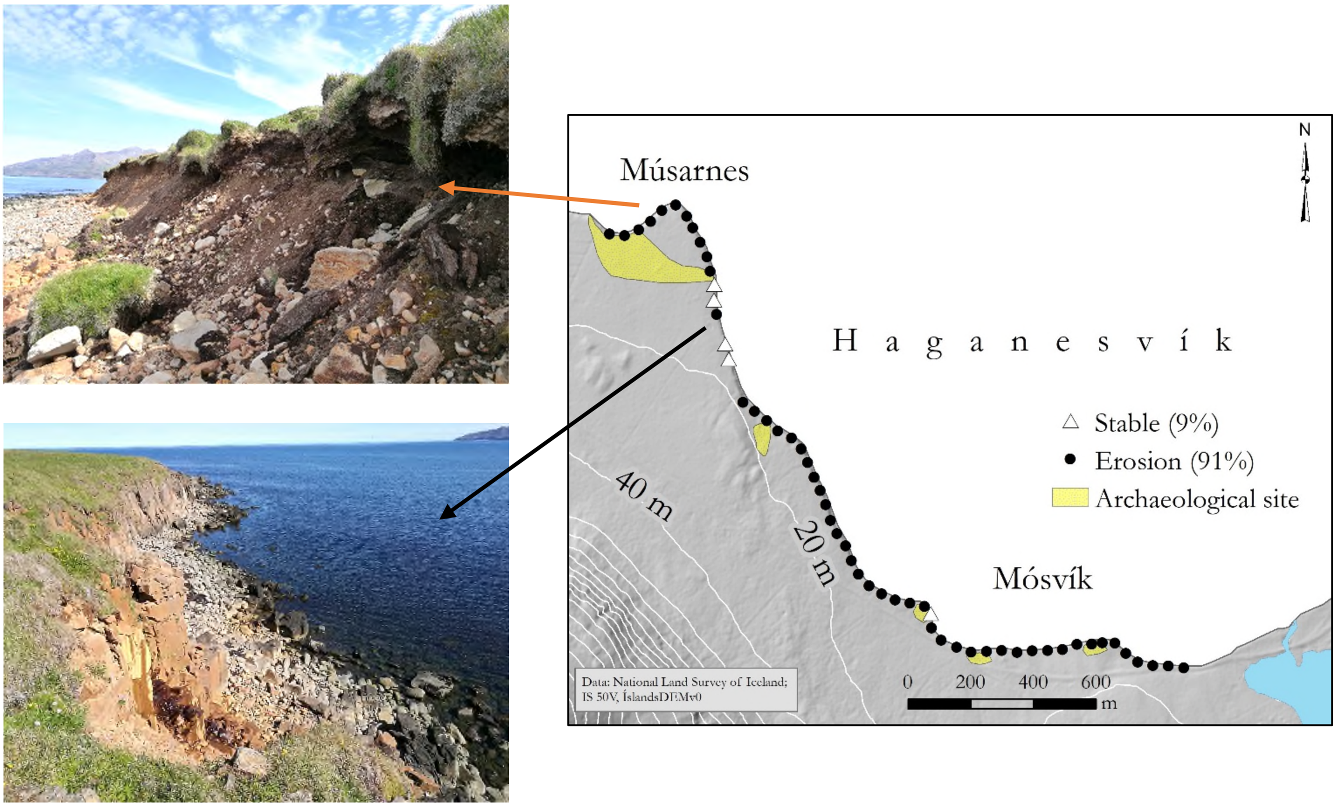


*Fig. 24. The map on the right shows the spatial distribution of erosion at study site 3, from 1999-2016. The upper picture on the left shows an actively eroding coastline (survey points 124-125) made up of loose materials and the lower picture shows a stable coastline (survey points 134-135), fronted by cliffs.*

**Study site 1** had the second most widespread erosion (Fig. 25). Erosion was measured at 30 out of 45 survey points whereas 15 of 45 survey points were stable. Erosion was more widespread along the east coast of Hegranes than the west coast, where more than half of the coastline was stable. Both archaeological sites at study site 1 are located along an actively eroding coastline. The archaeological site on the west coast is fronted with a coastline of loose sediments but the archaeological site on the east coast is fronted by a cliff.

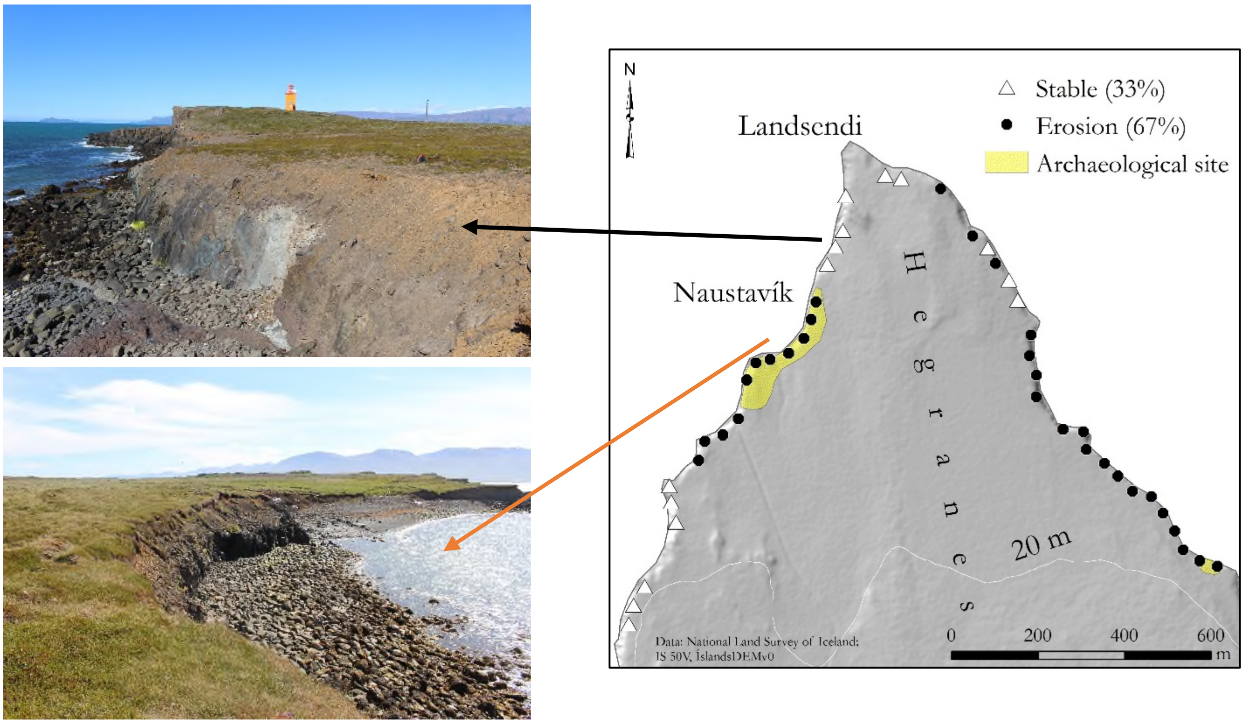


*Fig. 25. The map to the right shows the spatial distribution of erosion at study site 1 from 2003-2017. The upper left photo shows a stretch of a stable coastline (survey points 24-28). The lower left photo is from Naustavík (survey points 15-22), an area which has been actively eroding and has the highest erosion rates at study site 1.*

**Study site 2** stands out from the other two areas, because it was the only site where accretion was found. Accretion was measured at 14 of 40 survey points and erosion at the remaining 26 (Fig. 26). In the majority of cases, accretion was found at the base of vegetated bluffs (bluff toe) and in a few instances at the beach, where vegetation was present. Archaeological sites can be found on both sides of the Grafarós river mouth and erosion was present at both sites. The coast north of the river, is a bluff made up of weak materials and south of the river is a flat beach (10-40 m), which is in constant change due to the proximity to the river mouth. The third archaeological site, located at Skipagil, also shows visible signs of erosion, despite being fronted by a wide beach (just over 20 m).

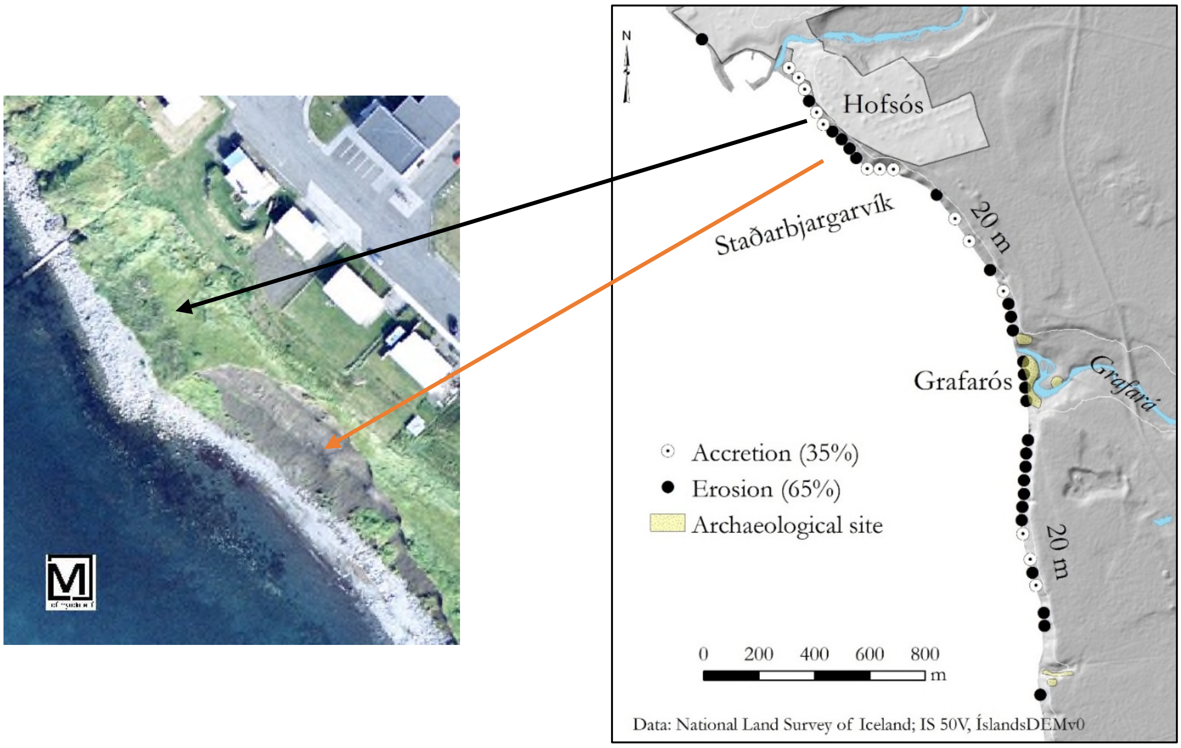


*Fig. 26. The map to the right shows the spatial distribution of erosion and accretion at study site 2 from 2003-2015/16. The photo to the left shows an example of an actively eroding bluff (orange arrow; survey points 108-111) and a stable bluff (black arrow: survey points 112-113).*

## 4.2 Shoreline changes and erosion rates

The results provide the mean shoreline change as well as the annual erosion rate and the annual median rate of change, for the study area as a whole, as well as for individual study sites (a table with the measurements for each survey point is in Appendix I). The mean shoreline change encompasses both accretion and erosion and is calculated for the time period, between the former and the current aerial photographs (Table 6). Mean shoreline change for the study area was -1.3 m and the mean erosion was -1.6 m. The annual rate of change is -0.10 m/a, and the annual erosion rate is -0.11 m/a. The mean shoreline erosion was highest at study site 3 (1999-2016), second highest at study site 2 (2003-2016) and lowest at study site 1 (2003-2016). The highest erosion measured in a single point (127) was found at study site 3, measuring -7.1 m and the annual rate for the same point is -0.42 m/a. The highest accretion in a single survey point (87) was found at study site 2, measuring +4.5 m and the annual rate for the same point is +0.37 m/a. The results are presented in Table 14.

*Table 14. Rate of shoreline change statistics for the whole study area and each study site, as well as the highest erosion/accretion rates, measured at a single survey point. Study site 2 is split up to show accretion and erosion. SD stands for Standard Deviation, m is for meters and m/a, for meters annually.*

| Area | Mean shoreline change / SD (m) | Mean annual rate of change / SD (m/a) | Median rate of change (m/a) | Highest erosion (m) and annual rate of erosion (m/a) (in single point) | Highest accretion (m) and annual rate of accretion (m/a) (in single point) |
|---|---|---|---|---|---|
| **Study area** | -1.30 / 1.63 | -0.10 / 0.10 | -0.09 | -7.1 / -0.42 | +4.50 / +0.37 |
| **Study area accretion** | 1.33 / 1.10 | 0.11 / 0.09 | 0.09 | not applicable | +4.50 / +0.37 |
| **Study area erosion** | -1.60 / 1.40 | -0.11 / 0.09 | -0.13 | -7.1/-0.42 | not applicable |
| **Study site 1** | -0.70 / 0.74 | -0.06 / 0.06 | -0.05 | -2.60 | not applicable |
| **Study site 2** | -0.72 / 1.96 | -0.06 / 0.16 | -0.02 | -4.60 / -0.38 | +4.50 / +0.37 |
| **Study site 2 accretion** | 1.33 / 1.10 | 0.11 / 0.09 | 0.09 | not applicable | +4.50 / +0.37 |
| **Study site 2 erosion** | -1.83 / 1.37 | -0.15 / 0.11 | -0.13 | -4.60 / -0.38 | not applicable |
| **Study site 3** | -2.26 / 1.46 | -0.13 / 0.09 | -0.12 | -7.1 / -0.42 | not applicable |

Table 15 shows the mean and median annual rate of change and shoreline erosion rates for hard, medium and weak rocks. The mean annual rate of change is highest for rocks of medium strength, measuring – 0.12 m/a. But all other values are highest for rocks of weak strength.

*Table 15. Rate of shoreline change statistics for hard, medium and weak rocks. Highest values are marked in bold. m stands for meters and m/a, for meters annually.*

| Geology | Mean annual rate of change (m/a) | Median annual rate of change (m/a) | Mean rate of shoreline erosion (m/a) | Median rate of shoreline erosion (m/a) |
|---|---|---|---|---|
| **Hard** | -0.05 / 0.01 | -0.03 | -0.07 / 0.01 | -0.03 |
| **Medium** | **-0.12 / 0.10** | -0.10 | -0.12 / 0.10 | -0.10 |
| **Weak** | -0.11 / 0.10 | **-0.11** | **-0.15 / 0.10** | **-0.15** |

The majority of shoreline change ranges from -2.5 - 0.5 m (Fig. 27). It should be noted that these measurements are subject to the shoreline position uncertainties (U) explained in chapter 3.5.3. The mean U for the study area is 1.01 m and the U for study sites 1, 2 and 3 are ± 0.77 m, ± 1.1 m and ± 0.95 m respectively.

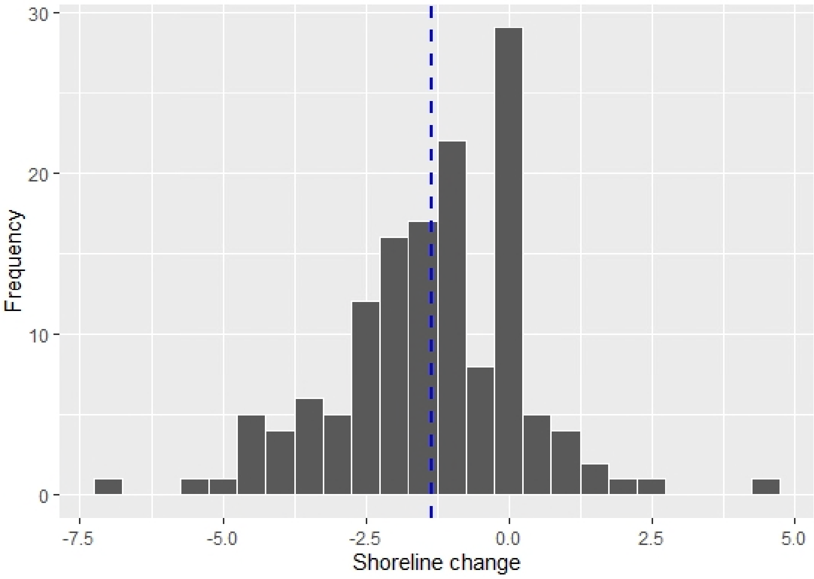


*Fig. 27. Frequency distribution of shoreline change rates for the whole study area. The blue line represents the mean shoreline change. Binwidth is set to 0.5 m. The uncertainty (U) for the study area is ± 1.01 m.*

The majority (76%) of annual rate of shoreline change ranges from -0.2 to 0 m/a (Fig. 28). The mean $U_R$ for the study area is 1.1 m/a and the $U_R$ for study sites 1, 2 and 3 are ± 0.81 m, ± 1.28 m and ± 0.97 m respectively.

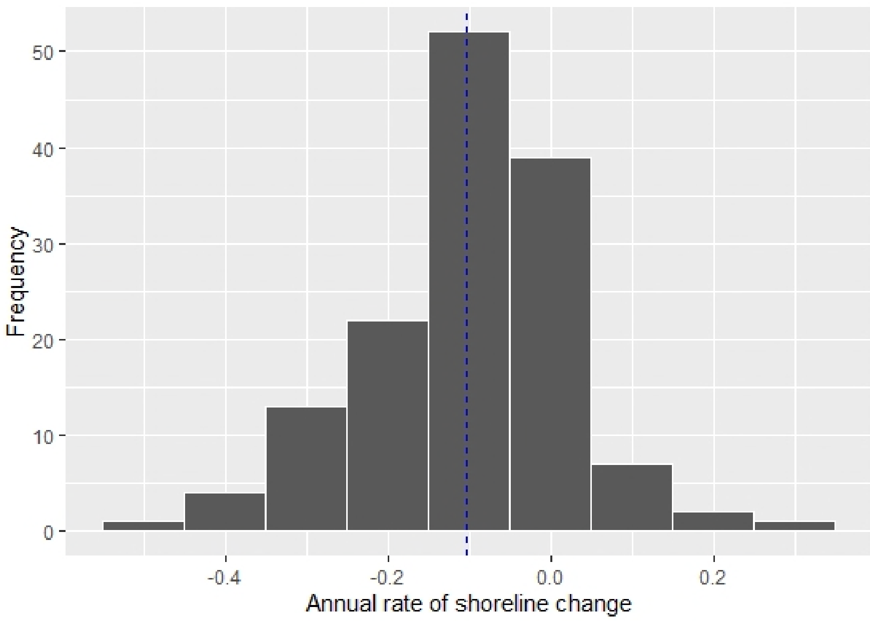


*Fig. 28. Frequency distribution of the annual rate of shoreline change for the study area. The blue line represents the mean shoreline change. Binwidth is 0.1 m. The uncertainty (U) for study site 1 is ± 0.81 m.*

**Study site 3**

Fig. 29 shows the shoreline change rates for study site 3. The highest erosion measured in a single survey point, was at the tip of the Músarnes promontory, -7,1 m (point 127), the corresponding annual rate for that point is -0,42 m/a. The tip of Músarnes promontory, as well as majority of the coastline at the study site, consists of loose sediments and is the area furthest north of all areas in this study.

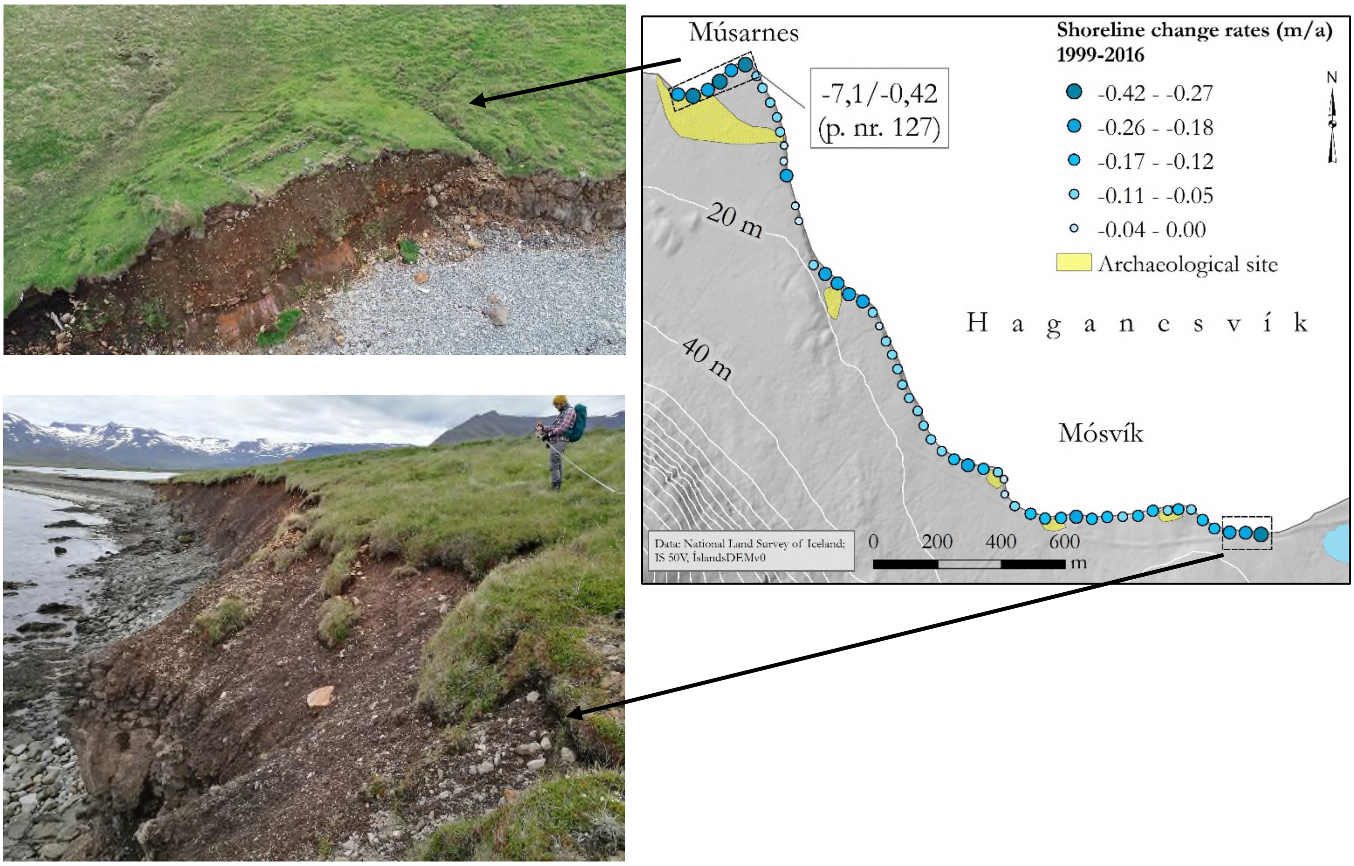


*Fig. 29. The map shows the spatial distribution of the mean annual rates for study site 3 (m/a). The highest erosion and highest mean annual erosion rates are displayed in the callout, with the number of the corresponding survey point in parenthesis. The photo above left is shows that the coast is made up of loose sediments and a crumbling rock (far right). Photo: Guðný Zoëga. The photo below left shows the coast below survey points 179 and 180, which is made up of loose sediments and has a sloping vegetation cover.*

The majority (70%) of shoreline erosion ranges from -3.5- 0 m (Fig. 30).

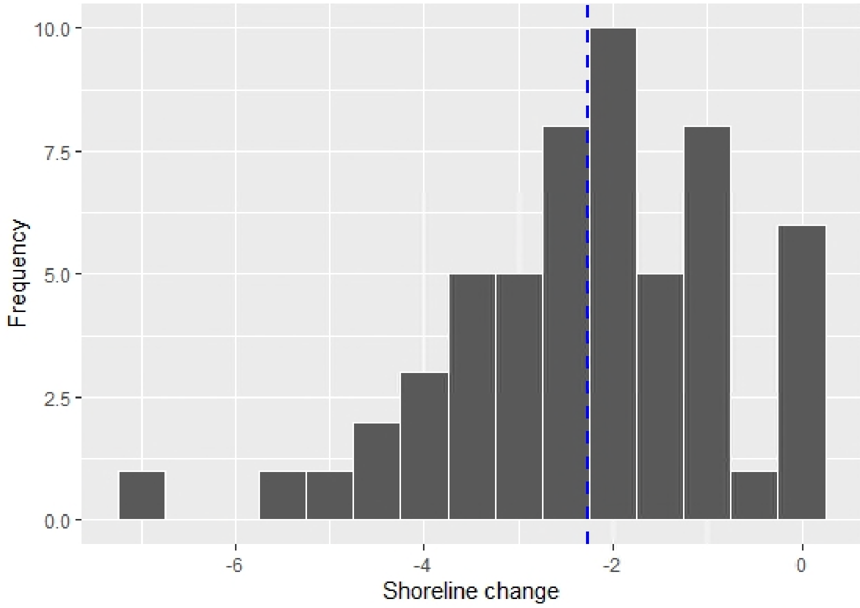


*Fig. 30. Frequency distribution of shoreline erosion for study site 3. The blue line represents the mean shoreline change. Binwidth is 0.5 m. The uncertainty (U) for study site 3 is ± 0.95 m.*

**Study site 2**

Fig. 31 shows the shoreline change rates (m/a) for study site 2. The highest erosion rate in a single survey point was found south of the mouth of Grafará river, in front of the ruins of the old trading place at Grafarós, -4.6 m, the corresponding annual rate for that point is -0,38 m/a. The erosion there was in the form of landward vegetation retreat. The trading place lies on a low hill fronted with a relatively flat and rather extensive (10-40 m) rocky beach. The survey point, with the highest accretion rate, +4,5 m, is located next to the river mouth of Hofsá, sheltered by the jetties at Hofsós harbour. Survey points measuring accretion were found scattered along the coastline at study site 2 and are all associated with high, seemingly stable, vegetated bluffs. The highest erosion rates, on the other hand, are associated with the southern half of the study area, which predominantly faces west.

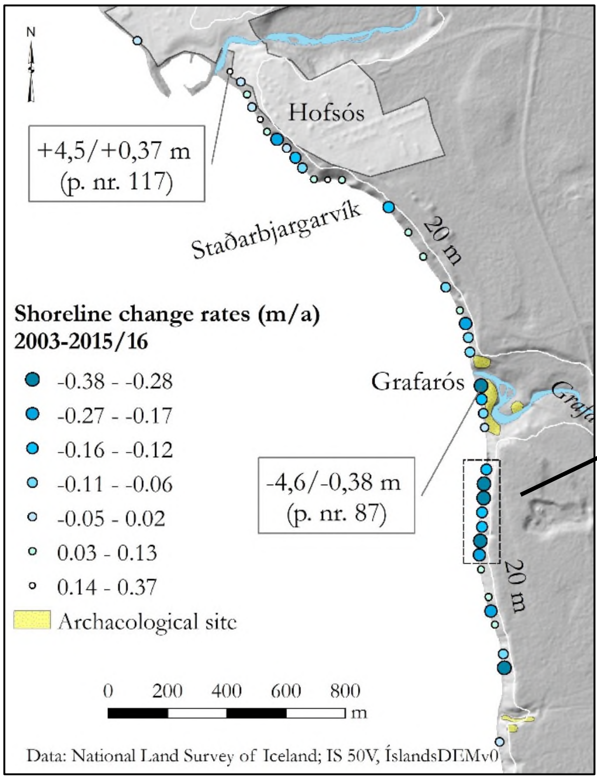


*Fig. 31. The map shows the spatial distribution of the mean annual rates of shoreline change (m/a) for study site 2. The highest erosion/accretion, mean annual erosion/accretion, measured at one survey point, are displayed in the callout with the number of the corresponding survey point in parenthesis. The photo on the right shows the trading site at Grafarós (below left) and the area with the highest erosion rates (above right). Photo: Guðný Zoëga.*

The majority of (73%) of shoreline change ranges from -2.6 to 1.4 m (Fig. 32).

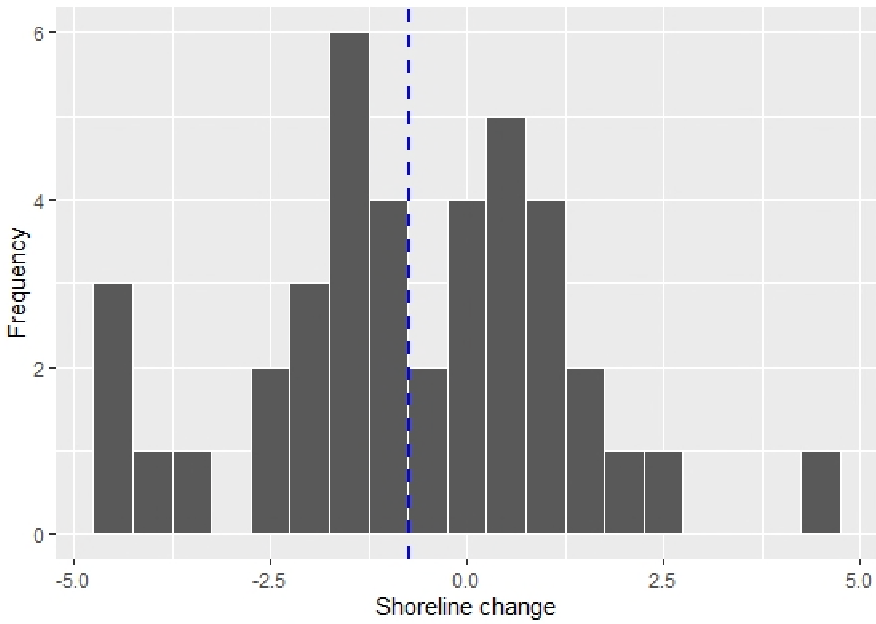


*Fig. 32. Frequency distribution of shoreline change for study site 2. The blue line represents the mean shoreline change. Binwidth is 0.5 m. The uncertainty (U) for study site 2 is ± 1.1 m.*

**Study site 1**

Fig. 33 shows shoreline change rates (m/a) for study site 1. The highest erosion measured in a single survey point was found at Naustavík measuring -2.57 m, the corresponding annual rate for that point is -0,20 m/a. The coastline there is relatively low and made up of glacial clay and loose sediments, topped with soil and an undercut vegetation cover (Fig. 33). Erosion was more widespread along the east coast of Hegranes, as mentioned earlier, but the erosion rates were higher along the west coast, which has longer stretches of coast made up of loose sediments. Most of the coastline at study site 1 is fronted with cliffs. The highest erosion rates were found where the coast is made up of weak materials, but erosion is also present at cliff tops, for example along the east coast of the peninsula. The stable stretches of coastlines are both associated with high and low cliffs.

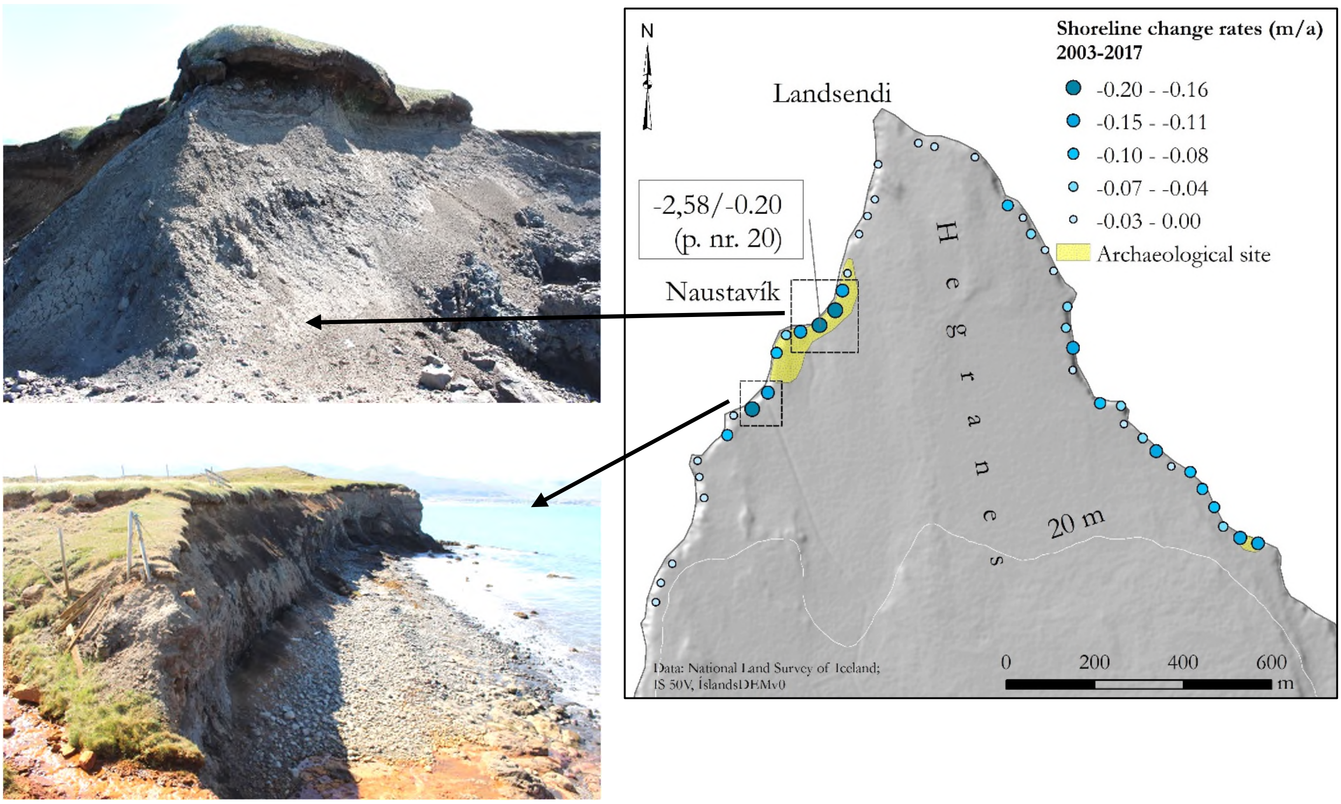


*Fig. 33. The map shows the spatial distribution of the mean annual rates of change (m/a) for study site 1. The highest erosion and mean erosion rates, measured at one survey point, are displayed in the callout with the number of the corresponding survey point in parenthesis. The black boxes demarcate the two areas with the most extensive erosion. The photo above left shows a part of the coastline which is made up of coastal clay topped with a sloping vegetation cover. The coastline on the photo below left, consists of a mixture of solid rock and low rocks with a thick layer of soil on top, with a sloping vegetation.*

Majority of the erosion values at study site 1 were in the range from 0- (-1) m. Three survey points had a shoreline change rate above -2 m (Fig. 34).

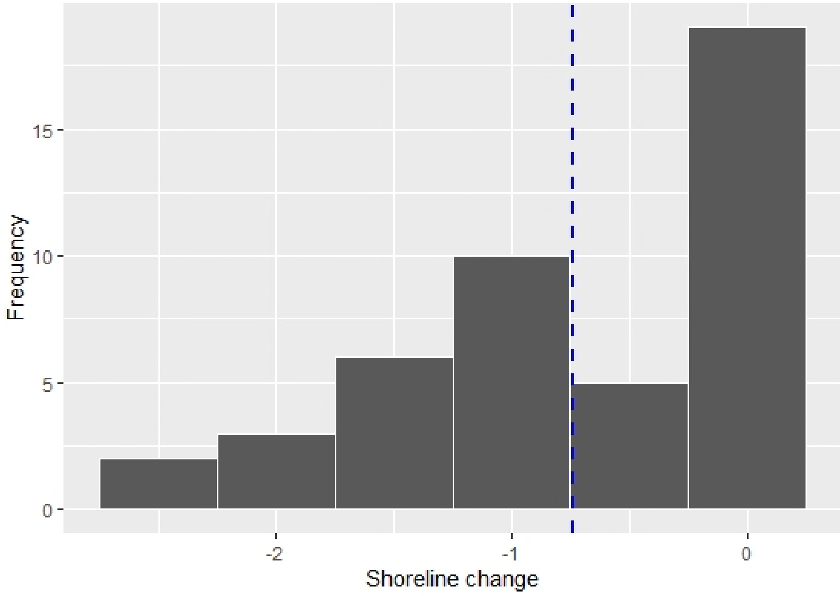


*Fig. 34. Frequency distribution of shoreline change rates at study site 1. The blue line represents the mean shoreline change. Binwidth is 0.5 m. The uncertainty (U) for study site 1 is ± 0.77 m.*

## 4.3 Shoreline change and ecological and environmental variables along the coast of Skagafjörður.

The linear regression model, Model 2, was the result of the Best Subset Selection process were *aspect* and *geology* were identified as the only variables that attributed significantly to the model (see chapter 3.6). Model 2 explains 23% of the variance in shoreline change and the variables *aspect* southwest and west and *geology* hard were statistically significant. The model summaries are presented in Table 16. The interpretation of Model 2 showed that for the reference levels (weak geology and northeast aspect) there was a mean shoreline change of -2.26 m (intercept). There was a significant positive effect of both southwest and west aspect, which means that, given the reference level, mean shoreline change (i.e. the intercept) would increase by 1.94 m for SW aspect and 0.83 m for W aspect. This means, that when everything else is constant, shoreline change for southwest aspect would change from -2.26 m to -0.32 m and from -2.26 m to -1.32 m for western aspect. There was also a significant positive effect of hard rocks (geology). Which means that when everything else is constant the shoreline change for hard rocks would change from -2.26 m to -1.15 m (Table 16).

*Table 16. Summary of model 2, with shoreline change as the dependent variable. The table shows the Multiple R2, Adjusted R2 and P, F and Degrees of Freedom (df), intercept and variables, along with the estimate, standard error, T-value and the P-value. Significant variables are written in italics.*

| **MODEL 2** | **Multiple $R^2$** | **Adjusted $R^2$** | **P value** | **F (df)** |
|---|---|---|---|---|
| | 0.28 | 0,23 | $p < .001$ | 5.68 (131) |
| **Variable** | **Estimate** | **Standard error** | **T value** | **P value** |
| ***(Intercept)*** | *-2.26* | *0.27* | *-8.27* | *< .001* |
| Aspect: east | 0.21 | 0.41 | 0.52 | .60 |
| Aspect: north | -0.15 | 0.38 | -0.41 | .69 |
| Aspect: northwest | -0.15 | 0.56 | -0.28 | .78 |
| Aspect: south | 1.89 | 1.46 | 1.30 | .20 |
| Aspect: southeast | 0.49 | 1.04 | 0.47 | .64 |
| *Aspect: southwest* | *1.94* | *0.41* | *4.71* | *< .001* |
| *Aspect: west* | *0.83* | *0.35* | *2.37* | *.02* |
| *Geology: hard* | *1.11* | *0.26* | *4.34* | *< .001* |
| Geology: medium | 0.07 | 0.54 | 0.13 | .89 |

Violin plots were produced to visualise the distribution of s*horeline change* for the categories of *aspect* and *geology*. Southwest, west and northeast were all associated with both erosion and accretion. Other cardinal directions were only associated with erosion. South (1) and southeast (2) were almost non-existent in the sample (Fig. 35).

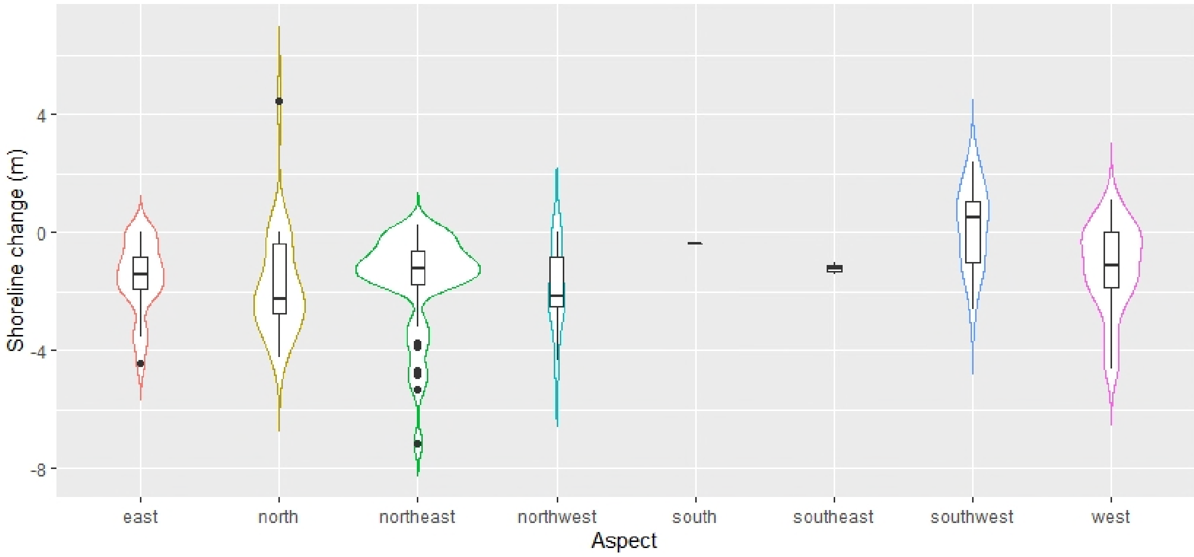


*Fig. 35. The violin plot depicts the distribution of shoreline change in relation to coastal aspect. The box represents the interquartile, range (50%), the black horizontal line is the median and the thin black line (whiskers) is the 95% confidence interval. The width of the violin represents frequency and is scaled proportional to N. The black dots are the outliers in the dataset.*

Fig. 36 shows that all categories of geology were highly concentrated around the median, which is just below zero on hard rocks. The greatest variance of shoreline change was on weak rocks (which was also the largest category). Highest erosion rates occur on weak rocks, second lowest on medium hard rocks and lowest on hard rocks.

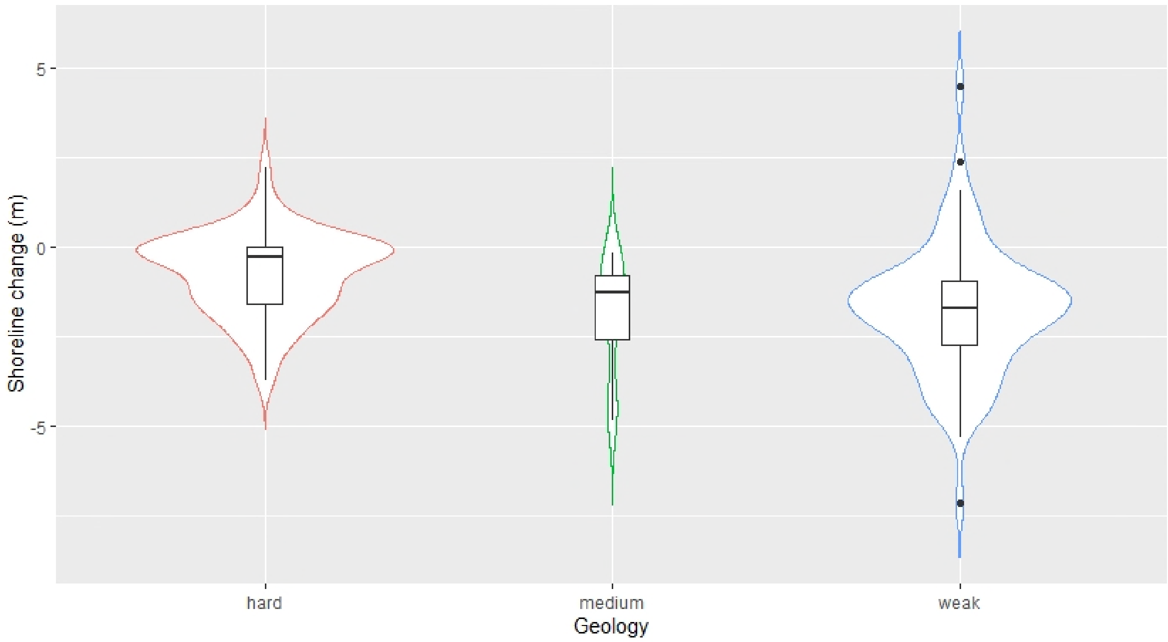


*Fig. 36. The violin plot depicts the distribution of shoreline change in relation to the geology of the coast. The box represents the interquartile, range (50%), the black horizontal line is the median and the thin black line (whiskers) is the 95% confidence interval. The width of the violin represents frequency and is scaled proportional to N. The black dots are the outliers in the dataset.*

# 5. Discussion

This study has focused on shoreline changes and related ecological and environmental factors along the coast of Skagafjörður, Northern Iceland. The objective of this study was not to identify the most “successful” model for the evolution of coastal erosion, but rather to explore the degree of relationship between shoreline change and selected - relatively easily attainable – variables. Using easily attainable variables, will facilitate the replication of the study, elsewhere in Iceland, since data is often lacking. A similar study has to the best of my knowledge not been conducted in Iceland before. In the following chapter, the results from the present study will be discussed in light of findings of previous studies, followed by a re-view of it’s limitations and finally recommendations for further work.

## 5.1 Spatial extent of coastal erosion in Skagafjörður, Northern Iceland.

The results of the present study show that erosion was present at all three study sites, but to a varying degree (Fig. 23). For the whole study area, 24% of the survey points were either stable or showed accretion, while 76% showed signs of erosion. Accretion was in the form of advance of the vegetation, usually at the bottom of high (15-20 m) vegetated bluffs.

Few studies on coastal cliff erosion have reported on the extent of coastal erosion, showing varying results. A National Coastal Change Assessment for Scotland, which is predominantly rocky, like the coast of Iceland, concluded that 11% of the Scottish coast had advanced, 12% had retreated and 77% had remained approximately stable (Rennie et al., 2017). Irrgang et al. (2018) found that 13% of Canada’s Yukon coast (210 km) was either stable or accumulating while 87% of the coastline was eroding. Although, comparisons among different coasts are challenging, due to factors like differences in wave activity, geology and morphology of coasts as well as the spatial scales of the studies (local, regional, national). The high degree of shoreline erosion, found in this study, can at least partly, be explained by the high proportion of coastline being made up of loose sediments (52%). In comparison, the percentage of coastline made up of “soft materials” in the Scotland study was 19% (Rennie et al., 2017).

The extent of erosion varied between the three individual study sites. The most extensive erosion was found at study site 3, followed by study site 1, and the least extensive erosion was found at study site 2. The difference can mainly be attributed to two factors, geology and aspect or exposure to wave activity. The coastline at study site 3 is largely made up of loose sediments, making it more susceptible to erosion, while the coastline at study site 2 is a mixture of bluffs (weak) and low cliffs and the coastline at study site 1 is predominantly cliffed. Waves and tides provide the energy for essentially all changes in coastal geomorphology (Masselink, 2017; Conley, 2014). Waves are produced by wind action and their size is controlled by wind strength, wind speed, wind duration and fetch (Sunamura, 1992). Study site 3 is more exposed to wave activity than the other two sites for several reasons. The study site is located at the mouth of the fjord, facing the open sea (Fig. 13). Due to longer fetch and prevailing north-easterly winds, known to be strong at the mouth of the fjord (Auðunsdóttir, 1998), the site is more exposed to higher waves than the other two study sites, located further in the fjord. The coastline at study site 3 is also generally lower than the coastline at the other two study site making it more exposed to waves.

In addition to variation in erosion extent among study sites, variation was also found within each of the three study sites. The coast along study site 3 is more or less, eroding. The only stretch of stable coastline is its east facing section, presumably because it is armoured by a cliff from top to bottom. Large sections of the coast at study site 1 are also eroding. Stable areas are mostly located at the tip and on the west coast of the Hegranes peninsula. Stability of the coastline at the tip of Hegranes can be explained by it being comprised of bare rock (categorized as hard) with no or little soil or vegetation cover. The area between Survey points (1-9) (Fig. 7), on the cliff top of the western shore, is also stable, seemingly due to being protected by high (10-20 m) cliffs, making the area less likely to be affected by waves (even storm waves). This point will be further discussed in chapter 5.2. Study site 2 was the only site were large parts (35%) were dominated by accretion (i.e. the encroachment of vegetation). The coast below the town of Hofsós (northern part of study site 2) is, for the most part comprised of relatively high, vegetated bluffs (15-20 m), made of up of loose sediments from the glacial period (Pétursson, 2006). The vegetation here reaches down to beach level, and accretion was measured at several (8) of the survey points in the area. The bluffs are seemingly stable where they are vegetated, but the vegetation cover has a wide (115 m) rupture (Fig. 26) most likely caused by storm waves (Pétursson, 2006). There is however little change in the aspect of the coast along this stretch and the vegetated and non-vegetated (ruptured) areas are probably equally sheltered from or exposed to waves. It seems most plausible that the vegetation was originally ruptured by waves as suggested by Pétursson (2006). The reason why the vegetation has not managed to re-establish itself, is likely a combination of continuing wave erosion at the bluff toe and the steepness of the bluff slope. This, though, can not be verified with the available data. Vegetation is known to aid in reducing erosion by dissipating wave energy or binding the soil in the littoral zone (Morton, 2003). It seems plausible that the presence of vegetation might aid in reducing erosion in this area. This notion is supported by the presence of erosive areas to the south, which all occur on non-vegetated bluffs (Fig. 31).

## 5.2 Shoreline changes and contributing factors

The highest *mean* annual erosion rates, at all study sites, where found where the coastline was categorized as being "weak" and conversely the lowest rates were found where the coastline was categorized as being "hard". Similar to comparisons of the extent of coastal erosion, the comparison of change and erosion rates among studies is challenged by differences in coastal settings and different methodologies.

In the current study, the *median* erosion rates for hard (-0.03 m/a) and medium hard cliffs (0.1 m/a), are in line with results from Prémaillon et al. (2018), who calculated *median* erosion rates (on a global scale) for hard rocks to be 2.9 cm $yr^{-1}$ and 10 cm $yr^{-1}$ for medium hard rocks (the sample for medium rocks was small and the authors emphasized that they should be viewed with "care"). However, the erosion rates on weak cliffs (-0.07 m/a) in the present study are considerably lower, than those reported by Prémaillon et al. (2018), where weak cliffs were shown to erode 23 cm $yr^{-1}$. The *mean* erosion rates for hard rocks (-0.07 m/a), are also similar to those reported from the rocky coast of Japan by Sunamura (1992), who calculated a mean annual rate of <0.001-0.1 m $yr^{-1}$ for shale. Sunamura's (1992) mean rates of glacially deposited materials (1-10 m $yr^{-1)}$, is however, considerably higher than the mean erosion rates for weak rocks (-0.15 m/a) found in the present study. Lower erosion rates on weak rocks, in the present study, can presumably, be explained by lower wave energy along the coast of Skagafjörður, compared to the coast of Japan, reported in the study of Sunamura (1992). As mentioned in chapter 5.1 the spatial extent of erosion found in the present study is only slightly lower than the extent of erosion reported by Irrgang et al. (2018) for the Yukon coast. But the *mean* rates of erosion for the arctic coast as reported by Lantuit et al. (2012) (-1.12 m/a) and Irrgang et al. (2018) (-0.7 ± 0.2 m/a), are much higher, irrespective of rock type, than reported in the present study. The difference can most likely be explained by the high extent of permafrost along arctic coasts which, upon thawing, can be affected by high erosion rates (Lantuit et al., 2012).

The most extensive *mean* shoreline change was found at site 3, second highest at study site 1 and the least extensive change at study site 2. This is concurrent with the extent of erosion, discussed in chapter 5.1, and the reasons are presumably the same. Differences in geology, the exposure to waves and prevailing wind directions, cause differences in shoreline change rates.

Study site 2, had the highest *mean* erosion rates, followed by study site 3. Study site 1 had the lowest *mean* erosion rates (Table 14). As expected, the highest *mean* annual erosion rates, at all study sites, where found where the coastline was categorized as being "weak" (Fig. 29, 31, 33). There were some internal differences of erosion rates within the individual study sites. While the extent of erosion at study site 1 was more widespread along the east coast of Hegranes peninsula (cf. chapter 5.2), the *mean* erosion rates were higher on the west coast, where there are longer stretches of "weak" coast (Fig. 33). At study site 1 *mean* annual rates of erosion are higher in the southern than the northern part. This is presumably due to the northern part being more sheltered from high energy waves (Fig. 31). At study site 3, the *mean* annual erosion rates are higher on the part of the coast facing northwest, north and northeast, while the east facing coastline generally has lower rates (Fig. 29). This is most likely due to a combination of factors; i.e. to the exposure of waves and prevailing winds and the presence of coastal cliffs (hard) as mentioned in chapter 5.1.

The best linear regression model (model 2) included two variables only, *aspect* (southwest, west) and *geology* (hard) and explained 23% of the variance in shoreline change. Fig. 36 depicts the distribution of shoreline change in relation to the hardness of the coastal materials and shows that shoreline change is slower on hard rocks than on weak rocks. These results are in line with the literature (Bird, 1985; Prémaillon et al., 2018; Sunamura, 1992; Lim, 2010). It is, therefore, not surprising that geology (strength of the rock) is a significant variable in the model. Rock strength is considered one of the most influential factors for coastal erosion (Prémaillon et al., 2018). Based on the importance of the resistance of rock to coastal erosion, one might have expected *geology* to have a greater explanatory effect in the model. This however was not the case. A number of reasons might have affected the explanatory effect of the variable. One reason might be related to the simplified method of testing rock strength in the field. The variable was only based on the strength of the rock and not the structure. Another reason, might be the low number of categories (3) used for evaluating rock strength. Possible improvements, which should not be too time consuming, might include incorporating a method accounting for structure as well as rock strength, like the Geological Strength Index by Hoek and Brown (1998). Another improvement might be to use the original seven categories of strength estimation, proposed by Hoek and Brown (1997) instead of the three aggregated categories recommended by Prémaillon et al. (2018).

Fig. 35 depicts the distribution of shoreline change in relation to coastal aspect. It shows that southwest is predominantly associated with accretion and the only cardinal direction with a median above 0 (i.e. accretion). Accretion was also found on west facing coasts and at one survey point facing north. These results are underlined in Fig. 26 which shows the spread of erosion and accretion at study site 2. The importance of aspect is presumably related to wave exposure and perhaps wind direction to some degree. The role of aspect and exposure in relation to shoreline changes was discussed in chapters 5.1. McLaughlin and Cooper (2010) claim that aspect (orientation) will only have effect on a large scale (national), which is in contrast with the results from the current study which showed aspect to be significant on a regional scale. Bryan et al. (2001), conversely, found that aspect was not a contributing factor in a study on coastal vulnerability to erosion.

The role of vegetation as a possible factor in reducing the effect of coastal erosion has been discussed in chapter 5.1. Vegetation was a statistically significant variable in the original regression model (model 0, introduced in chapter 3.6) but was later discarded due to multicollinearity with geology. Another possible solution, to remove or reduce multicollinearity would have been to keep the variable in the model, by combining the collinear variables into a single predictor (James et al., 2013). The degree of association between shoreline change and vegetation was not explored further in the present study but the preliminary results were promising and need further investigation.

It is interesting that none of the remaining variables, *elevation*, *slope* and *presence of a beach*, contributed significantly to the model. In fact, the model including all variables (except vegetation), explained only 22% of the variance in shoreline change (see summary of model 1 in appendix III). The variable *elevation* is represents the elevation of land, irrespective of cliff height. Large sections of the high bluffs at study site 2 were affected by erosion at the bluff toe but not at the top due to the height and slope of the bluffs. This meant that if the height of the top had been chosen, large sections of eroding coasts would have been categorized as stable, when they were in fact eroding. *Elevation* was, however, not a significant variable in the model which is in contrast to the findings of Bryan et al. (2001) who found elevation to be the most significant factor (explaining 47.7% of variance in coastal vulnerability) in relation to coastal vulnerability to erosion and inundation. These contradictory results are presumably related to the difference in variables used to measure the outcome, that is, coastal vulnerability vs. shoreline change. In chapter 5.2 it was proposed that the stability of the cliffs along parts (survey points 1-9) of the western coast of Hegranes might be due to the height of the cliffs (above 15 m). The results are partly in line with the findings of Dornbusch and Robinson (2005) who only found a weak correlation for cliff height for coasts of mixed geology. However, they did find higher correlation (-0.40) for stretches of coasts of similar geology (and/or aspect). Contrastingly, cliff height was found to noticeably improve the outcome of a model predicting cliff retreat on cliffed coasts (Hapke and Plant, 2010). Therefore, adding height as a variable might improve the explanatory effect of the model.

*Slope* was not a significant variable in the regression model. Similar results were reported by Bryan et al. (2001) who concluded that slope was not associated with vulnerability to coastal erosion and sea level rise. This differs from the results of Hapke and Plant (2010) who found slope to be one important factor in predicting coastal retreat on cliffed coasts. Bryan et al. (2001) suggest that the lacking significance of slope, might be due to the low variance in coastal slopes in their study area. However, in the present study, the coastal slope varies considerably and can therefore not explain the lack of significance of the variable. The method used in the present study is similar to the method of Bryan et al. (2001), except they did not calculate mean values. Hapke and Plant (2010), who found slope to be an important factor, calculated a straight-line slope between the cliff top edge and base. The conflicting results, suggest that the choice of methods might, at least partly, be the reason for the different outcomes of the variable. The method of Hapke and Plant (2010) is, however, not achievable for the present study, because the bottom of the cliffs/bluffs were, in many instances, not visible on the aerial photographs.

The *presence of beach* did not enter as a significant variable in the model. Studies have shown that the presence of a beach can protect against wave-driven erosion, but this effect is controlled by the width of the beach (Lee, 2008; Everts, 1991; Dornbusch and Robinson, 2008). Everts (1991) found that a marked decrease in erosion rates happened when the beach width exceeded 20 m. The beaches fronting the coast in the study area are generally narrow (≤ 20 m) and only surpass 20 m in few places at study site 2. They are also, relatively flat and the beach width therefore changes with tidal movements, resulting in wider beaches at low tides and narrower beaches at high tide. That said, it does seem that the presence of relatively wide beaches might reduce erosion at study site 2. This will be further discussed in chapter 5.3.

### 5.2.1 Uncertainty in calculations of shoreline positions

The shoreline change calculations in the present study are subject to errors that are introduced by the data sources used and the measurements methods. As Moore (2000) states, the calculations of shoreline changes can only be as accurate as the data from which they are derived. The same goes for the methods used for calculation. Several steps were taken in this study to minimize the errors as much as possible (see chapter 2.3.2). The uncertainty related to the data sources are related to the errors resulting from georeferencing and the ground resolution of aerial photographs. Another source of uncertainty lies in the digitization process, where several challenges were met, e.g. blurry cliff/bluff edges, shadows and unclear boundaries between non-vegetated bluffs and sandy beaches. Moore (2000) emphasizes the importance of performing an overall error assessment and quantifying the total error. Both the average U and the average $U_R$ for the whole study area are 1.1 m (see chapter 3.5.2 for calculations). The error related to the digitizing ($E_d$) was calculated so it would represent the maximum error and therefore it can be assumed that 1.1 m is the maximum uncertainty. An uncertainty of 1.1m is still high, especially, where shoreline change has been slow. Visual signs of erosion were registered during field work, so that measurements showing erosion, could be verified after the calculation process. All 107 points measuring erosion, do in fact show erosion, but the remaining uncertainty lies in the degree of erosion or shoreline change. Despite these measures, uncertainty remains in the shoreline change measurements and the results need to be reviewed with that in mind.

The variables represent the current coastline and it was therefore assumed that the former coastline looked approximately the same. This introduces an uncertainty in the calculation of the model, which could be affected, if the coastline has changed much. Dornbusch et al. (2005) state that the aspect can diverge significantly between the old and the present cliff top. This effect would presumably be greatest along coasts with considerable erosion, which was not the general case for the present study. The effect on the variables, *geology* and *elevation* is likely to be negligible since there have not been any major changes in the coastal landscape. But coastal *slope* and *aspect* might be more affected, due to changes in the cliff profile, which could possibly affect the outcome of the variable. However, mean and average values were calculated for *slope*, *elevation* and *aspect* (ch. 3.5.2) which should reduce the effect of extreme values and thus minimize the effect on the variable.

## 5.3 Threats to coastal archaeology

The discussion has, so far, focused on the interaction between coastal processes, coastal settings and the resulting shoreline changes. The present study has shown that erosion is widespread in the study area and that the extent of erosion and erosional rates are controlled by a combination of factors. Previous studies have shown that erosion has already affected coastal archaeology within the perimeters of the study area (Zoëga, 2013a; 2013b; 2017). The following chapter will assess the risks posed to archaeological sites in the study area in light of the findings presented in the chapters above.

Ten archaeological sites (some with several archaeological remains) are located within the study area and almost all of them are situated on eroding coastlines. The largest number of archaeological remains was found at study site 3 (Fig. 29). Many have already been affected by erosion and a few are currently eroding away (Zoëga. 2013b). Fig. 29 depicts the variation in shoreline change rates within the study site, showing that the archaeological site located west of the Músarnes promontory, is exposed to the highest rates, 27-42 cm per year. Geology (strength of coastal materials), exposure to high waves, prevailing winds and the height of the coast (top) seem to be the dominant factors in regard to coastal erosion at study site 3, as has been discussed in chapters 5.1 and 5.2. If these factors remain constant and the shoreline change rates stay the same for the next ten years, the coast will retreat about 2,7-4,2 m, resulting in further damage of the remains already affected by erosion and possibly causing damage to currently unaffected remains. This holds, true for all the archaeological remains located within study area 3.

The remains of the historic trading place at Grafarós has experienced the highest erosion rates of the archaeological sites at study site 2. The trading site lies on a low hill just south of where the river Grafará enters the sea. The hill is fronted with a relatively flat but rather extensive (10-40 m) rocky beach, which narrows (10-15 m) toward the south. Erosion, affects the coastline there in two ways. In front of the site, the erosion is in the form of landward retreat of the vegetation line. However, due to the width of the beach in front of the site, waves might only reach the coastline during storms. Erosion is also taking place at the southwestern part of the site, where waves are cutting into the hill, which will affect the remains at the top if erosion continues. The width of the beach fronting the site is presumably the dominant factor controlling the extent of erosion here. The remains, closest to the coastline, are at beach level and a narrower beach would mean easier access for waves. Waves reach, and erode, the coastline at the southernmost side of the hill, where the beach is narrower. If the erosion rates stay the same for the next 10 years, the coast will have retreated 2,8-3,8 m in front of the trading site, and 1,2-1,6 m at the south side. The proximity to the river and the river mouth poses a certain uncertainty regarding future erosion. Aerial photographs show that the area surrounding the river mouth has been subject to changes. If these changes lead to a narrower beach in front of the archaeological site, it might consequently lead to higher erosion rates. And conversely, if the beach becomes wider, erosion might slow down. Changes of the Grafará river's course or sediment load may in the future affect rate of erosion and retreat of the beach in front of the site. This, however, was not assessed in the present study. This interpretation is supported by Everts (1991) and Dornbusch et al. (2008) who found that erosion decreases as a beach becomes wider. Fig. 31 shows the shoreline change rates for study site 2. The archaeological remains north of the river have not been affected by erosion but erosion has occurred at the bottom of the bluff on which they are located. This poses a future threat to the remains, if erosion continues. The remains at Skipagil have, to some extent been affected by erosion (Zoëga, 2013a) but it seems that it only happens during storms, which may be explained by the protective effect of the beach in front of the site.

There are two archaeological sites located on the Hegranes peninsula, one on the western coast, the other on the eastern coast. The prevailing wind directions on Hegranes are from the south (offshore) and north (onshore), so it can be assumed that the strongest waves would come from the north. The archaeological site on the eastern coast lies on top of cliffs classified as being hard and have not yet been affected by erosion (Zoëga, 2017). The erosion rates at the site are relatively low or 4-7 cm per year. The archaeological site on the western coast is, however, located on a relatively low coast, made up of loose sediments and erosion has already affected some of the remains (Fig. 25) (Zoëga, 2017). The site faces north and northwest and is exposed to northerly winds. Erosion rates are 20 cm per year, the highest rates found at study site 1. Higher erosion rates can be explained by the geology and height of the coast and exposure to waves. If erosion rates remain the same for the next ten years, we could expect a retreat of 40-70 cm at the eastern archaeological site and 1.6-2.0 m at the western site. This will inflict further damage on archaeological remains at the western coast. But remains on the eastern coast are less likely to be affected.

The present study only focused on the effect of coastal erosion on archaeological sites within a designated study area. Although, the results only represent relatively few archaeological sites, the results from the study show that certain factors either increase or decrease the likelihood of erosion. These findings can be used to evaluate other sites that are potentially at risk. Shoreline change is controlled by a combination of factors that interact either by augmenting or diminishing the effect they have on each other. It is therefore important when evaluating the risk of erosion, that these factors are viewed together. The geology of the coast (strength of coastal materials) is an important factor since weaker coastal materials are more erosive than hard coastal materials (Fig. 36). However, coasts that are sheltered from high wave energy and/or strong winds, even those made up of weak materials, are not necessarily erosive. Thus, the role of geology is diminished in relation to aspect. Aspect or exposure to high wave energy and strong winds is also an important factor which essentially affects all the other factors explored here. Beach width becomes an important factor, when the beach is wide enough, to prevent waves from reaching the coastline. The presence of vegetation might aid in reducing erosion where wave energy is low. The results also imply that height might matter on (hard) cliffs, that are high enough to prevent the waves from reaching the cliff top.

## 5.4 Future recommendations

- Limited research exists on coastal erosion in Iceland and comparative studies from other parts of the country would be imperative for comparison and for improved knowledge of the subject.
- Recent studies have demonstrated increase in both the extent of shoreline erosion and shoreline change rates (Rennie et al., 2017; Irrgang et al., 2018). In this study, shoreline change was calculated for a relatively short period (17 year at most) and only between two time periods. By adding one or more time periods (older aerial photographs) it would be possible to study the temporal variation in shoreline extent and the shoreline change rates.
- The aim of this study was to explore the relationship between shoreline change and few relatively easily attainable variables. Improving the current variables, as discussed in chapter five and/or exploring new variables might improve the model and shed a further light on erosion processes.
    - It would be an improvement to the study to look at sites where data on wave height and strength are available.
    - As the results of the present study indicate the importance of cliff height in relation to coastal changes, adding cliff height as a variable might improve the variance explained by the model.
    - Frost day frequency and rainfall could be included in the model as they have been found to show positive trend with erosion rate for weak rocks (Prémaillon et al. 2018). This requires a study area within the proximity of multiple weather stations.
- Coastal erosion is a current threat to coastal archaeology in Iceland. Studies suggest that this might vary between regions (Edvardsson, 2017a; 2017b). Further studies would be an important addition to the current state of knowledge. This would allow for more structured research, and/or protection efforts of coastal archaeological sites.
- Archaeological surveys for parts of Scotland have shown that coastal archaeological sites are often located on relatively low-lying coasts made of soft materials, making them more vulnerable to erosion (Dawson, 2013). Due to similarities in coastal settings,

an equivalent study on coastal archaeology in Iceland, would make for an interesting comparison.

# 6. Conclusions

The findings of the present study show that erosion is, to a varying degree, widespread along the coast of the whole study area, as well as, within the individual study sites. The widespread extent of shoreline erosion can mainly be attributed to high proportions of coastline being made up of relatively weak coastal materials. The most extensive erosion was found along coasts which were made up of weak materials and exposed to relatively high wave energy and to some degree, prevailing wind directions. Furthermore, shoreline change rates were found to be higher on coasts which are categorized as weak than on coasts categorized as hard. Erosion rates on cliffs categorized as "hard" and "medium hard", reported here, are in line with results from a global study on retreat rates. But retreat rates on "weak" cliffs were found to be considerably lower.

The linear regression model showed a significant association between shoreline change, coastal *aspect* and coastal *geology*, but significant relationships were not found between shoreline change and coastal *slope*, coastal *elevation* and the *presence of beach*. Cliff height and beach width were found to aid in the reduction of erosion, in combination with other factors. The results also showed that the presence of vegetation in the littoral zone might aid in the reduction of erosion, but this factor needs to be explored further. Shoreline changes are therefore the results of combination of factors where the strength of rock and exposure to waves are presumably the largest contributors.

Most of the archaeological sites in the study area are located along eroding coastlines and many of the remains have already been affected by coastal retreat. Based on the erosion rates demonstrated by the present study, even more archaeological sites will be affected by erosion in the near future.

The focus of this study has been on the current status of shoreline changes. Recent studies from Canada and Scotland indicate that rates of erosion have been accelerating since the 1960's and 70's and erosion rates are expected to rise even further during this century due to climate changes. Increase in sea-level and more frequent storm surges will presumably lead to more extensive erosion and higher erosion rates, which will pose an even larger threat to coastal archaeology. Identifying and evaluating the aforementioned factors in areas with coastal archaeological sites can be the initial step in assessing the risk posed to archaeological sites, as well as, to determine future research areas and/or areas for conservation or protection. These findings may also be of use in the planning of coastal areas in general.

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# Appendix

Appendix I: A list of all survey points

Appendix II: Summary: model 0

Appendix III: Summary: Model 1

Appendix IV: Correlation table

**Appendix I:** A list of all survey points

| Study site | Survey point | X | Y | Shoreline change (m) | EPR (m/a) | $U_R$ (m) | Slope | Elevation | Aspect | Geology | Vegetation | Beach |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site1 | 1 | 474616 | 585000 | 0.00 | 0.0 | 0.81 | 25.75 | 18.67 | west | hard | rock | yes |
| site1 | 2 | 474627 | 585044 | 0.00 | 0.0 | 0.81 | 19.49 | 19.84 | west | hard | rock | yes |
| site1 | 3 | 474653 | 585087 | 0.00 | 0.0 | 0.81 | 9.39 | 22.35 | west | hard | rock | yes |
| site1 | 7 | 474725 | 585236 | 0.00 | 0.0 | 0.81 | 18.71 | 16.59 | west | hard | rock | yes |
| site1 | 8 | 474714 | 585283 | 0.00 | 0.0 | 0.81 | 35.25 | 12.02 | southwest | hard | rock | yes |
| site1 | 9 | 474710 | 585320 | 0.00 | 0.0 | 0.81 | 7.59 | 13.75 | north | hard | rock | no |
| site1 | 11 | 474778 | 585378 | -1.10 | -0.1 | 0.81 | 11.61 | 12.87 | northwest | hard | rock | yes |
| site1 | 12 | 474792 | 585422 | -0.15 | 0.0 | 0.81 | 7.29 | 11.00 | north | hard | rock | yes |
| site1 | 13 | 474834 | 585437 | -2.03 | -0.2 | 0.81 | 9.05 | 8.99 | northwest | medium | rock | yes |
| site1 | 14 | 474869 | 585474 | -1.45 | -0.1 | 0.81 | 14.21 | 7.09 | west | medium | rock | yes |
| site1 | 16 | 474889 | 585564 | -1.10 | -0.1 | 0.81 | 6.76 | 8.95 | west | medium | rock | no |
| site1 | 17 | 474910 | 585604 | -0.88 | -0.1 | 0.81 | 15.17 | 6.12 | west | weak | grasslands | yes |
| site1 | 18 | 474943 | 585611 | -1.84 | -0.1 | 0.81 | 13.23 | 4.45 | north | weak | grasslands | yes |
| site1 | 19 | 474986 | 585626 | -2.26 | -0.2 | 0.81 | 9.46 | 4.66 | northwest | weak | grasslands | yes |
| site1 | 20 | 475021 | 585660 | -2.58 | -0.2 | 0.81 | 9.57 | 6.06 | northwest | hard | heathlands | yes |
| site1 | 21 | 475038 | 585704 | -1.76 | -0.1 | 0.81 | 15.39 | 5.56 | west | hard | heathlands | yes |
| site1 | 22 | 475049 | 585744 | -0.39 | 0.0 | 0.81 | 10.98 | 7.05 | west | medium | heathlands | yes |
| site1 | 24 | 475075 | 585832 | 0.00 | 0.0 | 0.81 | 23.67 | 4.89 | west | hard | rock | yes |
| site1 | 25 | 475094 | 585873 | 0.00 | 0.0 | 0.81 | 13.51 | 5.42 | northwest | hard | rock | no |
| site1 | 26 | 475111 | 585910 | 0.00 | 0.0 | 0.81 | 17.83 | 6.67 | west | weak | heathlands | yes |
| site1 | 28 | 475118 | 585990 | 0.00 | 0.0 | 0.81 | 15.11 | 6.33 | southwest | hard | rock | no |
| site1 | 32 | 475209 | 586038 | 0.00 | 0.0 | 0.81 | 5.85 | 7.00 | north | hard | rock | no |
| site1 | 33 | 475246 | 586030 | 0.00 | 0.0 | 0.81 | 4.03 | 8.86 | northwest | hard | rock | no |
| site1 | 35 | 475337 | 586006 | -0.21 | 0.0 | 0.81 | 10.11 | 9.41 | northeast | hard | rock | yes |
| site1 | 38 | 475411 | 585897 | -1.24 | -0.1 | 0.81 | 11.87 | 8.76 | northeast | hard | rock | yes |
| site1 | 39 | 475446 | 585869 | 0.00 | 0.0 | 0.81 | 13.76 | 7.68 | northeast | hard | rock | no |
| site1 | 40 | 475464 | 585833 | -0.63 | 0.0 | 0.81 | 13.82 | 7.91 | northeast | hard | rock | yes |
| site1 | 41 | 475495 | 585796 | 0.00 | 0.0 | 0.81 | 12.37 | 7.63 | northeast | hard | rock | yes |
| site1 | 42 | 475515 | 585749 | 0.00 | 0.0 | 0.81 | 18.90 | 7.26 | east | hard | rock | yes |
| site1 | 44 | 475546 | 585668 | -0.93 | -0.1 | 0.81 | 25.11 | 4.37 | east | medium | rock | yes |
| site1 | 45 | 475543 | 585620 | -0.75 | -0.1 | 0.81 | 24.30 | 7.90 | east | hard | rock | yes |
| site1 | 46 | 475559 | 585575 | -1.61 | -0.1 | 0.81 | 17.50 | 9.04 | east | hard | rock | yes |
| site1 | 47 | 475558 | 585525 | -0.14 | 0.0 | 0.81 | 21.35 | 10.73 | east | hard | rock | yes |
| site1 | 49 | 475620 | 585450 | -1.00 | -0.1 | 0.81 | 17.64 | 9.71 | northeast | hard | rock | yes |
| site1 | 50 | 475667 | 585444 | -0.80 | -0.1 | 0.81 | 16.69 | 8.85 | northeast | hard | rock | no |
| site1 | 51 | 475674 | 585403 | -0.33 | 0.0 | 0.81 | 10.00 | 9.99 | northeast | hard | rock | yes |
| site1 | 52 | 475716 | 585371 | -0.58 | 0.0 | 0.81 | 10.04 | 8.35 | northeast | hard | rock | yes |
| site1 | 53 | 475747 | 585342 | -1.66 | -0.1 | 0.81 | 11.32 | 8.92 | northeast | hard | rock | yes |
| site1 | 54 | 475781 | 585307 | -0.15 | 0.0 | 0.81 | 9.65 | 8.97 | northeast | medium | rock | yes |
| site1 | 55 | 475824 | 585294 | -1.09 | -0.1 | 0.81 | 5.08 | 8.21 | northeast | hard | rock | yes |
| site1 | 56 | 475851 | 585256 | -1.16 | -0.1 | 0.81 | 19.45 | 7.24 | northeast | hard | rock | yes |
| site1 | 57 | 475878 | 585215 | -1.34 | -0.1 | 0.81 | 6.26 | 9.06 | northeast | hard | rock | no |
| site1 | 58 | 475898 | 585171 | -0.87 | -0.1 | 0.81 | 17.15 | 9.97 | northeast | hard | rock | yes |

| Study site | Survey point | X | Y | Shoreline change (m) | EPR (m/a) | $U_R$ (m) | Slope | Elevation | Aspect | Geology | Vegetation | Beach |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site1 | 59 | 475936 | 585146 | -1.61 | -0.1 | 0.81 | 13.51 | 9.30 | northeast | hard | rock | yes |
| site1 | 60 | 475977 | 585133 | -1.59 | -0.1 | 0.81 | 21.47 | 7.43 | northeast | hard | rock | yes |
| site2 | 61 | 481888 | 597980 | -0.25 | 0.0 | 1.28 | 24.15 | 6.26 | west | hard | rock | no |
| site2 | 67 | 481903 | 598229 | -4.43 | -0.3 | 1.28 | 23.21 | 4.41 | west | weak | fell fields, moraines and sands | yes |
| site2 | 68 | 481900 | 598276 | -1.29 | -0.1 | 1.28 | 25.14 | 5.45 | west | weak | fell fields, moraines and sands | no |
| site2 | 70 | 481872 | 598375 | 0.58 | 0.0 | 1.28 | 29.41 | 5.21 | west | hard | rock | no |
| site2 | 71 | 481859 | 598421 | -2.20 | -0.2 | 1.28 | 34.77 | 5.15 | west | hard | rock | no |
| site2 | 72 | 481851 | 598469 | 0.70 | 0.1 | 1.28 | 24.53 | 9.50 | west | hard | rock | no |
| site2 | 74 | 481825 | 598561 | 0.63 | 0.1 | 1.28 | 25.57 | 5.20 | southwest | hard | rock | no |
| site2 | 75 | 481820 | 598610 | -2.68 | -0.2 | 1.28 | 22.58 | 6.56 | west | hard | rock | no |
| site2 | 76 | 481823 | 598658 | -3.41 | -0.3 | 1.28 | 25.19 | 7.61 | west | weak | grasslands | yes |
| site2 | 77 | 481829 | 598705 | -1.51 | -0.1 | 1.28 | 28.66 | 4.16 | west | weak | heathlands | yes |
| site2 | 78 | 481829 | 598754 | -1.71 | -0.1 | 1.28 | 25.64 | 3.83 | west | weak | heathlands | yes |
| site2 | 79 | 481834 | 598803 | -4.14 | -0.3 | 1.28 | 16.19 | 6.41 | west | weak | heathlands | yes |
| site2 | 80 | 481836 | 598851 | -4.35 | -0.4 | 1.28 | 14.17 | 5.06 | northwest | weak | fell fields, moraines and sands | yes |
| site2 | 81 | 481843 | 598899 | -1.90 | -0.2 | 1.28 | 15.79 | 8.83 | west | weak | fell fields, moraines and sands | yes |
| site2 | 84 | 481838 | 599040 | -0.22 | 0.0 | 1.28 | 15.06 | 4.63 | west | weak | grasslands | yes |
| site2 | 85 | 481833 | 599088 | -1.00 | -0.1 | 1.28 | 22.77 | 6.21 | southwest | weak | grasslands | yes |
| site2 | 86 | 481828 | 599136 | -1.39 | -0.1 | 1.28 | 26.37 | 3.81 | west | weak | heathlands | yes |
| site2 | 87 | 481826 | 599182 | -4.61 | -0.4 | 1.28 | 6.29 | 2.51 | west | weak | heathlands | yes |
| site2 | 89 | 481788 | 599295 | -1.11 | -0.1 | 1.28 | 36.33 | 5.81 | west | weak | heathlands | yes |
| site2 | 90 | 481782 | 599344 | -1.23 | -0.1 | 1.28 | 34.16 | 7.77 | southwest | weak | fell fields, moraines and sands | yes |
| site2 | 91 | 481773 | 599391 | -2.05 | -0.2 | 1.28 | 32.18 | 7.66 | west | weak | fell fields, moraines and sands | yes |
| site2 | 92 | 481754 | 599436 | 1.05 | 0.1 | 1.28 | 26.78 | 3.08 | southwest | weak | grasslands | yes |
| site2 | 94 | 481706 | 599513 | -1.1 | -0.1 | 1.28 | 31.8 | 6.07 | southwest | hard | rock | yes |
| site2 | 97 | 481631 | 599617 | 0.54 | 0.0 | 1.28 | 28.06 | 5.52 | southwest | weak | grasslands | yes |
| site2 | 99 | 481580 | 599698 | 0.91 | 0.1 | 1.28 | 17.78 | 4.02 | southwest | hard | rock | yes |
| site2 | 101 | 481514 | 599784 | -1.43 | -0.1 | 1.28 | 18.75 | 15.97 | southeast | hard | rock | yes |
| site2 | 105 | 481357 | 599875 | 0.83 | 0.1 | 1.28 | 19.52 | 3.51 | southwest | weak | rock | yes |
| site2 | 106 | 481308 | 599877 | 2.22 | 0.2 | 1.28 | 24.23 | 4.67 | southwest | hard | rock | yes |
| site2 | 107 | 481262 | 599878 | 1.34 | 0.1 | 1.28 | 23.38 | 9.26 | southwest | hard | rock | yes |
| site2 | 108 | 481223 | 599917 | -0.74 | -0.1 | 1.28 | 30.91 | 6.29 | southwest | weak | grasslands | yes |
| site2 | 109 | 481199 | 599951 | -1.52 | -0.1 | 1.28 | 33.12 | 6.98 | southwest | weak | grasslands | yes |
| site2 | 110 | 481170 | 599984 | -0.24 | 0.0 | 1.28 | 31.01 | 5.89 | west | weak | grasslands | yes |
| site2 | 111 | 481137 | 600012 | -2.62 | -0.2 | 1.28 | 28.80 | 4.89 | southwest | weak | fell fields, moraines and sands | yes |
| site2 | 112 | 481104 | 600038 | 1.13 | 0.1 | 1.28 | 24.13 | 4.72 | west | weak | grasslands | yes |
| site2 | 113 | 481080 | 600081 | 2.38 | 0.2 | 1.28 | 34.31 | 6.45 | southwest | weak | grasslands | yes |
| site2 | 114 | 481052 | 600122 | -0.36 | 0.0 | 1.28 | 26.53 | 4.51 | south | weak | heathlands | yes |
| site2 | 115 | 481036 | 600164 | 1.59 | 0.1 | 1.28 | 14.26 | 3.79 | southwest | weak | grasslands | yes |
| site2 | 116 | 481015 | 600206 | 0.28 | 0.0 | 1.28 | 14.66 | 3.51 | northeast | weak | grasslands | yes |
| site2 | 117 | 480979 | 600242 | 4.49 | 0.4 | 1.28 | 6.60 | 1.82 | north | weak | grasslands | yes |
| site2 | 119 | 480666 | 600345 | -0.11 | 0.0 | 1.28 | 10.58 | 5.13 | north | hard | rock | no |

| Study site | Survey point | X | Y | Shoreline change (m) | EPR (m/a) | $U_R$ (m) | Slope | Elevation | Aspect | Geology | Vegetation | Beach |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site3 | 122 | 491310 | 620458 | -4.21 | -0.2 | 0.97 | 18.26 | 8.13 | north | medium | rock | yes |
| site3 | 123 | 491358 | 620453 | -4.82 | -0.3 | 0.97 | 17.80 | 6.64 | northeast | medium | rock | yes |
| site3 | 124 | 491403 | 620472 | -3.87 | -0.2 | 0.97 | 18.62 | 5.94 | northeast | weak | grasslands | yes |
| site3 | 125 | 491441 | 620498 | -4.65 | -0.3 | 0.97 | 12.16 | 6.04 | northeast | weak | grasslands | yes |
| site3 | 126 | 491477 | 620533 | -3.53 | -0.2 | 0.97 | 20.22 | 3.65 | east | weak | grasslands | yes |
| site3 | 127 | 491521 | 620551 | -7.14 | -0.4 | 0.97 | 18.00 | 4.32 | northeast | weak | grasslands | yes |
| site3 | 128 | 491556 | 620515 | -1.22 | -0.1 | 0.97 | 16.80 | 7.06 | east | weak | grasslands | yes |
| site3 | 129 | 491575 | 620478 | -0.96 | -0.1 | 0.97 | 18.26 | 7.53 | east | weak | grasslands | yes |
| site3 | 130 | 491599 | 620432 | -1.49 | -0.1 | 0.97 | 18.55 | 7.81 | northeast | weak | grasslands | yes |
| site3 | 131 | 491621 | 620386 | -1.26 | -0.1 | 0.97 | 19.36 | 7.25 | northeast | weak | grasslands | yes |
| site3 | 132 | 491631 | 620340 | -1.75 | -0.1 | 0.97 | 15.60 | 7.81 | east | hard | rock | yes |
| site3 | 133 | 491643 | 620297 | 0.00 | 0.0 | 0.97 | 25.12 | 7.37 | northeast | hard | rock | yes |
| site3 | 134 | 491642 | 620248 | 0.00 | 0.0 | 0.97 | 24.21 | 7.64 | east | hard | rock | yes |
| site3 | 135 | 491651 | 620202 | -3.72 | -0.2 | 0.97 | 16.99 | 9.29 | northeast | hard | rock | yes |
| site3 | 137 | 491678 | 620108 | 0.00 | 0.0 | 0.97 | 18.92 | 12.79 | northeast | hard | rock | yes |
| site3 | 138 | 491689 | 620060 | 0.00 | 0.0 | 0.97 | 31.60 | 12.03 | east | hard | rock | yes |
| site3 | 141 | 491735 | 619922 | -1.72 | -0.1 | 0.97 | 12.52 | 16.69 | northeast | weak | grasslands | yes |
| site3 | 142 | 491772 | 619894 | -3.43 | -0.2 | 0.97 | 12.92 | 12.51 | east | hard | rock | yes |
| site3 | 143 | 491811 | 619864 | -3.21 | -0.2 | 0.97 | 9.43 | 10.16 | northeast | weak | grasslands | yes |
| site3 | 144 | 491846 | 619831 | -3.08 | -0.2 | 0.97 | 8.81 | 12.04 | northeast | weak | grasslands | yes |
| site3 | 145 | 491890 | 619808 | -4.43 | -0.3 | 0.97 | 12.30 | 11.15 | east | weak | grasslands | yes |
| site3 | 146 | 491921 | 619774 | -1.61 | -0.1 | 0.97 | 16.99 | 13.00 | northeast | weak | grasslands | yes |
| site3 | 147 | 491942 | 619731 | -0.64 | 0.0 | 0.97 | 23.33 | 9.84 | northeast | weak | grasslands | yes |
| site3 | 148 | 491962 | 619683 | -1.81 | -0.1 | 0.97 | 19.43 | 10.07 | east | weak | grasslands | yes |
| site3 | 149 | 491982 | 619641 | -1.17 | -0.1 | 0.97 | 20.13 | 10.30 | east | weak | grasslands | yes |
| site3 | 150 | 491999 | 619596 | -0.92 | -0.1 | 0.97 | 14.88 | 11.25 | northeast | weak | grasslands | yes |
| site3 | 151 | 492014 | 619546 | -1.35 | -0.1 | 0.97 | 20.60 | 12.15 | northeast | weak | grasslands | yes |
| site3 | 152 | 492035 | 619504 | -1.21 | -0.1 | 0.97 | 9.21 | 15.08 | northeast | weak | grasslands | yes |
| site3 | 153 | 492062 | 619465 | -1.87 | -0.1 | 0.97 | 20.13 | 12.38 | north | weak | grasslands | yes |
| site3 | 154 | 492081 | 619418 | -0.95 | -0.1 | 0.97 | 15.73 | 11.54 | northeast | weak | grasslands | yes |
| site3 | 155 | 492104 | 619375 | -1.82 | -0.1 | 0.97 | 12.45 | 10.78 | east | weak | grasslands | yes |
| site3 | 156 | 492137 | 619338 | -0.99 | -0.1 | 0.97 | 5.92 | 12.01 | southeast | weak | grasslands | yes |
| site3 | 157 | 492177 | 619312 | -2.34 | -0.1 | 0.97 | 14.70 | 9.49 | east | weak | grasslands | yes |
| site3 | 158 | 492220 | 619293 | -3.40 | -0.2 | 0.97 | 9.72 | 9.35 | north | weak | grasslands | yes |
| site3 | 159 | 492268 | 619282 | -2.73 | -0.2 | 0.97 | 20.85 | 6.92 | north | weak | grasslands | yes |
| site3 | 160 | 492314 | 619272 | -1.75 | -0.1 | 0.97 | 14.43 | 4.05 | northeast | hard | rock | yes |
| site3 | 161 | 492333 | 619250 | 0.00 | 0.0 | 0.97 | 4.98 | 5.02 | north | hard | rock | yes |
| site3 | 162 | 492336 | 619203 | -0.13 | 0.0 | 0.97 | 14.14 | 4.49 | north | weak | grasslands | yes |
| site3 | 163 | 492367 | 619165 | -1.10 | -0.1 | 0.97 | 14.31 | 5.54 | north | weak | grasslands | yes |
| site3 | 164 | 492416 | 619142 | -2.88 | -0.2 | 0.97 | 8.78 | 7.05 | north | weak | grasslands | yes |
| site3 | 165 | 492462 | 619127 | -2.41 | -0.1 | 0.97 | 9.82 | 6.84 | north | weak | grasslands | yes |
| site3 | 166 | 492512 | 619129 | -2.60 | -0.2 | 0.97 | 13.44 | 5.57 | north | weak | grasslands | yes |
| site3 | 167 | 492560 | 619132 | -3.21 | -0.2 | 0.97 | 10.11 | 7.44 | north | weak | grasslands | yes |
| site3 | 168 | 492609 | 619126 | -2.47 | -0.1 | 0.97 | 11.79 | 6.84 | northwest | weak | grasslands | yes |
| site3 | 169 | 492657 | 619131 | -2.09 | -0.1 | 0.97 | 11.83 | 6.30 | north | weak | grasslands | yes |

| Study site | Survey point | X | Y | Shoreline change (m) | EPR (m/a) | $U_R$ (m) | Slope | Elevation | Aspect | Geology | Vegetation | Beach |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site3 | 170 | 492706 | 619132 | -1.92 | -0.1 | 0.97 | 11.44 | 6.36 | east | weak | grasslands | yes |
| site3 | 171 | 492754 | 619135 | -2.29 | -0.1 | 0.97 | 12.78 | 7.44 | north | weak | grasslands | yes |
| site3 | 172 | 492800 | 619151 | -2.37 | -0.1 | 0.97 | 15.30 | 6.28 | north | hard | rock | yes |
| site3 | 173 | 492847 | 619152 | -1.92 | -0.1 | 0.97 | 17.16 | 8.56 | north | weak | heathlands | yes |
| site3 | 174 | 492881 | 619156 | -2.77 | -0.2 | 0.97 | 15.49 | 6.83 | north | hard | rock | yes |
| site3 | 175 | 492921 | 619155 | -1.86 | -0.1 | 0.97 | 6.61 | 5.98 | northeast | hard | rock | yes |
| site3 | 176 | 492956 | 619122 | -2.23 | -0.1 | 0.97 | 7.37 | 6.81 | north | weak | grasslands | yes |
| site3 | 177 | 492994 | 619095 | -2.37 | -0.1 | 0.97 | 11.76 | 8.55 | north | hard | rock | yes |
| site3 | 178 | 493042 | 619083 | -3.55 | -0.2 | 0.97 | 13.57 | 9.12 | north | weak | grasslands | yes |
| site3 | 179 | 493091 | 619082 | -3.86 | -0.2 | 0.97 | 18.91 | 6.92 | north | weak | grasslands | yes |
| site3 | 180 | 493140 | 619076 | -5.31 | -0.3 | 0.97 | 11.27 | 5.82 | northeast | weak | grasslands | yes |

**Appendix II:** Summary: model 0

```
> summary(model0)

Call:
lm(formula = s ~ a + h + sd + el + v + b)

Residuals:
    Min      1Q  Median      3Q     Max 
-5.0090 -0.6443  0.0547  0.8707  5.0247 

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)    
(Intercept)                 -1.39993    1.23548  -1.133  0.25934    
aeast                        0.25258    0.41138   0.614  0.54034    
anorth                      -0.20994    0.37507  -0.560  0.57666    
anorthwest                   0.14007    0.57673   0.243  0.80851    
asouth                       2.84698    1.54596   1.842  0.06791 .  
asoutheast                   0.46510    1.03614   0.449  0.65430    
asouthwest                   2.18740    0.47285   4.626 9.18e-06 ***
awest                        1.37255    0.41786   3.285  0.00132 ** 
hhard                        0.66602    0.83111   0.801  0.42445    
hmedium                     -0.38576    0.91306  -0.422  0.67340    
sd                          -0.10551    0.16775  -0.629  0.53051    
el                          -0.05604    0.33391  -0.168  0.86700    
vfell fields, moraines and sands -1.97200    0.98806  -1.996  0.04813 *  
vgrasslands                 -0.20491    0.84356  -0.243  0.80848    
vheathlands                 -1.18108    0.78332  -1.508  0.13413    
bno                          0.06975    0.41779   0.167  0.86768    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.406 on 125 degrees of freedom
Multiple R-squared:  0.3439,	Adjusted R-squared:  0.2651 
F-statistic: 4.368 on 15 and 125 DF,  p-value: 1.596e-06
```

**Appendix III:** Summary: Model 1

```
> summary(model1)

Call:
lm(formula = s ~ a + h + sd + el + b)

Residuals:
    Min      1Q  Median      3Q     Max 
-4.8161 -0.7782  0.1407  0.9460  5.6456 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) -1.67175    0.95832  -1.744 0.083480 .  
aeast        0.31003    0.42307   0.733 0.465016    
anorth      -0.21071    0.38597  -0.546 0.586069    
anorthwest  -0.27179    0.57692  -0.471 0.638364    
asouth       2.11296    1.50202   1.407 0.161926    
asoutheast   0.42684    1.06672   0.400 0.689715    
asouthwest   2.12107    0.48570   4.367 2.57e-05 ***
awest        0.91869    0.39280   2.339 0.020895 *  
hhard        1.04008    0.28788   3.613 0.000434 ***
hmedium     -0.01363    0.55211  -0.025 0.980345    
sd          -0.16374    0.17053  -0.960 0.338774    
el           0.02672    0.33676   0.079 0.936887    
bno          0.18863    0.42030   0.449 0.654332    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.448 on 128 degrees of freedom
Multiple R-squared:  0.2875,	Adjusted R-squared:  0.2207 
F-statistic: 4.303 on 12 and 128 DF,  p-value: 1.025e-05
```

## **Appendix IV:** Correlation table

*Correlation between Shoreline change (DV) and the independent variables, elevation, slope and the presence of beach (N=141).*

| **Variables** | **N** | **Spearman correlation (rho)** | **Sig.** | | |
|---|---|---|---|---|---|
| **Elevation (log)** | 141 | .000 | .996 | | |
| **Slope (squared)** | 141 | **.198** | **.018** | | |
| | | **Pearson's Chi-squared test** | | **X-squared** | |
| **Presence of beach** | 141 | | .99 | 101.39 | NA |