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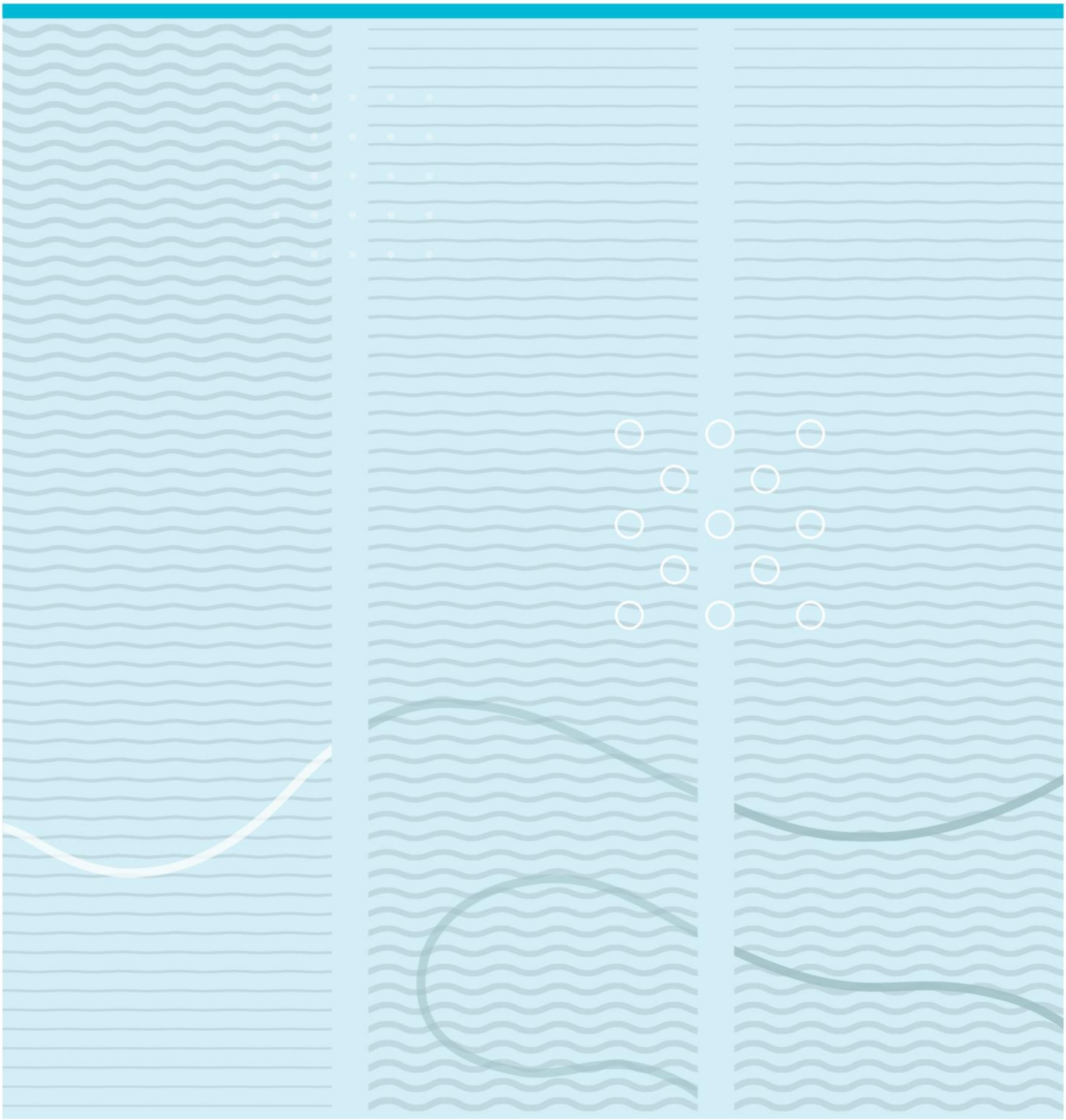
Fluvial Terraces and Sea Level Changes in the Stabbursnes Study Area: A LiDAR-Based Analysis



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This thesis is worth 60 study points

Summary

This research work uses a LiDAR-based approach to map fluvial terraces, distinguish contemporaneous terraces, and decipher the complex link between sea-level fluctuations and terrace formations. The research aims to assess the efficacy of this strategy for larger applications. Through Mapping, I discovered a succession of six unique terrace levels (T1 to T6) in the study area, using Jenks Natural breaks categorization and mean elevation analysis. Terraces T1–T6 are thoroughly examined to reveal their kinds, formations, heights, sizes, and long-term stability, T1, T2, T3, and T4 exhibit fluvial features, T5 and T6, which are glaciofluvial in origin, hint at former glacial events. This study has discovered terraces that arose concurrently with its goal of understanding the temporal dynamics of terrace creation. This sheds light on the delicate interplay of forces that have guided their evolution throughout time. The findings contribute significantly to our understanding of terrace formations, glacial effects, and sea-level variations; all of this suggests that LiDar Data should be obtained wherever possible to increase the quality of geological mapping.

Keywords: LiDar, Terraces Mapping and formation, fluvial, Norway

Abstract

This research work uses a LiDAR-based approach to map fluvial terraces, distinguish contemporaneous terraces, and decipher the complex link between sea-level fluctuations and terrace formations. The research aims to assess the efficacy of this strategy for larger applications. Through Mapping, I discovered a succession of six unique terrace levels (T1 to T6) in the study area, using Jenks Natural breaks categorization and mean elevation analysis. Terraces T1–T6 are thoroughly examined to reveal their kinds, formations, heights, sizes, and long-term stability, T1, T2, T3, and T4 exhibit fluvial features, T5 and T6, which are glaciofluvial in origin, hint at former glacial events. This study has discovered terraces that arose concurrently with its goal of understanding the temporal dynamics of terrace creation. This sheds light on the delicate interplay of forces that have guided their evolution throughout time. The findings contribute significantly to our understanding of terrace formations, glacial effects, and sea-level variations; all of this suggests that LiDar Data should be obtained wherever possible to increase the quality of geological mapping.

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I want to congratulate myself on this enormous feat of completing this thesis and master's program. Firstly, I would like to thank the management and staff of the faculty of Technology, Natural Sciences, and Maritime Sciences USN BØ for giving me the opportunity as an international student to study at this prestigious institution of learning. I would also like to give special gratitude to my supervisor, Johanna Anjar for her unwavering support, feedback, suggestions, and guidance during the entire duration of this thesis and my master’s program. Special gratitude also goes to Erik Martin Lund for stepping in when Johanna was away, thank you so much. I would also like to give my sincere thanks to all staff members of the Department of Natural Science and Environmental Health of the USN BØ campus for their support during my master’s studies.

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BØ Telemark, 12/11/2023

Idris Olarewaju Olaniyi

1 Introduction

1.1. Background of the study

The rate of rising sea levels is quickly increasing worldwide. The rate of change has changed in recent decades from a few millimeters per century during the late Holocene to a few tens of centimeters per century (Milne *et al.*, 2009; Gehrels and Woodworth, 2013). According to the Intergovernmental Panel on Climate Change's special report on the ocean and cryosphere in a changing climate (IPCC, 2019), global sea level rose by 3.6 millimeters per year on average between 2006 and 2015. This change is closely tied to climate change and has been regarded as one of the most significant global challenges of our time (Gornitz, 2013: 149; Dutton *et al.*, 2015). Sea levels might increase at a rate of up to 15 millimeters per year by 2100 (Oppenheimer *et al.*, 2019).

The movement of water between the ocean and ice correlates with changes in average temperature, whereas isostatic sea-level change is mostly caused by the Earth's dynamic response to the shifting surface load (Lambeck *et al.*, 2014). Knowing how sea levels varied throughout the pre-industrial century is crucial for projecting future sea-level variations depending on future climatic predictions (Barnett *et al.*, 2015).

At the time of the last glacial maximum (LGM), around 21,000 years ago, the eustatic sea level was 125 ±5 m below the present-day sea (Benn and Evans, 2013:240-1). Since the LGM's conclusion, the sea level has been generally increasing (Lambeck *et al.*, 2014). However, relative (local) rising sea levels just haven't been accelerating consistently (Milne *et al.*, 2009), and have been declining in areas that were covered by ice during the previous glaciation (~11600 cal BP) (Chappell, 1983; Møller, 1989; Rasmussen *et al.*, 2006; Lohne *et al.*, 2007; Benn and Evans, 2013). In a global context, the sea level and/or topography are vertically adjusted, resulting in changes to relative sea level (RSL); crustal movements brought on by tectonic activity or isostatic shift may also result in vertical movement. Sea level variations are caused by the land, isostasy (glacial, tectonic, and geoid), as well as regional weather, hydrological, and oceanographic changes (Mörner, 1976; Shennan *et al*., 2015).

After the Younger Dryas, the Scandinavian ice sheet and smaller glaciers withdrew, causing a glacio-isostatic rebound in Fennoscandia (Berglund, 2004). Because of this, Norway's coastal regions have generally experienced a relative sea-level decline all through the Holocene, except the mid-Holocene transgression, which occurred at many Norwegian coastal areas as a result of a faster rate of global ice melting than vertical land uplift (Simpson *et al*., 2015). Because isolation basins, a type of naturally occurring depression located below the postglacial marine limit and cut off from the sea by variations in relative sea level, are so common in Norway, it is a renowned place to study historic shorelines and sea-level histories (Kjemperud, 1986; Svendsen and Mangerud, 1987; Lohne *et al*., 2007; Balascio *et al*., 2011; Long *et al*., 2011; Romundset *et al*., 2018; Vasskog *et al*., 2019). Isolation basins are among the various coastal environments that have been used to reconstruct relative sea-level changes because they can preserve continuous sedimentary archives of marine-lacustrine transitions and because the facies switching can be reliably dated on centennial timescales by radiocarbon dating of aquatic plant debris. A stable sea-level index point that represents the palaeo-shoreline (mean high-tide sea level) at the time of isolation is also made possible by the elevation of the basin threshold (Svendsen and Mangerud, 1987; Long *et al*., 2011; Romundset *et al*., 2018; Vasskog *et al*., 2019).

1.2. Statement of Problem

In the past, considerable fieldwork and analyses of aerial images and maps of varying quality and accuracy were used to study landforms. A new tool has entered the toolkit of the geomorphologist with the expansion of LiDAR elevation data availability.

1.3. Aim and objectives of the study

This study aims to use LiDAR images obtained from the Norwegian Mapping Authority (Statens Kartverk) to:

i. Map fluvial terraces in the Stabbursnes study area.
ii. identify which terraces formed at the same time.
iii. to identify the sea level changes in the study area.
iv. determine the relationship between sea level changes and terrace levels in the study area.
v. evaluate this method: if it is effective and may be recommended for use in other areas.

In Norwegian fjord valleys below the postglacial marine limit, where they originated by delta progradation and fluvial incision under conditions of glacial-isostatic uplift during and after glacier retreat, depositional terraces are a frequent and distinctive geomorphological feature (Corner 2006; Eilertsen *et al*. 2006,2011). It can be difficult to discern between terraces of various origins, though. Depending on whether sediments were primarily supplied by glacial or non-glacial rivers, the Geologic Survey of Norway classified terrace deposits as either fluvial or glaciofluvial for mapping purposes (Bergstrøm *et al*. 2001). Even though both deltaic (intertidal) and non-deltaic (subaerial) terraces are found among fluvial and glaciofluvial generated terraces and are supracrustal significant for comprehending deglacial and postglacial valley-fill history, delta progradation, and base-level change, it does not differentiate between these two types of terraces (Corner 2006).

1.4. Scope of the study

The scope of this study was to present the result of the relationship between sea level changes and terrace levels in Stabursness, Finnmark Norway, using light detection and ranging LiDAR data obtained from the Norwegian Mapping Authority (Statens Kartverk).

2. Literature Review

Numerous studies have shown that fluvial terrace staircases are long-term reactions to regional uplift (Maddy, 1997). Due to the fluvial sensitivity to tectonic and climate fluctuation, geomorphic and stratigraphic records can be used as quantitative archives of previous tectonic and climate circumstances. If we concentrate on the most recent glacial-interglacial cycle, the fluvial sequence is frequently characterized by several fill-cut episodes that have created two or three (or more) terrace steps since the last

glacial maximum during the Holocene (Starkel, 2007; Tlapáková *et al.*, 2021).

A lot of places around the world have minor aggradation episodes along the inner valley sectors from the Holocene. Both increasing mass wasting along hillslopes and anthropogenic soil erosion frequently speed up these stages. As stated by (Iacobucci et. al 2022) The late glacial and Holocene terrace sequences are among the most well-known and exposed alluvial records in the world, but their complexity and intriguing arrangement encourage additional research perspectives aimed at elucidating the types and ages as well as the altimetric arrangement and along-valley distribution. Indeed, in adjacent valleys in the same location, the late glacial and Holocene terrace sequences are frequently different from one another in addition to having different morphoclimatic and geodynamic contexts.

Fluvial terrace mapping is a standard geomorphological process. In actuality, there are several reasons why it is difficult to identify Holocene fluvial terraces in the field and to differentiate them from the older late Pleistocene terrace generation, including (i) the size of the terrace surfaces, which are frequently too large to be fully seen in the field, and (ii) the examiner's subjectivity in identifying all terrace features and their geometric and geomorphological characteristics (such as external scarp, inner edge, lateral edges, basal characteristics (Iacobucci et. al 2022).

Digital terrain models (DTMs) have made it possible to analyze terrace morphology and surficial geometry remotely using geographic information systems (GIS). Over the past 20 years, various efforts have been made to automatically extract terrace features, such as terrace surfaces and terrace scarps, using low-resolution interpolated DTMs (Demoulin *et al.*, 2007) and high-resolution DTMs derived from light detection and ranging (LiDAR) (del Val *et al.*, 2015 and Hassenruck-Gudipati *et al.*, 2022). Fluvial terraces may be extracted using automated approaches in a variety of situations, and they are frequently used to recover terrace characteristics even in situations where terrace remains are hardly visible (Stout and Belmont 2013). However, it can be problematic to undertake analyses of late Pleistocene-Holocene floodplains, which are distinguished by a very complex spatial arrangement of terrace morphology and structure, and it can be difficult to do completely automatic terrace feature recognition. Therefore, a significant opportunity is presented by the combination of land-surface quantitative (LSQ) analysis based on high-resolution DTMs with ground-truth geomorphological investigations, which have shown to be successful for the analysis of Earth surface processes and landforms at various space-time scales (Tlapáková *et al.*, 2021).

2.1 Types of Fluvial Terraces

Fluvial terraces may be divided into two categories, fill terraces and strath terraces as shown in Figure 1. Fill terraces can then be further subdivided into cut terraces and nested fill terraces. Based on the relative heights of these terraces' surfaces, both fill and strath terraces are occasionally referred to as either paired or unpaired terraces (Pazzaglia, 2010).

Fill terraces are formed when alluvium is poured into an existing valley. For a variety of reasons, the valley may fill with alluvium, such as an increase in bed load brought on by glaciers or a shift in stream power that causes the valley, which was downcast by a stream or river, to be filled in with material (Easterbrook, 1999). Until an equilibrium is established and the stream or river can move the material rather than deposit it, the stream or river will continue to deposit material. If the circumstances do not alter, this equilibrium may endure for a very long time or for a very short time, like after a glacial. When the weather conditions alter once more and a stream or river flows through, the fill terrace is formed. Following this, benches made entirely of alluvium develop on the valley's edges. The fill terraces are the seats at the top. Fill terraces are left above the river channel as the alluvium is cut through in further sections (sometimes 100 m or more). If there are many terraces below the fill terrace, they are referred to as "cut terraces." The fill terrace is merely the very highest terrace created by the depositional phase (Easterbrook 1999).

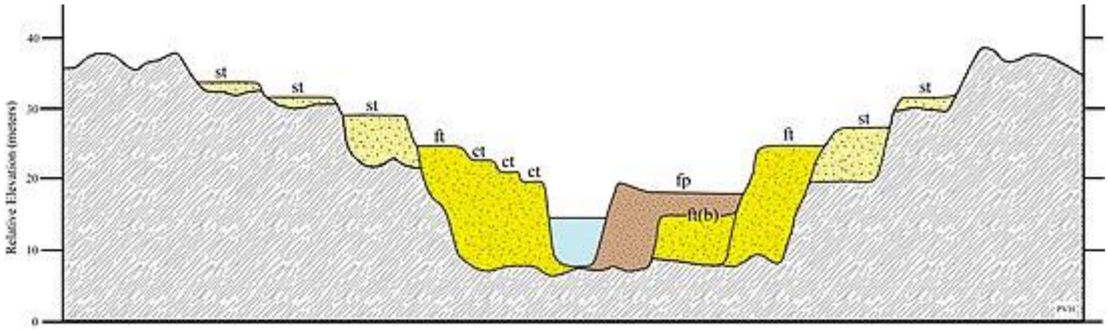

Figure 1. Hypothetical valley cross-section illustrating a complex sequence of aggradational (fill) and degradational (cut and strath) terraces. Note ct = cut terrace, ft = fill terrace, ft(b) = buried fill terrace, fp = active floodplain, and st = strath terrace. (Cristellaria, 2011)

2.1.1 Cut terraces

This is also known as "cut-in-fill" terraces, cut terraces resemble the fill terraces discussed before but are the result of erosion. Cut terraces may also develop beneath the fill terraces once the alluvium that was deposited in the valley has started to erode and fill terraces have started to form along the valley walls. Multiple tiers of terraces may develop when a stream or river continues to cut through the substrate. The bottom terraces are cut terraces, and the highest terraces are filled terraces (Easterbrook 1999).

2.1.2 Nested Fill Terraces

Nested fill terraces are formed when alluvium is deposited in a valley, it is excavated, and then the valley is refilled with material to a lower level than previously. As a result of the second filling, a terrace is created.

2.1.3 Strath terraces

Bedrock is downcast by a stream or a river, creating a terraced landscape. A phase of valley expansion may occur and increase the valley's breadth while the flow continues to downcast. This might happen as a result of the fluvial system reaching equilibrium as a result of delayed or stopped uplift, climatic change, or a change in bedrock type. After further downcutting, a bedrock-only valley bottom, maybe covered in a thin layer of alluvium, is left above a stream or river channel. These strath terraces, which are bedrock terraces, are erosional in origin (Burbank *et al*., 2002).

2.1.4 Terraces with and without partners

Paired terraces are those with the same height on either side of a stream or a river. They appear when the river's banks are equally downcast and the height of the terraces on either side of the river are equal. River renewal is the cause of paired terraces. When a stream or river comes into contact with a material that resists erosion on one side, unpaired terraces form, leaving one terrace without a corresponding terrace on the resistant side (Leet *et al*., 1982).

2.2 Characteristics of fluvial terraces

Step-like features

Fluvial terraces are stair-like structures found on riverbanks, some of which are over 100 feet tall (Kiprop 2018).

Thickness

Fluvial sediments of wildly varying thickness are found beneath fluvial terraces due to the way they originate (Pazzaglia, 2010).

Deposits

River terrace deposits are unconsolidated all stratigraphic units having an aggradational (constructional) bench-like top termed a "tread" that often rests under a basal unconformity called a "strath" cut across bedrock (Karl and Sean, 2022). An abandoned surface, or tread, and an incised surface, or riser, make up a river terrace (Easterbrook, 1999). You may determine the age of the incision and the age of abandonment of that surface by dating the tread on the terrace. The average rate of incision (ri) may be calculated using the simple formula hi/ti, where hi is the height of the river terrace from the river and it is the age of the surface (Blum and Tornqvist, 2000,). The assumption made by these incision rates is that they will occur at a consistent pace.

Hydrological or climatic shift

Any hydrological or climatic change that results in fresh downcutting creates a terrace. It often has a sharp fore-edge and a flat top built of sedimentary deposits. It may be the remnants of an ancient floodplain that the river cut through and left standing above the current floodplain level (Britannica, 1998). Figure 2 shows a series of terraces along a river and Figure 3 shows the formation of river terraces.

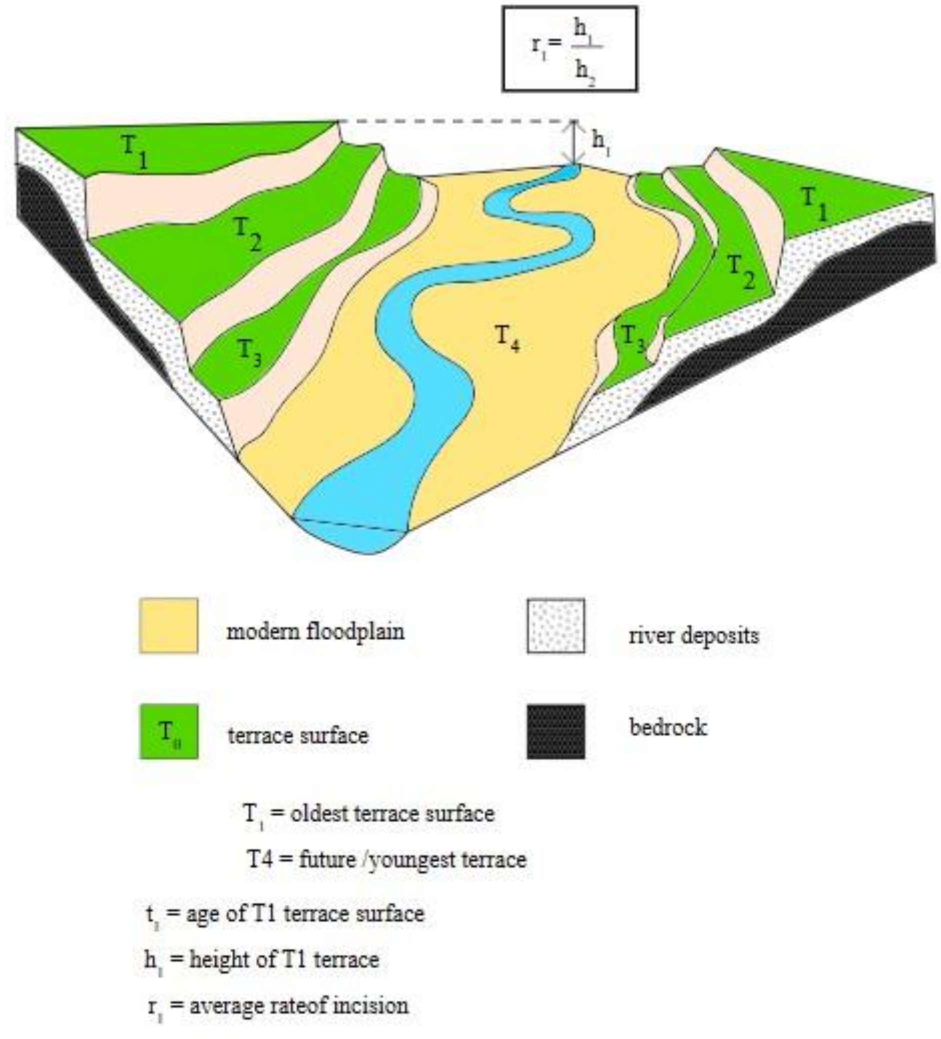

Figure 2: A series of terraces along a river. The oldest terraces (T1) are higher standing than the younger terraces (T3). The present floodplain (T4) will soon become the youngest terrace surface as the river incises ("River terraces (tectonic–climatic interaction)", 2020).

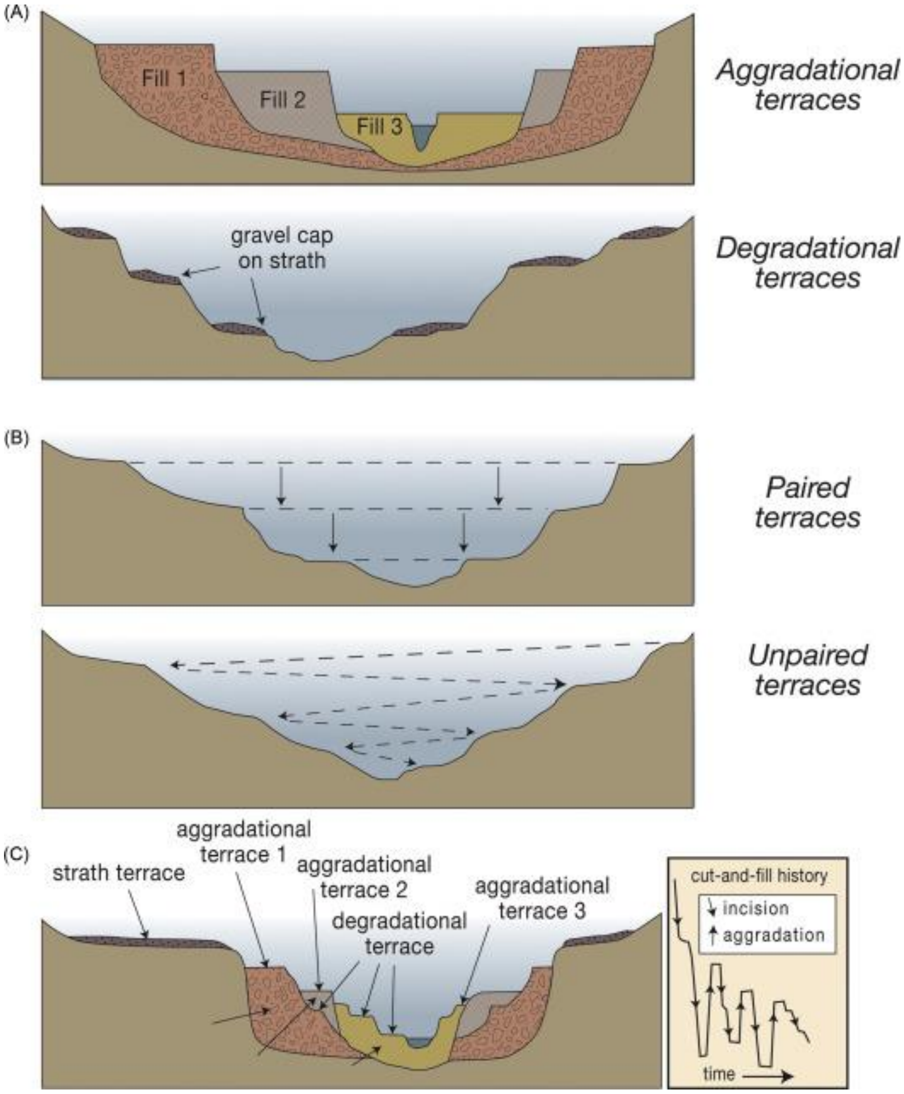

Figure 3: Formation of river terraces. (A) Aggradational and degradational fluvial terraces. (B) Paired and unpaired river terraces. (C) The complex sequence of aggradational and degradational surfaces. Multiple cut-and-fill events are outlined in the right-hand box (Burbank *et al*., 2002).

2.3 Roles of tectonic

Terraces are a type of landform that may develop in a variety of geological and environmental contexts. The geologic processes that generated terraces may be ascertained by examining their size, shape, and age. When terraces are uniform in age and/or shape over an area, this is sometimes a sign that a powerful geologic or environmental force is at work (Leeder and Mack, 2002).

It is believed that tectonic uplift and climatic change are the two main processes that may erode the earth's surface and modify its shape. In certain ways, tectonic and climatic variables are connected. For instance, intense uplift produces high mountains that are prone to glacial, changing the river regime and sediment supply (Strom and Abdrakhmatov, 2018). River erosion may be caused by tectonic uplift, climatic change, or maybe both (Leeder and Mack, 2002).

Evaluation of the shorter climate cycles, local to regional erosion, and how they could influence terrace formation can be done on geologically short periods (103-105 a). Terrace development in a region most likely occurred when stream erosion was substantially more severe than sedimentation (Leeder and Mack, 2002).

Studies have demonstrated that depending on the region, tectonics and climate can play different roles. For instance, research on the Yellow River in China discovered that the pace of rock uplift fluctuated throughout time and affected the construction and preservation of terraces (Pan *et al*. 2009). Due to the interaction between tectonic activity, climate, and sea-level rise, different research on the Suriname River Valley in South America discovered that the development of terraces along rivers in Suriname is strongly tied to climatic variations over the Quaternary (Gersie *et al*., 2021).

In conclusion, depending on the region and period being investigated, the contribution of tectonics, climate, and base-level changes to terrace growth might differ. Climate change and tectonic uplift are considered to be the two main factors that might affect the earth's surface.

2.4 LiDAR technology

A pulsed laser is used in the remote sensing technique known as LiDAR, or light detection and ranging, to estimate ranges or distances to the Earth's surface. It is extensively employed in many different industries, including surveying, forestry, agriculture, and geomorphology (Qinghua *et al.*, 2023).

2.4.1 Principles of LiDAR Technology

1. The length of time it takes for laser pulses to travel to and from the ground is measured by LiDAR devices. This period is utilized to determine the distance traveled and convert it to elevation (Leah A. Wasser, 2023).
2. A GPS that locates the source of the light energy and an Inertial Measurement Unit (IMU) that determines the plane's direction in the sky are essential parts of a LiDAR system (Leah, 2023).

The shape of the Earth and its surface features may be accurately determined using LiDAR technology (Doug *et al.*, 2011).

2.4.2 Applications of LiDAR Technology in Geomorphology:

1. LiDAR is used for height mapping, gathering incredibly precise and dense elevation data across landscapes, enabling the creation of high-resolution elevation models (Doug *et al.*, 2011).
2. Terrain analysis; the topography and landforms of a region may be examined and studied using LiDAR data, offering important details for geomorphological research (Leah, 2023).
3. Landform Change Analysis; Scientists may identify and evaluate changes in landforms, such as erosion, deposition, and other geomorphic processes, by comparing LiDAR data from various periods (Leah, 2023).
4. LiDAR may be used to precisely map floodplains and identify regions that are vulnerable to flooding, assisting in the evaluation and management of flood risk (Leah, 2023).

5. LiDAR is used in coastal zone mapping to create more precise shoreline maps, track coastal erosion, and research coastal geomorphology (Doug *et al*., 2011).
6. Geohazard Assessment: LiDAR data may be used to locate and evaluate geohazards including landslides, rockfalls, and slope instability. This information is crucial for hazard planning and mitigation (Qinghua *et al*., 2023).

The use of precise and reliable data from LiDAR technology has changed the study of landforms, processes, and changes to the Earth's surface. It is a useful instrument for geomorphological study and analysis since it can record high-resolution elevation data and produce exact 3D models. Figure 4 shows the Light detection and ranging (LiDAR) survey and Figure 5 shows a typical airborne LiDAR system

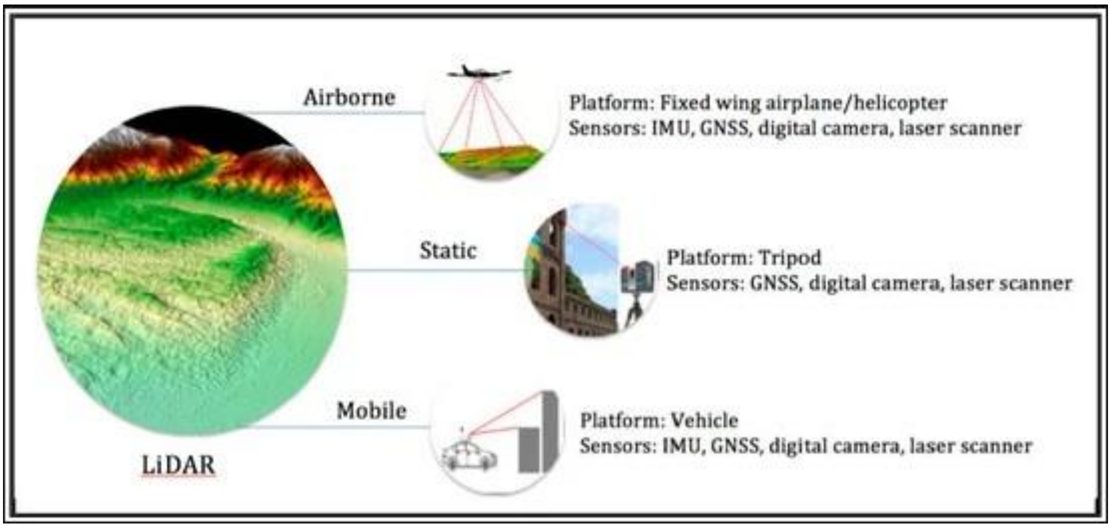

Figure 4. Light detection and ranging (LiDAR) survey data acquisition (Muhadi *et al*., 2020).

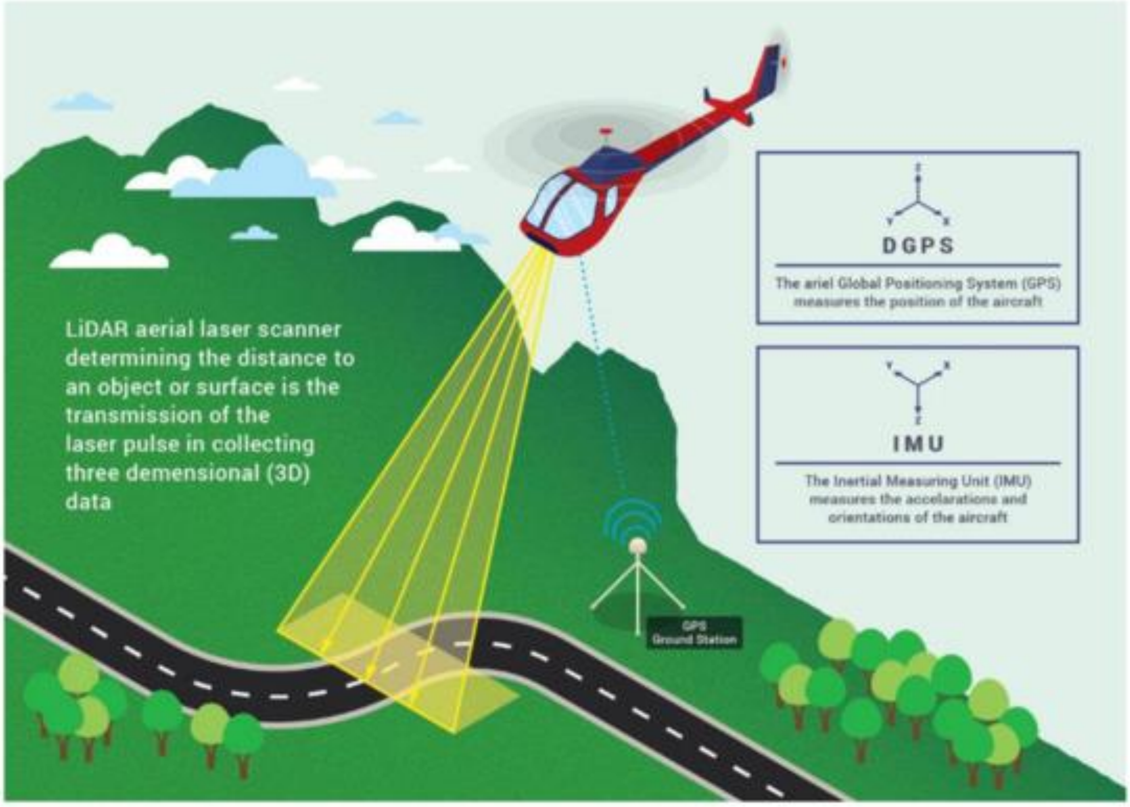

Figure 5. Typical airborne LiDAR system (Hatta Antah *et al*., 2021).

2.5 Significance of sea level change studies in understanding landscape evolution

Sea level change studies play a significant role in understanding landscape evolution. Here are the key reasons why:

1. Geological Process Indicators: Sedimentation, volcanism, and tectonic deformation are only a few of the geological processes that have an impact on sea level variations. Scientists may learn more about the underlying geological processes that sculpt landscapes across a variety of periods by examining sea level variations (King *et al*., 2012).
2. Identification of Former Landscapes: Land regions may become exposed or submerged as a result of changes in sea level. Researchers may rebuild earlier landscapes and comprehend how they have changed over time by examining old sea-level indicators and drowned landscapes (Bailey & Cawthra, 2023).

3. Sea level fluctuations have an immediate influence on the coastal areas. Increased coastal erosion, flooding, and the creation of new landforms are all effects of rising sea levels. By examining these changes, scientists may learn more about how coastal features like beaches, dunes, and coastal cliffs originate and evolve through time. 2009 (Williams)
4. Understanding Human Dispersal: The history and migration of humans have been greatly influenced by changes in sea level. The shifting of coastlines caused by changes in sea level may allow or prohibit migration. Understanding sea level variations can help us understand the patterns of ancient human migration and the rise of human civilization (Bailey & Cawthra, 2023).
5. Impacts on Coastal Communities: Coastal communities are at serious risk as a result of sea level rise. For risk assessment, adaptation planning, and the implementation of successful coastal management plans, it is crucial to comprehend sea level increases and their effects on coastal landscapes (Khojasteh *et al*., 2023).

Scientists may learn a great deal about the dynamic character of landscapes and the processes that shape them by examining sea level variations. This information is essential for comprehending the historical development of the terrain, forecasting future changes, and making wise decisions about land use and coastal management.

3 Methods

The availability of high-resolution digital elevation models (DEMs) derived from airborne light detection and ranging (LiDAR) surveys has spurred the development of several methods to identify and map fluvial terraces.

This study aims to utilize Light Detection and Ranging (LiDAR) data obtained from the Norwegian Mapping Authority (Statens Kartverk) to map fluvial terraces in the Stabbursnes study area, identify contemporaneous terraces, investigate sea level changes, establish the relationship between sea level changes and terrace formation, and evaluate the effectiveness of this method for potential application in other areas.

3.1 Study Area

The study area Stabbursnes is located at 70.17507°N; 24.93703°E. It is situated in the municipality of Porsanger, Finnmark, Norway, at the innermost section of the Porsangerfjord, at the exit of the Stabburselva river, and was formed as a delta of this river (store norske leksikon). The mean annual air temperature is close to 2.0 °C at sea level; with mean winter temperatures a few degrees below zero (Norwegian Meteorological Institute, 2010). The landscape is characterized by undulating, arid mountain plateaux, where extensive autochthonous block fields reach down to about one hundred m a.s.l. Other surficial deposits in the area are limited and mostly consist of high beach ridges, terminal moraines, and scattered patches of till. (Sollid *et al.*, 1973, Geological Survey of Norway, 2010). The study area is experiencing an isostatic rebound of about 1 ± 0.05 mm/yr relative to the sea level (Vestøl, 2006).

This region was covered by the Scandinavian Ice Sheet (SIS) during the Last Glacial Maximum (LGM), which merged with the Barents Sea Ice Sheet (BSIS) to the north (Hughes *et al*. 2016, Svendsen *et al* 2004, Sollid *et al* 1973). Radiocarbon dates of mollusk shell fragments contained in tills and post-deglaciation deposits atop till have been used to approximate the timing of glacial retreat in the Barents Sea region (Romundset *et al*. 2011) These findings show that rapid retreat began along the western margin of the ice sheet at ca 17.000 cal yr BP and that the southern Barents Sea became deglaciated over ca 2000 years, and was ice-free around 15.000 cal yr BP (Polyak *et al*., 1995, Winsborrow *et al*., 2010, Romundset *et al*. 2011). During deglaciation, the glacier front retreated in stages, revealing a sequence of ice-contact deposits as relatively high-lying terraces. Glacio-isostatic rebound during and after glacier retreat has resulted in river incision as well as elevation and tilting of terrace surfaces (Eilertsen *et al*. 2005).

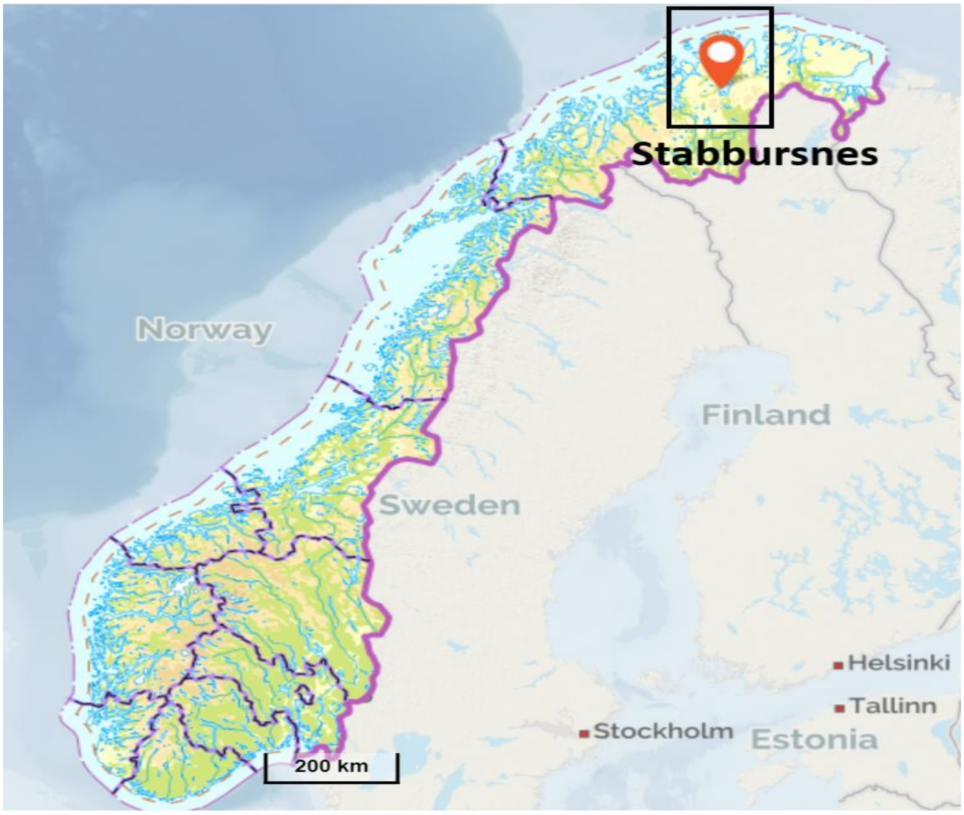

Figure 6. Map showing the location of the study area in Norway

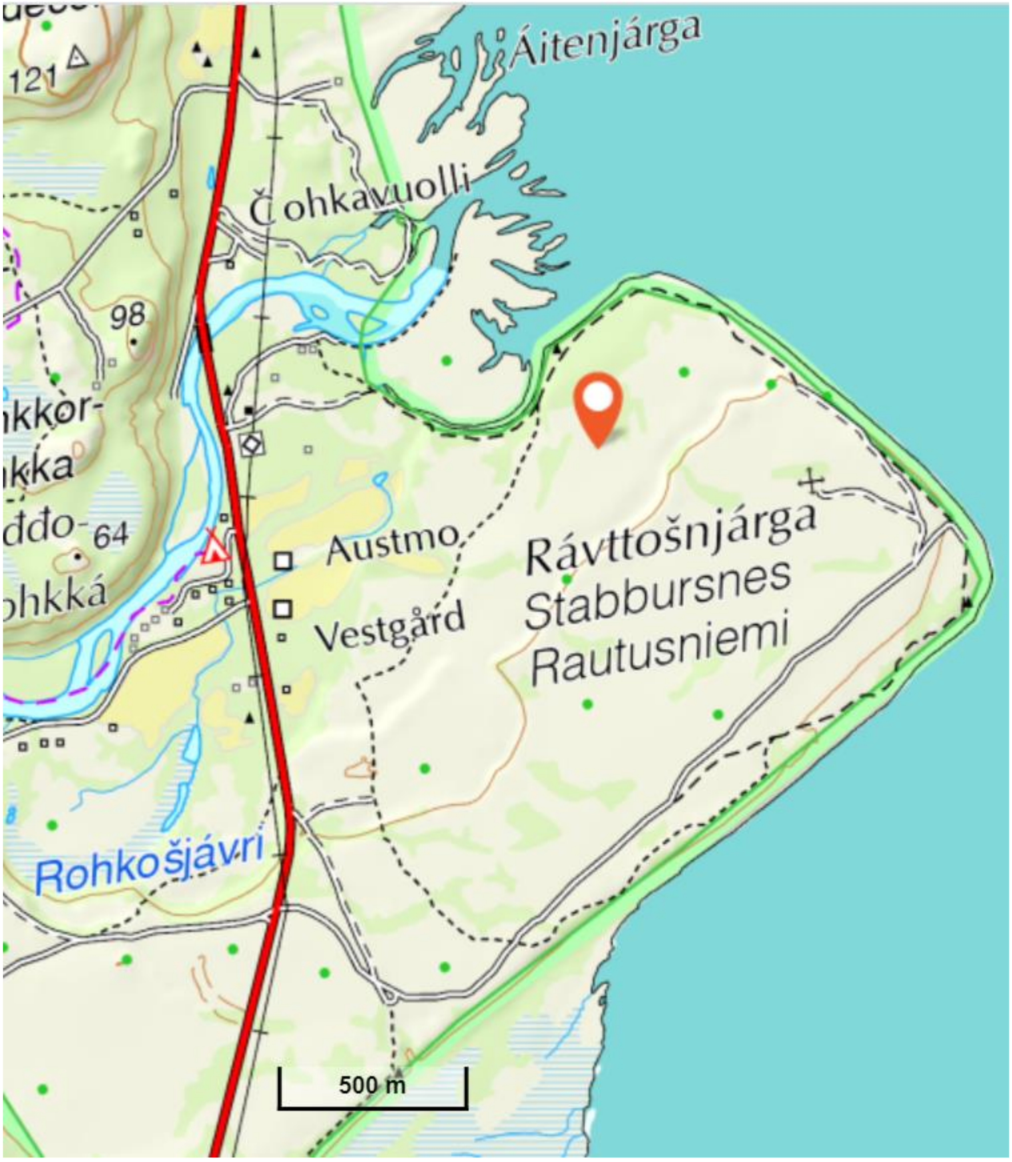

Figure 7. shows an inset map of the study area.

3.2 LiDAR

The study of different landforms has traditionally depended on considerable fieldwork as well as examinations of aerial pictures and maps of different quality and accuracy. However, with the advent of high-resolution digital elevation models (DEM) obtained from light detection and ranging (LiDAR) surveys, numerous approaches for identifying and mapping fluvial terraces have emerged (Roering *et al*. 2013). LiDAR DEMs have become increasingly useful for mapping fluvial terraces due to their ability to provide greater spatial resolution and accuracy than traditional methods (Brocklehurst, 2010).

Terrace mapping using DEMs supports the extraction of additional data from these landforms, such as their height above the river channel or thickness and volume. By using topographic data that has been acquired through remote sensing technologies, such as airborne laser scanning (ALS), these models can create a 3D image of the terrain, which can then be used to identify changes in the landscape. This is especially beneficial for fluvial terraces, which are often difficult to detect due to their subtle topography. Additionally, the ability to utilize a higher resolution of data allows for greater precision when mapping these features, which is essential for accurately characterizing their extent and location. Furthermore, LiDAR DEMs are also capable of providing data on the surface roughness of the terrain, which helps identify the type of sediment that is present in the area (Kristen *et al* 2013). The use of LiDAR DEMs for mapping fluvial terraces has been explored by several researchers (Dumoulin *et al* 2007, Brocklehurst, 2010, Eilertsen *et al* 2015, & Schneider *et al* 2021). The adoption of this technology is promising; however, it is important to consider the potential challenges that may face researchers attempting to use this method. One of the main issues is the accuracy of the DEM data, and the ability to identify the specific boundaries of fluvial terraces (Brocklehurst, 2010). The terrain surface is often very complex, and the accuracy of the data can be affected by several factors, including the resolution of the data, and the scale of the features being mapped (Brocklehurst, 2010). Another challenge is the identification of the fluvial terraces themselves, as they can be difficult to distinguish from other landforms. This is especially true in areas where fluvial terraces are less well-developed (Brocklehurst, 2010).

3.2.1 LiDAR Data Acquisition

The primary dataset for this study is the LiDAR data provided by the Norwegian Mapping Authority. These LiDAR data encompass the Stabbursnes study area and were acquired using aerial surveys. The dataset consists of point cloud data in LAS format, which includes information on elevation and terrain characteristics.

3.3 Mapping Fluvial Terraces

In November 2022, I acquired Airborne LiDAR data from the Norwegian Mapping Authority (Statens Kartverk). These data were presented as a Digital Elevation Model (DEM) with a pixel resolution of 1×1 meters. This high-resolution DEM was then imported into QGIS 3.16.16. Subsequently, I created hillside and slope images for the study area, enabling the identification of various morphological features.

Terraces were specifically mapped through a visual interpretation process, utilizing a LiDAR-shaded relief image. This involved tracing the outlines of these terraces by considering the adjacent scarp alongside the river channel and the alterations in slope between the flat terrace and the enclosing hillslope, following the methodology outlined in Hopkins & Snyder (2016). The mapped terraces were represented as vector datasets.

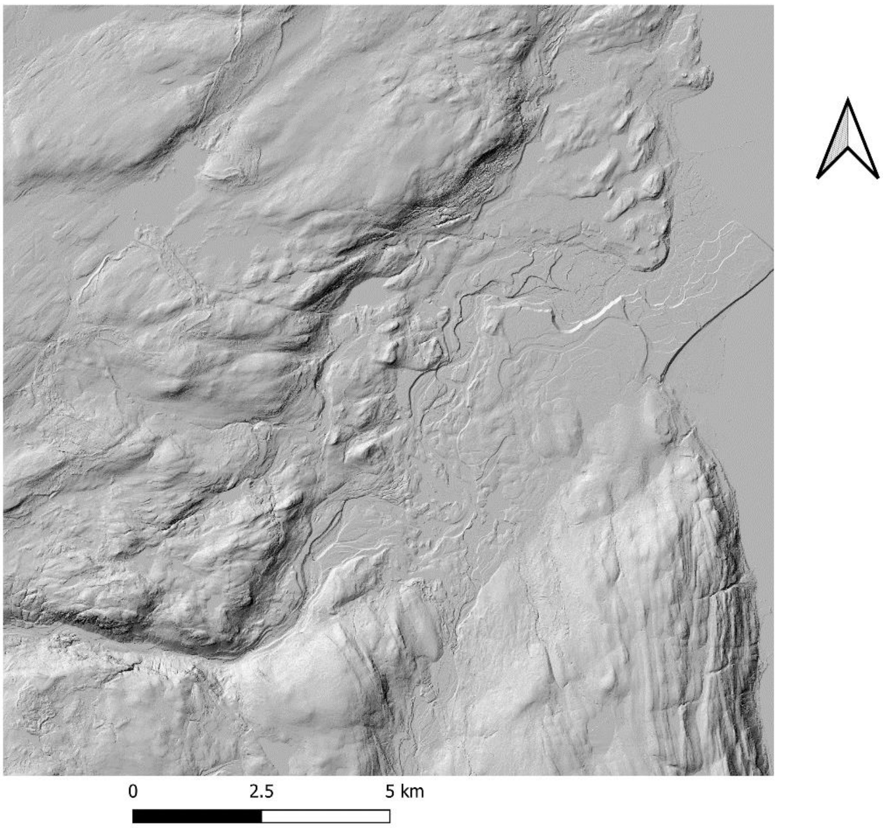

Figure 8 shows a LiDAR-derived hillshade relief map of the study area.

3.3.1 QGIS Analysis

In my research, I used a method that combines Geographic Information Systems (GIS) and manual techniques to make a detailed map of terrace surfaces and figure out their exact heights. We did this by carefully studying high-quality elevation data obtained from airborne LiDAR scans. Our main goal was to find out how many terraces there are in the area we were studying and in what order they appear.

This approach allowed us to have a clear picture of the landscape and how these terraces were organized, which is crucial for understanding the area better and conducting further research.

3.3.2 Topographic Maps

To aid in the interpretation and validation of LiDAR-derived results, topographic maps obtained from the Norwegian Mapping Authority were used.

3.4 Evaluation of Methodology

The effectiveness of the methodology employed in this study will be evaluated. This assessment will involve comparing the results obtained from LiDAR-based terrace identification and sea level change analysis with existing geological data.

This chapter has outlined the methodology used to achieve the objectives of this study, including data acquisition, preprocessing, sea level change analysis, and the evaluation of the methodology's effectiveness. The subsequent chapters will present and discuss the results obtained from the application of this methodology in the Stabbursnes study area.

4. Results

This chapter presents the results obtained from the application of the methodology outlined in Chapter 3 to achieve the research objectives of mapping fluvial terraces, identifying contemporaneous terraces, assessing sea level changes, determining the relationship between sea level changes and terrace levels, and evaluating the effectiveness of the LiDAR-based method for potential application in other areas.

4.1. Identification of Fluvial Terraces

In my research, I employed a method known as Jenk natural breaks classification, which helps in finding meaningful break points in my data. This technique groups similar values together while minimizing differences within a group and maximizing differences between groups. It's a way to make sense of complex data.

I used the mean elevation to identify terraces that likely formed around the same time because they share a similar elevation. This is crucial for understanding the geological history of the area.

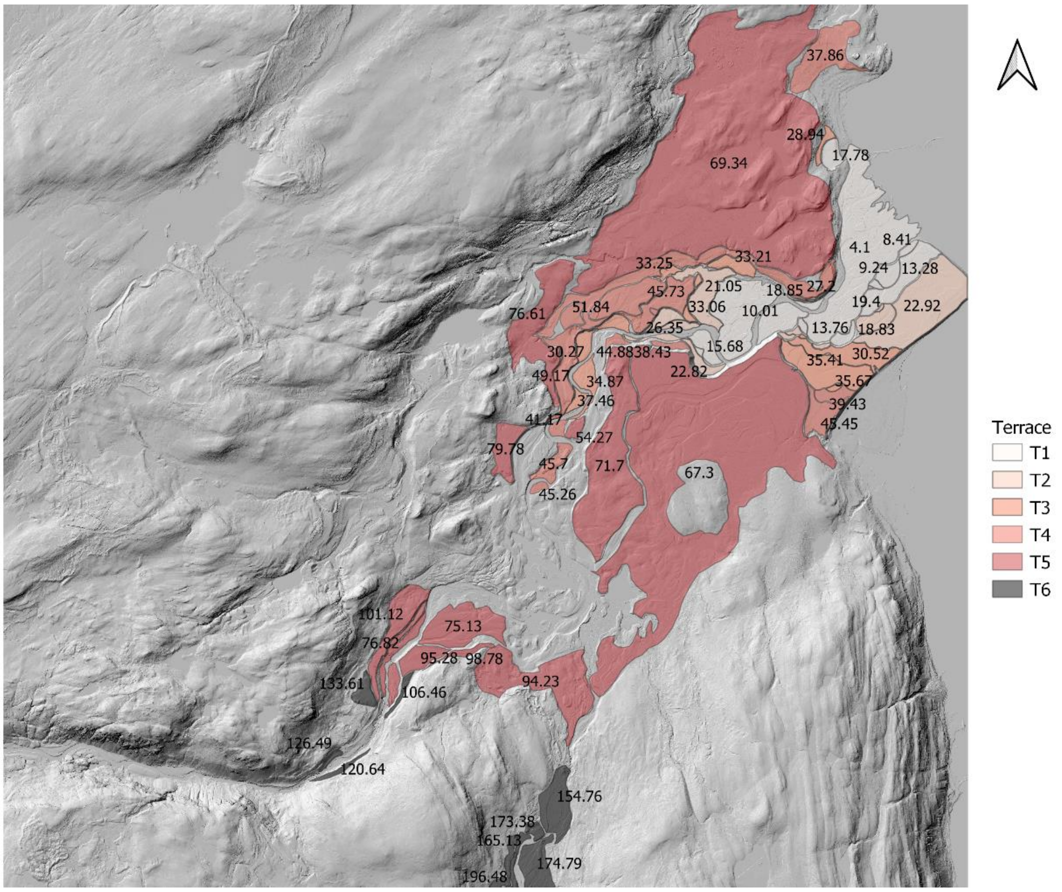

Figure 9 map shows the terrace mapped with the mean altitude values of each polygon.

Through the detailed DEM (Digital Elevation Model) analysis, I uncovered a sequence of six distinct terrace levels, labeled T1 to T6. These labels correspond to the elevations of the terraces within the sequence, with T1 being the youngest and closest to the current sea level, while T6 represents the oldest terrace.

To make the findings visually accessible, we color-coded terraces that share the same elevation consistently4.2 Mapped Terraces

4.2.1 Terraces T1

This terrace appears to be formed because of fluvial processes and is paired with an adjacent terrace, The maximum elevation of Terrace T1 is approximately 5 meters above the current sea level, while the minimum elevation is around 2 meters. The average height is approximately 2.5 meters covering a substantial area and extending over several square kilometers. Detailed hill shade images reveal that Terrace T1 exhibits a relatively flat surface with subtle undulations, consistent with typical fluvial terrace morphology. :

4.2.2 Terraces T2

Terrace T2 is another example of a fluvial terrace, paired with a neighboring terrace. Terrace T2 ranges from approximately 18 to 22 meters in elevation, with an average height of around 20 meters, It occupies a sizable area, extending over multiple square kilometers. Hillshade images highlight the relatively flat and gently undulating surface typical of fluvial terraces, Like Terrace T1, T2 appears to be a past feature, with no signs of recent fluvial activity or sediment deposition. Vegetation: Forest cover dominates Terrace T2, indicating long-term stability.

4.2.3 Terraces T3

Fluvial Terrace, Unpaired Terrace Formation: Terrace T3 shows characteristics of a fluvial origin,. It ranges from approximately 25 to 30 meters in elevation, with an average height of around 27.5 meters. Terrace T3 encompasses a substantial area, covering several square kilometers.: Hillshade images provide a clear view of the terrace's flat and gently sloping surface, typical of glaciofluvial terraces. Terrace T3 is likely a relic of past glaciofluvial activity, with no observable recent changes. Vegetation: The terrace is predominantly covered by forest vegetation, indicating long-term stability

4.2.4 Terraces T4

Terrace T4 is an unpaired glaciofluvial terrace with no immediate paired counterpart. Terrace T4 shows characteristics of a glaciofluvial origin, possibly associated with processes linked to glacial retreat It ranges from approximately 40 to 45 meters in elevation, with an average height of around 43.5 meters, Although smaller than some other terraces, Terrace T4 still extends over a significant area. : Detailed hillshade images provide a close-up view of its flat and gently undulating surface. Terrace T4 is likely a past feature, with no recent evidence of fluvial activity. Vegetation: The terrace is characterized by forest cover, indicative of its long-term stability.

4.2.5 Terraces T5

Terrace T5 exhibits glaciofluvial characteristics and is paired with an adjacent terrace. It ranges from approximately 50 to 70 meters in elevation, with an average height of around 60 meters, Terrace T5 extends over a sizable area, covering multiple square kilometers. : Hillshade images reveal a relatively flat surface with subtle undulations, consistent with typical fluvial terraces, This terrace appears to be a past feature, as there is no observable recent fluvial activity. Vegetation: The presence of forest cover suggests long-term stability for Terrace T5.

4.2.6 Terraces T6

GlacioFluvial Terrace, Unpaired Terrace. Terrace T6 is another example of a glaciofluvial terrace without a directly paired counterpart. It ranges from approximately 150 to 170 meters in elevation, with an average height of around 160 meters. It is the highest of all the terraces in elevation, Terrace T6 covers a significant area, Detailed hillshade images provide a close-up view of the terrace's flat and gently undulating surface, Terrace T6 is likely a past feature, with no observable recent fluvial activity. Forest cover dominates Terrace T6, indicating its long-term stability.

These descriptions provide a comprehensive overview of each terrace, including its type, geometry, formation, elevation characteristics, size, status, vegetation cover, and other relevant details. The information presented here serves as a valuable contribution to understanding the geological history of the study area.

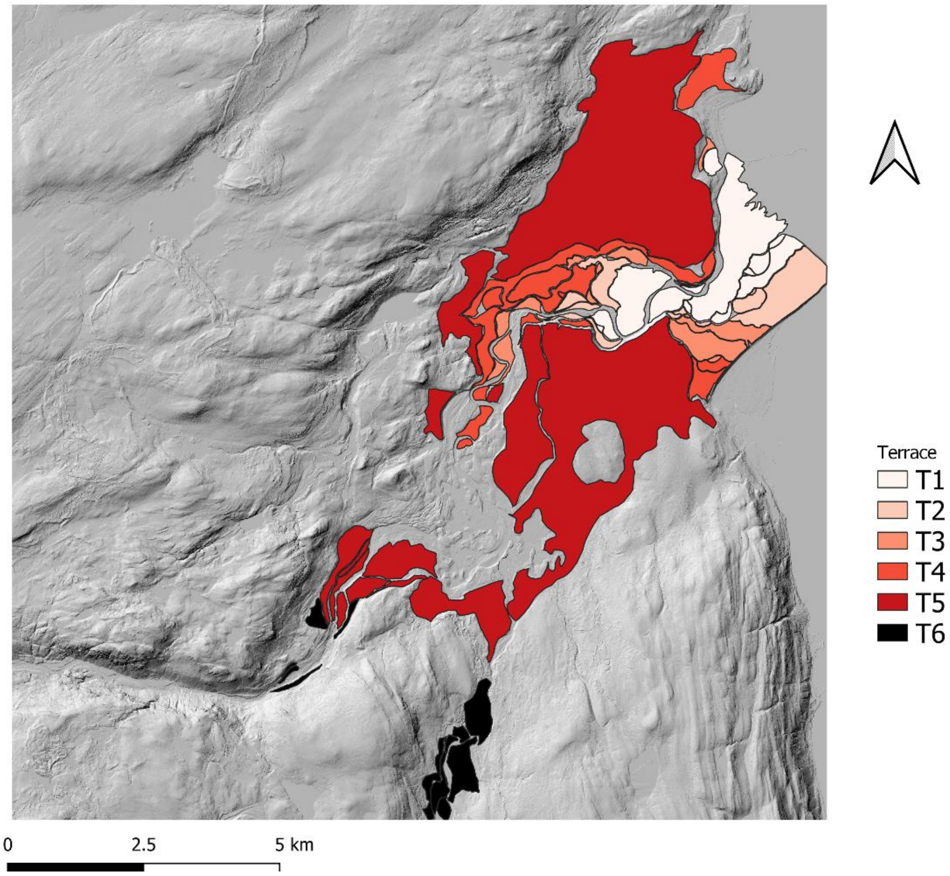

Figure 10 shows mapped fluvial terraces in the study area with terraces that may formed at the same time indicated with same colour

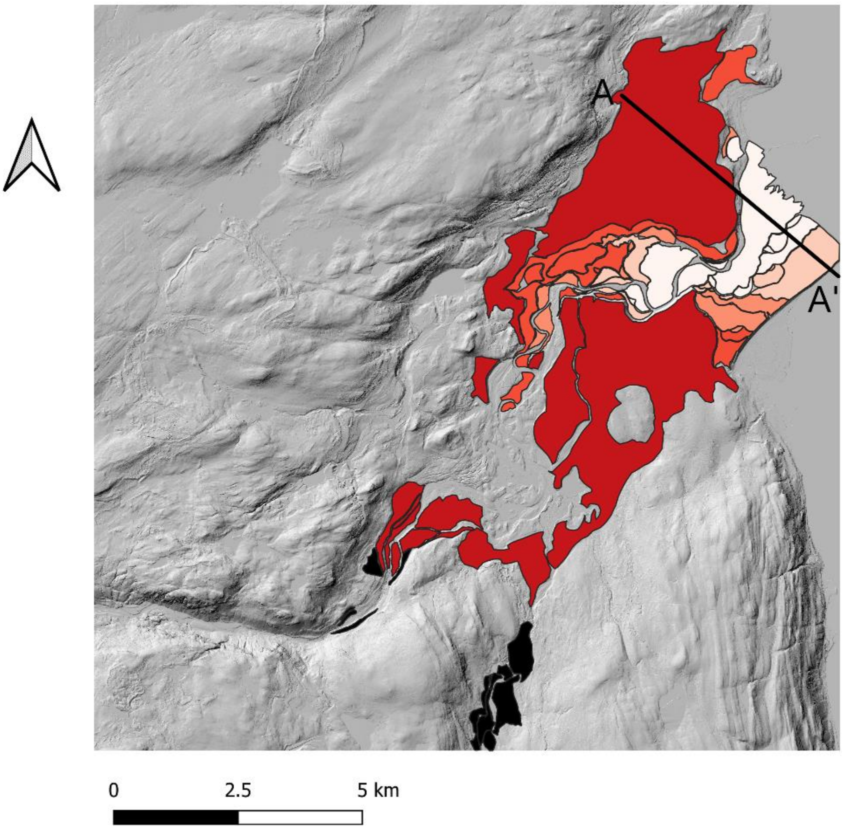

Figure 11 shows a hill shade mapping of terraces with black lines A-A´ which details the position of the profile in Figure 12

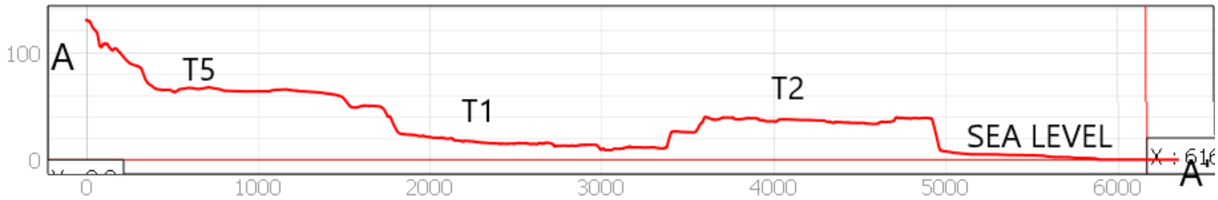

Figure 12 shows a cross-valley profile illustrating terrace morphology.

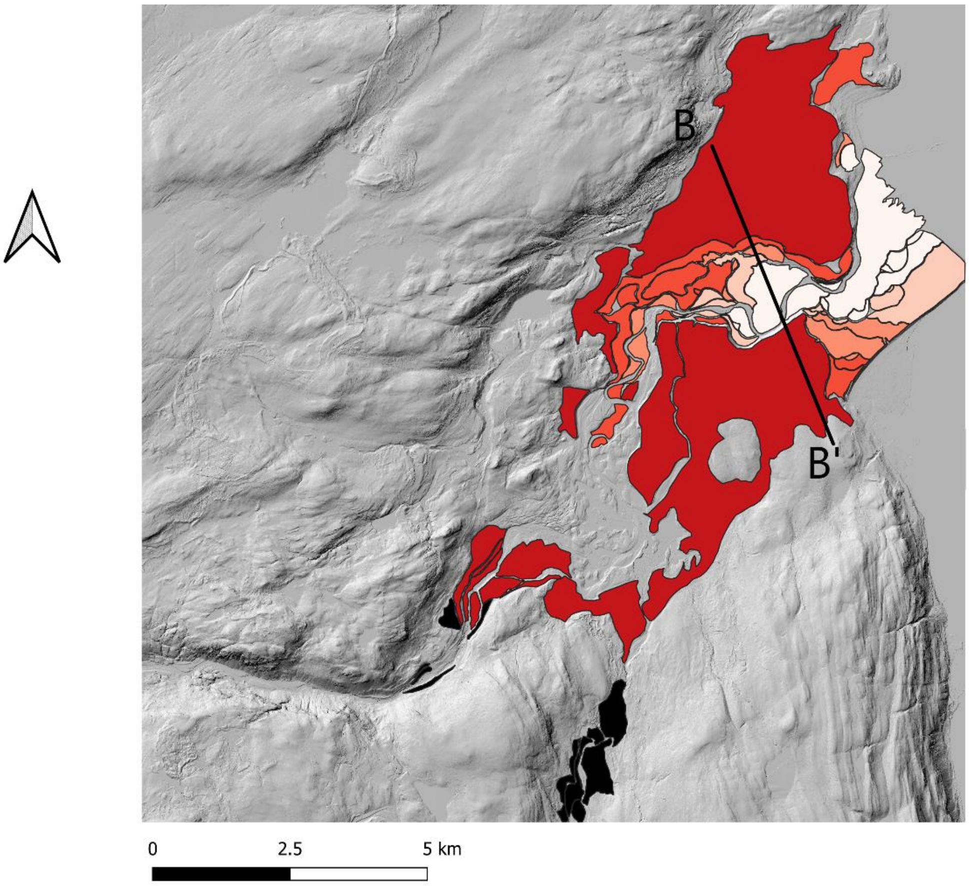

Figure 13 shows a hill shade mapping of terraces with black line B-B´ which details the position of the profile below.

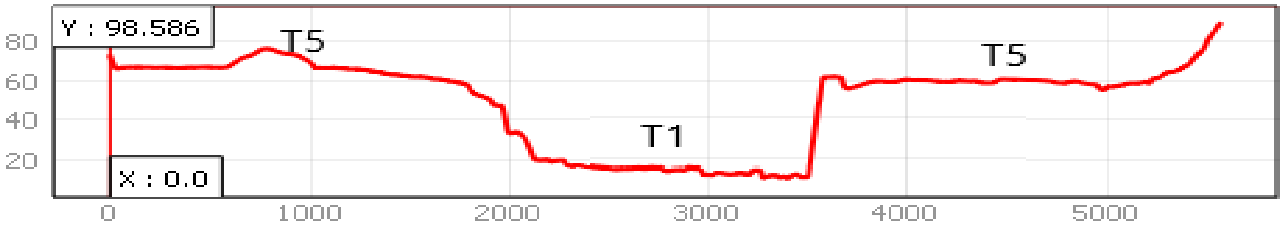

Figure 14 shows a cross-valley profile illustrating terrace morphology.

5. Discussion

The morphological differences between the terraces mapped are easily seen in the LiDar data and they were identified to be fluvial and glaciofluvial in origin. Terraces T1, T2, T3 and T4 are of fluvial origin, while T5 and T6 are glaciofluvial.

The marine limit in the study area is 69 m above the present sea level, implying that all terraces except T6 are situated below the marine limit, but T5 is situated just below the marine limit and was likely formed shortly after the marine limit was formed. This was just after the area became ice-free and there is expected to be lots of melting ice in the surrounding areas, resulting in lots of meltwaters and lots of sediments, explaining why this terrace is so much bigger than the others.

Terraces T4-T1 (T4 is the oldest and T1 the youngest) are all eroded into T5 and must therefore be younger than T5. They must have formed later when the sea level had sunk. This means that the ice has been expected to have disappeared, at least for the lower terraces, so we no longer have the same input of meltwater and sediments. As a result, the lower terraces are much smaller, and much of the material in them was probably eroded from T5.

5.1 Comparison of previous research on terraces and sea-level changes

According to Eilertsen *et al* (2015), which proposes a need for mapping distinction between terrace types, mapping terraces enhances understanding of terrace characteristics and highlights features not previously seen or poorly recognized in the field. This contributes to a more comprehensive understanding of terrace development and provides the groundwork for future assessments of landscape development, river dynamics, and geological processes that impact the region and describe the morphology of various terrace types.

The current delta plain at the study location is characterized by sandy, gravelly terrain influenced by the river, with a unique tidal pattern of moderate amplitude, ranging from 1 to 2.5 meters. Its dimensions are quite significant, measuring about 5 kilometers in length, 1 to 1.8 kilometers in width, and encompassing an area of approximately 8 square kilometers from its apex to its rim. Interestingly, this delta plain experiences regular inundation, with roughly half of its expanse lying below the mean low tide level. Above this present-day delta six different terrace levels, T1 to T6 have been identified.

One prominent feature in the landscape of Finnmark is the 'Main' and 'Tapes' shorelines, which were first documented as distinct markers of increasing sea levels by Bravais (1842). These shorelines extend along the fjords of Finnmark for considerable distances. However, deciphering the chronological sea-level history of the area has posed challenges, primarily due to the variable and non-uniform nature of beach ridges. Radiocarbon dating of marine terrace materials, often involving bivalves like blue mussels, serves as a valuable indicator of past sea levels when certain criteria are met, such as finding unbroken shells in a growth position near the top of a marine terrace formed during a past sea level. The characteristics of raised beach deposits, such as their size, shape, and distribution, are significantly influenced by the local topography and the availability of surficial deposits in the surrounding environment.

The marine limit in the study area is 69 m above the present sea level, implying that all terraces except T6 are situated below the marine limit.

One of the key focuses in this study has been on marine terraces, particularly their role in identifying sea-level rise events, notably the Tapes and Younger Dryas (YD) transgressions. The research also delves into the complex interplay of factors influencing the geomorphology of Scandinavia, including global mean sea level (GMSL) rise, glacial isostatic adjustment (GIA)-driven rebound, and smaller-scale tectonic events.

Scandinavia's extensive geomorphological records, comprising raised beaches, marine deltas, and numerous lakes, provide valuable insights into these processes. In particular, raised beaches found in Finnmark, predominantly composed of various littoral materials, owe their existence to the uplifting effects of glacioisostasy, which raises shorelines above the reach of wave action.

The shoreline gradients in Finnmark are notably steeper compared to other parts of the Norwegian coast. This phenomenon is attributed to the significant uplift of the Barents Sea, and it's closely linked to the region's exceptionally high marine limit elevation. Essentially, the study area's uplift serves as compelling evidence, contributing to the abundant terraces observed in the region.

In summary, this study has decoded the link between sea level variations and terrace elevations in the Stabbursnes study region. This research has substantially improved our understanding of the geological history embedded in Stabbursnes' topography.

Similar work has been successfully done elsewhere. For example, Demoulin *et al*. (2007) identified and examined terrace remnants in the Vesdre River basin using a novel DEM-based technique. Using an irregular network of points provided by the Belgian National Geographical Institute, they created a 20x20m resolution DEM. The DEM's hydrologic correction was then carried out using sink filling and outlet incision. The current study differs in that it used digital elevation modeling (DEM) to identify a series of six different terrace levels, designated T1 through T6, and the observation implies that glacial events may have contributed to the formation of some of the terraces. Robinson (2016) provides another interesting example of how Digital Terrain Models (DTMs) can be used to locate and extract low-relief landscape features, such as marine terraces. To compute uplift rates, terrace heights related to sea-level high stands and supplemented with isotopic age data. Using DTMs built in ArcGIS, the study effectively modifies the terrace extraction technique for the Nicoya Peninsula in Costa Rica, enhancing the process with lower cell sizes. In contrast to the current study, which compared contemporaneous terrace formations and their relationship to sea level variations. Including these elements would improve the current study and further our understanding of the mechanisms forming low-relief landscape surfaces.

According to the study by Litchfield and Clark, (2015), there is evidence of sea level rise-related aggradation along the lower sections of river basins in New Zealand. This aggravation is probably going to lead to more frequent flooding and possibly even avalanches along the river channel. Factors like valley width and gradient affect how much aggradation occurs; narrow, low-grade valleys suffer more aggradation. In addition to being influenced by gradient and valley width, the rate and amount of aggradation are primarily determined by the rate of sea level rise and the availability of sediment. It makes a difference in this study that investigates the function of marine terraces in detecting instances of sea level rise and the intricate interactions between many elements impacting Scandinavia's geomorphology, such as elevated lakes and beaches.

This chapter presented the results of the research, highlighting the achievement of the objectives outlined in Chapter 1. The findings support the effectiveness of the LiDAR-based methodology for mapping fluvial terraces, understanding their formation, and assessing past sea level changes. These results have significant implications for both the Stabbursnes study area and the broader field of geography. The next chapter will provide recommendations and conclusions based on these findings.

6 Conclusions and Recommendations

The use of high-resolution LiDAR imagery obtained from the Norwegian Mapping Authority was critical in enabling a comprehensive mapping effort centred on fluvial terraces within the Stabbursnes research region. This new imaging technique has provided an unparalleled degree of detail, allowing for a rigorous analysis and categorization procedure. The resultant information not only provides a thorough inventory of fluvial terraces but also sets the framework for a more in-depth study of the various geomorphological characteristics found in the Stabbursnes region.

The high-resolution quality of the LiDAR data has proven useful in capturing minor differences in topography, allowing for a comprehensive investigation of the topographic subtleties associated with river terraces. The study efficiently distinguished different properties and spatial distributions of these terraces by extensive analysis and categorization, giving a rich dataset for future interpretation.

This mapping endeavor is more than just a cartographic exercise; it serves as a foundation for larger geoscientific inquiries. The precise depiction of fluvial terraces, enhanced by LiDAR technology, not only improves our understanding of the Stabbursnes study area, but also provides the groundwork for future assessments of landscape development, river dynamics, and geological processes impacting the region.

This study has discovered terraces that arose concurrently with its goal of understanding the temporal dynamics of terrace creation. This sheds light on the delicate interplay of forces that have guided their evolution throughout time. The research has revealed a unified story of terrace creation via mapping and analysis, adding significantly to a nuanced understanding of the developing terrain in Stabbursnes.

This study has set a solid platform for future research into the causal elements underlying such synchronization by unraveling the temporal synchrony of terrace growth. This new knowledge not only adds to our understanding of Stabbursnes but also serves as a useful foundation for larger geological investigations, as the interdependencies of numerous elements converge to produce the landscape's ever-changing tapestry.

6.1 Implications and Importance.

The study's findings have far-reaching consequences for both the Stabbursnes study region and the larger discipline of geography. The advent of the high-resolution quality of LiDAR data has proven useful by eliminating the constraints that are associated with fieldwork.

6.2 Recommendations for Future Research

6.2.1 Advancing the LiDAR Paradigm: Towards Enhanced Validation and Methodological Refinement

Recognizing the effectiveness of the LiDAR-based technique in accomplishing the research goals, it is critical to further its usability via extensive validation and refining efforts. While the original application was successful, the following phase entails widening the frontiers of LiDAR deployment to multiple geographical locations and exposing it to rigorous inspection across diverse terrains.

6.2.2 Refinement Mandate

A deliberate effort in refining is recommended to raise the LiDAR-based technique to a level of optimal performance. This step entails a rigorous assessment of LiDAR accuracy in a variety of terrains, ranging from difficult terrain to more subtle slopes. The goal is to discover potential problems and anomalies that may develop in various environmental circumstances, allowing the process to be fine-tuned to ensure consistent and dependable performance.

By pursuing this dual method of validation and refining, the study aims to not only strengthen the credibility of LiDAR applications in the Stabbursnes study region but also to position it as a resilient and flexible instrument for larger geographical use. This phase's findings will not only add to the methodological repertory of geography but will also provide practical insights for scholars and practitioners using LiDAR technology in a global setting.

6.2.3 Prolonged Vigilance: The Imperative for Long-Term Monitoring of Fluvial Terraces

Recognizing the changing character of landscapes, the study emphasizes the crucial importance of establishing long-term and diligent monitoring techniques for fluvial terraces. To go beyond static observations, the emphasis is on long-term, continuous monitoring using cutting-edge technology. This strategic approach attempts to broaden our understanding of landscape development and untangle the various elements that influence the delicate process of terrace creation.

6.2.4. The Dynamics of Landscape Evolution

Understanding the subtle transitions and alterations that occur within landscapes necessitates a temporal perspective that extends beyond snapshots. Fluvial terraces, being important components of dynamic landscapes, are constantly impacted by diverse natural factors. Long-term monitoring allows for the capturing of these evolutionary intricacies, offering a comprehensive understanding of the interplay of geological, hydrological, and climatic variables generating terraced landscapes.

6.2.5. Continuous Observation Through Advanced Technologies

The research suggests the use of modern technology to achieve the objective of continuous monitoring. The incorporation of cutting-edge techniques and approaches, such as remote sensing and geospatial analysis, guarantees a steady flow of data, allowing researchers to monitor and understand developments in real-time. This technology integration not only makes it easier to notice tiny deviations but also enables a proactive reaction to developing trends, adding to a dynamic knowledge of landscape evolution.

Finally, the proposal for long-term monitoring of fluvial terraces goes beyond typical observation practices. It is a proactive strategy that connects with the changing character of landscapes, providing a constant evolution story. By embracing this strategic goal, the project hopes to not only contribute to a deeper understanding of landscape dynamics but also to set a precedent for long-term monitoring practices that may be applied in a variety of geographical situations.

6.2.6 Integration of Multi-disciplinary Approaches

The integration of multidisciplinary methodologies, merging LiDAR data with other geological, climatological, and archaeological information, might assist future studies. This comprehensive approach would result in a more sophisticated knowledge of landscape dynamics.

6.7 Conclusion

Finally, this thesis has achieved the objectives described in Chapter 1, Mapping of terraces, thereby providing insights into the geomorphological characteristics and processes in the Stabbursnes study area. The findings corroborate the effectiveness of the LiDAR-based technique and add to our understanding of landscape evolution, sea level variations, and terrace creation. This research provides the groundwork for future inquiries in comparable circumstances as we dive further into the complexity of location.

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