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MASS MOVEMENTS IN SVALBARD: A STUDY OF IMPACT ON INFRASTRUCTURE IN THE LONGYEAR VALLEY

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Abstract

Geomorphological mass movements are projected to increase as the local climate changes in the Arctic, following global climate change. This poses a threat to Arctic settlements, as these movements may disturb and threaten infrastructure and people. Longyearbyen, Svalbard, has experienced these changes firsthand, as three major mass movement events occurred in close succession following a change in climate and environmental conditions. These events were previously unprecedented at this scale, and previous studies on mass movement events in the Longyear Valley have been sparse. This study aims to fill in some of the existing knowledge gaps by identifying what geomorphological activities exist within the valley and how the society of Longyearbyen has adapted in response to current and future projections. This is done by comparing aerial images from 1936, 2008, and 2014, digital elevation models from 2008 and 2018, NIR data from 2008, and ground truth imagery during an excursion in May 2023. These comparisons enable observation and analysis regarding geomorphological activities, changes to infrastructure, and the ability to assess avalanche conditions in connection to infrastructure. The results indicate that several measures have been taken within the town in response to previous and future projected events, as it is continuously densifying as a recreational town. Several geomorphological activities have additionally been identified within the valley, with a strong presence of colluvial fans caused by cornice falls.

Keywords:

Geomorphology, Mass movements, Longyear Valley, Svalbard, Infrastructure

Sammanfattning

Geomorfologiska massrörelser förväntas öka när det lokala klimatet förändras i Arktis till följd av de globala klimatförändringarna. Detta utgör ett hot mot arktiska bosättningar, eftersom dessa rörelser kan störa och hota infrastruktur och människor. Longyearbyen på Svalbard har upplevt dessa förändringar i direkt form, då tre stora massrörelser inträffade i nära följd efter förändrade klimat- och miljöförhållanden. Sådana händelser hade tidigare inte inträffat på så stor skala, och det finns få tidigare studier om massrörelser i Longyeardalen. Denna studie syftar till att fylla några av de befintliga kunskapsluckorna genom att identifiera vilka geomorfologiska aktiviteter som finns i dalen och hur samhället i Longyearbyen har anpassat sig i respons till existerande och framtida prognoser. Detta görs genom att jämföra flygbilder från 1936, 2008, och 2014, digitala höjdmodeller från 2008 och 2018, NIR-data från 2008, och egen insamlad data från en exkursion i maj 2023. Dessa jämförelser möjliggör observation och analys gällande geomorfologisk aktivitet, förändringar i infrastruktur, och möjligheten att bedöma lavinförhållanden i anslutning till infrastruktur. Resultaten visar på att flera åtgärder har vidtagits i staden som svar på tidigare och framtida prognostiserade händelser, då staden kontinuerligt förtätas som en rekreationsort. Flera geomorfologiska aktiviteter har även identifieras i dalen, med en stark förekomst av kolluviala koner som orsakats av fall av överhängande snötungor från bergskanterna.

Nyckelord:

Geomorfologi, Massrörelser, Longyeardalen, Svalbard, Infrastruktur

Preface

This bachelor thesis represents the end of 3 years of geography studies at the University of Gothenburg. Our common interest in physical geography made us consider focusing on climate-related processes in a sub-Arctic or Arctic region. While thinking and spawning ideas of what our thesis could be, we thought of Svalbard and its unique and vulnerable climatic conditions in the face of the ongoing global climate crisis. This, and the fact that the northernmost settlement in the world is located on the island of Spitsbergen, made us reach out to Dr. Andreas Johnsson for inspiration and consultation regarding what would be possible for a bachelor's thesis.

As such, we would like to extend our deepest gratitude to our supervisor dr. Andreas Johnsson for providing us with data in need of analysis and guidance whenever we had questions. We would also like to thank our classmates for providing motivation and feedback during the writing process, as well as our course coordinators Sofia Thorsson and Jonas Lindberg. Lastly, we would like to thank Norwegian Polar Institute for the open access to their geographical data, the German Space Agency and the University of Münster for access to HRSC-AX data, and the people Longyearbyen of which we had the pleasure of speaking with for insight on the valley and town.

Oscar Amin & Wilma Rydell, Gothenburg 24-05-2023.

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1. Introduction

Like many other regions on Earth, the Arctic is heavily impacted by environmental changes due to climate change. Changes to the local environment such as temperature, seasonal weather patterns, amount of precipitation, and other environmental aspects can lead to drastic results. As a permafrost region, this in turn has a strong effect on periglacial and geomorphological mass movement processes in the Arctic (Ramage, Jungsberg, Meyer, & Gartler, 2022).

The archipelago of Svalbard, located in the Arctic, is surrounded by unique climate conditions which are contributing factors to the islands' status as one of the most climatically sensitive areas in the world. Conditions such as avalanche activity have thus been difficult to predict, resulting in limited research conducted in the past (Prokop, Hancock, Praz, & Jahn, 2018; Rogers, Yang, & Li, 2005). Furthermore, changes in weather patterns have been attributed to recent changes in the climate due to global warming, which reduces the effectiveness of safety assessments for people and infrastructure. Another of the major challenges with accurately forecasting avalanches and other forms of mass movement in the Arctic is the sparse data sources, creating further knowledge gaps (Hancock, Prokop, Eckerstorfer, & Hendrikx, 2018).

Longyearbyen, located in central Svalbard in the Longyear Valley, is heavily affected by these challenges. Initially established as a small mining community, the town today hosts about 2000 citizens with further plans to densify and grow as a settlement. As more houses and structures are built on permafrost ground, permafrost degradation poses a serious threat to the integrity of the structures (Humlum, Instanes, & Ludvig, 2003). This is particularly true for older buildings and infrastructure. In addition, the increased susceptibility of mass movements reduces the safety of further growth, and Longyearbyen has seen direct results of these changes in the form of an unprecedented snow avalanche in the year 2015, dislocating multiple houses located in Lia closest to the northwestern slope of Sukkertoppen and claiming two victims consequently (Indreiten & Svarstad, 2016).

Svalbard has for hundreds of years been a semi-polar desert, with low precipitation year-round. The year after the snow avalanche ended up being the warmest and wettest year ever recorded on the islands. Due to the increased precipitation, a large active-layer detachment slide followed by a high-volume debris flow occurred in October 2016 on the western side of the valley. Large blocks of sediment and rock could be observed moving down the slopes during the event, crossing over the road and toward the river (Christiansen et al., 2016).

Later in the winter season, the precipitation changed from rain to snow and several rain-on-snow events occurred. This, in combination with increased deposition of high-density snow wind slabs, triggered another snow avalanche close to the previous site of 2015 in February 2017, with no casualties. (Jonsson, Nerland, Lande, Kanstad, & Hellum, 2018; Hancock et al., 2018; A.K. Sydnes, M. Sydnes, & Hamnevoll, 2021). But the increased rate of environmental changes combined with the surge of activity and densification of Longyearbyen continues to pose a serious challenge to the future of the Arctic settlement.

1.1 Purpose

The purpose of this study is to investigate and map out geomorphological mass movements within the Longyear Valley, Svalbard, using aerial imagery, digital elevation models (DEMs), and ground truth observations. These will be combined with an overview of the current infrastructure and mitigation strategies used by Longyearbyen in response to these geomorphological activities.

1.2 Research questions

- What geomorphological activities exist within the Longyear Valley that may affect Longyearbyen?
- How does Longyearbyen as a society deal with the effects caused by geomorphological activity, and what responses have been made about the current and future development of infrastructure and landslide management in the Longyear Valley?

2. Knowledge overview

2.1 Periglacial and paraglacial processes

Periglacial and paraglacial processes differ because the forces which drive them are different. Periglacial processes, which are most prominent in the Longyear Valley, are conditioned by freeze-thaw action and permafrost-related processes. Paraglacial processes are non-glacial processes directly conditioned by glacial movements of an area, as deglaciation exposes ground that is in an unstable state to erosion, modification, and sediment release (Miller, 2011; Curry, 1999).

Solifluction is a common periglacial process in polar regions and occurs when thawed earth materials become saturated, causing slow-moving debris flows on top of the permafrost layer due to gravity, with an observable example in Figure 1 (Harris et al., 2008). This process may be initiated by thawing, where excess pore pressure is created in the soil (Rowley, Giardino, Granados-Aguilar, & Vitek, 2015).

Debris flow deposits, often creating fan-shaped accumulations, are another one of the most common landforms in polar regions and may be both periglacial and paraglacial (Ballantyne, 2002; de Haas, Kleinhans, Garbonnaeu, Rubensdotter, & Hauber, 2015; Lancaster, Nolin, Copeland, & Grant, 2012). Debris flows are defined by saturated poorly sorted sediment, which moves or surges downslope due to the gravitational pull, as seen in Figure 1. Due to the distinguished interaction of solid and fluid forces of these flows, they may occur with little warning and can cause great damage to objects in their way (Iverson, 1997). Debris flows in the Arctic are primarily triggered and caused by heavy rain events, rather than snow melting. These flows require a certain minimum of water input per time interval to be triggered, which is a cause for concern as precipitation is projected to increase (Adakudlu et al., 2019; Bernhardt, Reiss, Hiesinger, Hauber, & Johnsson, 2017; Guzzetti, Peruccacci, Rossi, & Stark, 2008).

Colluvial fans, or talus cones, may be periglacial and paraglacial and are defined by fragmental debris at the lower part of steep topographic slopes such as mountains (Ballantyne, 2002; Blikra & Nemec, 1998; de Haas et al., 2015). These fans are often characterised by coarse-grained material as seen in Figure 1. Due to the characteristics of such avalanche processes, colluvial fans are distinguishable from alluvial fans.

Avalanches are defined by the rapid movements caused by gravity in steep slopes of dry or wet rock debris, snow, or a mix of the two. These may include rock and debris falls, flows of debris and snow, and slides of debris or rock (Blikra & Nemec, 1998). Slush flows, defined as water-saturated snow, may also create colluvial fans as the mixture of water and snow may drag rocks and sediment along, depositing debris along its path (Bones, 2018; Gude & Scherer, 2017).

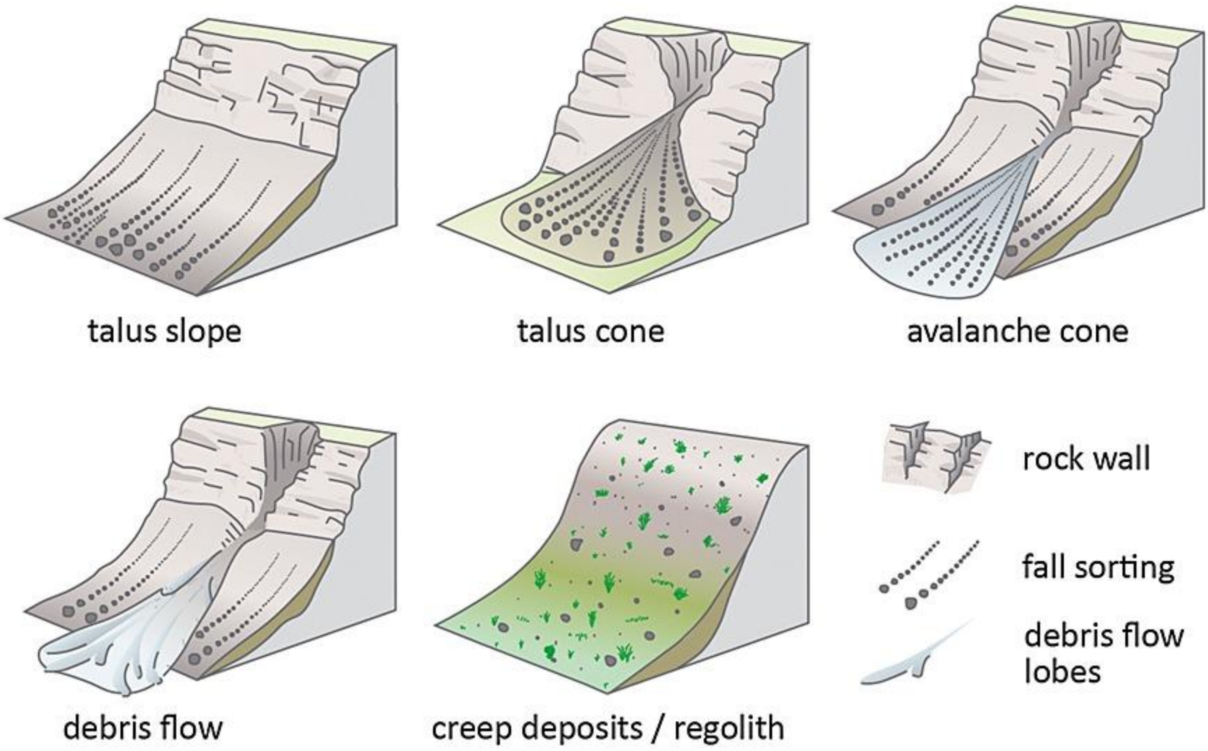

Figure 1: A visualization of different geomorphological processes in slope areas. Source: Hoffman, Müller, Johnson, & Martin (2013).
Figur 1: En visualisering av olika geomorfologiska processer i sluttningsområden. Källa: Hoffman, Müller, Johnson, & Martin (2013).

Alluvial fans are conical landforms defined by the sedimentary deposits of water channels from an upland drainage area, which develop from the emergence point and into a fan downslope. These deposits are often coarse-grained due to being poorly sorted and change over time due to erosion and sedimentation determined by the stream of water (Blair & McPherson, 2009). This landform may form during periglacial and paraglacial conditions (Ballantyne, 2002; de Haas et al., 2015).

Cornice falls are defined by an overhanging mass of snow formed by the wind over a sharp terrain feature such as a mountain cliff side, being released down a steep slope. This break-off may pull snow with it from the top of the cliff, which can largely increase the snow mass being released (Colorado Avalanche Information Center [CAIC], n.d.). Cornice falls may also break away rocks of varying sizes from the point of break-off, depositing these in a fan shape below. This geomorphological process is the most efficient erosion and transport agent on the slopes facing northwest in the Longyear Valley (Eckerstorfer, Christiansen, Rubensdotter, & Vogel, 2013).

Coastlines are shaped by a myriad of processes, by waves, tides and currents, river sedimentation, ice, and wind. These processes either feed or erode at the coastline, changing its shape over time (de Blij, Muller, & Williams, 2004:610-611). Arctic coastlines are vulnerable to climate warming as the processes dictating the build-up of sedimentation are heavily influenced by the presence of snow and ice both on land and sea, permafrost and ground-ice content in the sediments, and thaw subsidence and thermal erosion. All of these are sensitive to changes in the local climate and environment and are thus directly and indirectly affecting coastal erosion (Bendixen & Kroon, 2016).

Arctic floodplains and rivers are equally sensitive to these changes, though the relation between climate change and change in river run-off is complex. Changes in the climate may impact sedimentation and nutrient transport, which may affect the ecology as well as the humans relying on the river for water (White et al., 2007).

2.2 Research of Arctic climate change

The climate in the Arctic is changing rapidly, faster than the global average (Warwick, 2019). One of the reasons why the Arctic is warming faster is due to Arctic amplification. This affects atmospheric circulation over the Arctic and studies have shown that this may remotely affect areas outside of the Arctic as well (Sellevold, Sobolowski, & Li, 2016; Xu, Tian, Zhang, Screen, Zhang & Wang, 2023). Exactly how the warming affects remote regions is under debate within the scientific community, but the fact that it plays a role in the climate both within and outside the Arctic region has been proven correct (Xu et al., 2023).

The climate of central and western Svalbard is strongly dependent on the warm Norwegian Atlantic Ocean current, which flows along the western coast of Spitsbergen. Svalbard is also located within the North Atlantic cyclone track, exposing the islands to relatively high air temperatures. This makes Svalbard warmer than other locations at similar latitudes, which affects both weather and ground conditions (Orr, Hansen, Lappalainen, Hübner & Lihavainen, 2019).

Changes in weather and temperature patterns occur because of and result in decreasing amounts of whole-year sea ice (Koenigk, Key & Vihma, 2020; McBean, 2021; Smith et al., 2022; Wickström, Jonassen, Cassano & Vihma, 2020). The albedo in the Arctic is decreasing as more of the dark ocean water is exposed, absorbing, and storing large amounts of heat from the atmosphere (Du, Zhang & Shi, 2019).

These changes to the ocean brought by global warming also affect the atmosphere, which in turn affects the Arctic polar vortex. The vortex usually locks cold air in the Arctic but due to the effect of these changes, it is weakening which affects weather patterns globally through the jet stream (McBean, 2021). Over Svalbard, these changes show in the form of increased precipitation and temperatures. Precipitation on the islands has been increasing in recent decades due to the changes in atmospheric circulation patterns and changes in the amount of sea ice, and events such as rain-on-snow during the winter season have increased (Adakudlu et al., 2019; Jonsson et al., 2018; Wickström et al., 2020).

Despite this, the amount of precipitation over Longyearbyen is less than in the surrounding areas, with as little as half the measured amount elsewhere on the island of Spitsbergen. Precipitation on Spitsbergen is strongly affected by its topography, and in the Longyear Valley, this creates a rain shadow (Førland, Isaksen, Lutz, & Hanssen-Bauer, 2020). However, an increase in “mild weather days” during the winter months has been observed and is projected to increase in the Longyear Valley, with precipitation in the form of rain and average temperatures of >0°C (Adakudlu et al., 2019).

The weather changes predicted over Svalbard may increase the occurrence of snow avalanches and slushflows. This increase is due to the stability in the snowpack becoming less stable, as the structure and temperature of the snow play an important role in its stability.

These mass movements differ because of their contents, where snow avalanches occur because of the instability in the snowpack while slushflows occur when melting or precipitation result in the snowpack becoming saturated. (Adakudlu et al., 2019; Hancock et al., 2018; Gude & Scherer, 2017).

2.3 Permafrost research

Permafrost is defined by soil, rock, sediment, clear ice, and even bedrock, which remains at or below 0°C for two consecutive years and covers most of the Arctic surface (Adakudlu et al., 2019; Ramage et al., 2022; Tedrow, 2005). Research has found that permafrost is highly affected by climate change, as its negative thermal state is sensitive to changes in temperatures. These are mediated by conditions at or near the ground surface, such as how snow cover insulates the ground during winter and how the thermal properties of the active layer reduce the heat flow further into the ground. (Orr et al., 2019). This results in permafrost being warmest at coastal sites or where the snow cover accumulates more (Adakudlu et al., 2019).

Permafrost on Svalbard differs from other locations at comparable latitudes because of the mild climate over the islands, affecting both temperature and weather. This results in Svalbard having the comparatively warmest permafrost at these latitudes, with observed steadily warming temperatures. The permafrost on Svalbard is estimated to range from several hundred meters in depth on the mountain peaks to a few meters along the coast and coastal areas (Adakudlu et al., 2019; Gilbert, Instanes, Sinitsyn & Aalberg, 2019; Orr et al., 2019). As the climate warms, problems with periglacial processes will increase as the active-layer thickness increases, posing a threat to houses and infrastructure within the valley (Hestnes, Bakkehøi, & Jaedicke, 2016).

2.4 Arctic vegetation

Though the Arctic may be a harsh environment for plant life, it is still prevalent and prevailing on the islands. This is made possible by the Norwegian Atlantic Current as a continuation of the Gulf Stream, which is making the high latitudes of Svalbard hospitable for certain vegetation. Most of the plants found on Svalbard are low-lying and grow by creeping, and many communities have been identified as moss tundra, fen, or marsh containing plants such as dwarf shrubs, mosses, lichens, herbs, grasses, reeds, sedges, and some ferns (Norsk Polarinstitutt [NPI], n.d.; Orvik, 2022; Vanderpuye, Elvebakk, & Nilsen, 2002).

Different periglacial and paraglacial processes alter the landscape structure and vegetation as local pulse drivers, as they remove or move soils (Ravolainen, 2020). Even though the low vegetation and shallow roots do little to stabilise cryosoil, it serves as an excellent indicator of mass movement events in Arctic landscapes.

2.5 Hanaskogdalen

Previous studies have shown that similar geomorphological processes occur with similar frequencies in Hanaskogdalen and the Longyear Valley (de Haas et al., 2015; Ellermann, 2023; Holm Hjelmerud & Persson, 2022). Documented processes include debris flows, active layer detachments, and different types of avalanches, including cornice falls, slab, snow, and slush avalanches. This makes the valleys viable for comparison and showcases the natural occurrence of flows and processes that might be more controlled within the settlement of Longyearbyen. One such process is sedimentation of the rivers, where the river runoff is heavily monitored in the Longyear Valley to control flooding and limit damage to infrastructure (de Haas et al., 2015; Meyer, 2022). Ellermann (2023) shows the coastline of Hanaskogdalen in Figure 2, where sedimentation is driven by the same variables and where the run-off is unmonitored, making it viable for comparison with sedimentation along the coast of the Longyear Valley.

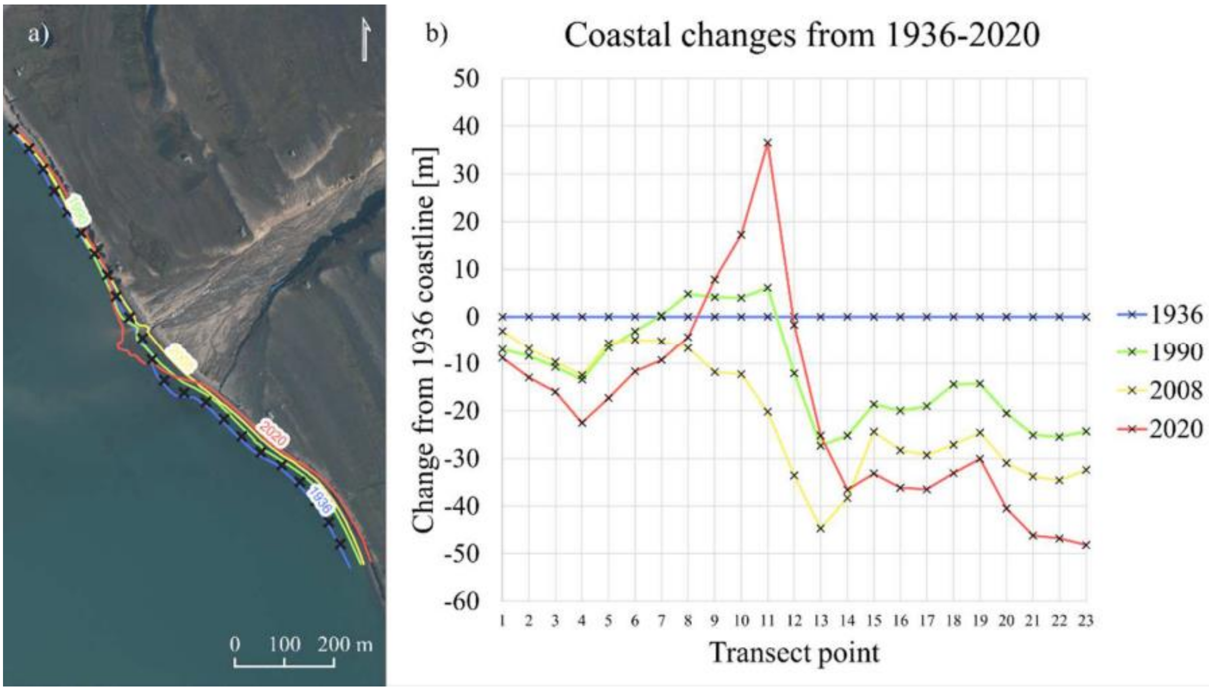

Figure 2: a), an orthophoto (2013) of Hanaskogdalen's coast and the mapped coastlines with the respective year as a label. b), coastal propagation and retreat [m] at one transect point (x-axis) by 1990, 2008, and 2020 with respect to the coastline of 1936. Point 1 marks the northernmost transect and point 23 is the southernmost transect point. Cited from source: Ellermann (2023).

Figur 2: a), ett ortofoto (2013) över kusten i Hanaskogdalen och kartlagda kustlinjer med respektive år som en etikett. b), kustutbredning och -reträtt [m] vid en transektpunkt (x-axeln) vid 1990, 2008 och 2020 med avseende till kustlinjen 1936. Punkt 1 markerar den nordligaste transekten och punkt 23 är den sydligaste transektpunkten. Citerad från källa: Ellermann (2023).

2.6 Previous hazard assessment in Longyearbyen

Up until recently, there has been a lack of knowledge regarding mass movements on Svalbard due to limited research done in the past (Prokop et al. 2018). However, several hazard assessments have been done by the Norwegian Geotechnical Institute (NGI) for residential sites in Longyearbyen. The geographical regions in the focus of these were primarily around Vannledningsdalen and Lia, where assessments for slush flows and dry snow avalanches respectively were made during the 1990s. The results of these included recommendations by NGI for the construction of dams and snow fences, but they were not implemented. Later in September 2015, NGI advised to revise the plans and hazard zones from the 1990s, based on updated knowledge regarding global warming's role in mass movements in the Arctic, but the granting authority declined a request for financial aid and support (Hestnes et al., 2016; Jónsson, Kronholm, Eid Nilsen, Birgisson, & Eiður, 2019).

Other hazards have occurred and been sparsely documented before NGI conducted hazard assessments in the area. Some of these include, aside from avalanches and the snowdrifts that may trigger them - debris and slush flows, glacier rivers, cornice breakoffs, and rockfalls from the steep cliffs surrounding the valley. All these occurrences have previously caused or been close to causing damage to areas with infrastructure, which highlights the challenges that lie ahead for a densifying town in the Arctic. However, due to frequent replacements of staff connected to authorities and other important knowledgeable persons, valuable knowledge is often lost along the way due to the infrequency of the hazardous events compared to the frequency of replacements. NGI noted as early as 1986 that all the houses on the hill foot of the mountainside were endangered. The safety deputy of the community at the time confirmed their evaluation with the conclusion that the houses on roads 228 and 230 were the most exposed. This evaluation turned out to be correct, as the houses which were hit by the avalanches previously mentioned were located on these roads (Hestnes et al., 2016).

Several studies have since then been conducted to take measurements to protect infrastructure and people. One such study was undertaken by Sydnes et al. (2021), who conducted a study on post-crisis learning in Longyearbyen. In response to the events, a local and regional avalanche warning and preparedness system has been established and implemented.

The study found that this system, which was first implemented after the first avalanche in 2015, failed to consider the consequences of climate change. Precipitation in the form of rain undermined stability, which had failed to be considered when developing the risk assessment framework. This goes to show that learning is a continuous process, through the identification and implementation of lessons, as was the case in 2017.

2.7 Infrastructure damages and expected future geomorphological changes

Following the damage done to infrastructure during the avalanches in 2015 and 2017 and the debris flow in 2016, concern has risen regarding future damages in Longyearbyen. In response to the events, national and local authorities issued mitigation measures focused on the mountainside of Sukkertoppen. Two new risk hazard assessments for the area were initiated, one after each avalanche event, which divided the calculated affected areas into different risk zones.

Snow fences were built anchored to the bedrock beneath, and supporting structures such as a catching dam for mass movements and a drainage canal were established in 2018. A concern for the long-term safety of these mitigation efforts was already prominent at the point of establishment, due to the changes in permafrost conditions. The snow fence already showed signs of solifluction of about 3-5 cm/y, due to permafrost degradation one year after its establishment (Jónsson et al., 2019; Jonsson et al., 2018).

Climate data shows that trends that have been observed for the past decades are likely to increase, which is a serious threat to already existing infrastructure as well as to new development plans (Bekele & Sinitsyn, 2020). One major concern is infrastructure placed on sloping terrains, where changes in ground and air temperature are believed to be among the most important variables along with soil moisture. These factors affect the active layer thickness and thus the permafrost beneath, and it is expected that the stability of the slopes and bearing capacity of existing foundations are to be affected in turn. Evaluations for slope stability show a decrease in stability with increasing active layer thickness, increasing the risk of solifluction. This mass movement was not accounted for when planning for buildings in Longyearbyen, causing yet another problem in need of a safety assessment for the future (Bekele & Sinitsyn, 2020; Harris et al., 2008).

Another concern that has been a known occurrence is cornice fall avalanches, as they are known to erode the plateau edge that has been weathered by ice segregation. Either this allows the rock to be brought down with the snow, by collapsing cornices or cornice fall avalanches, as the weathered sediment is mechanically plucked from the ridge. This counts as a type of avalanche sedimentation, where the rock debris is being deposited onto and forming avalanche plains. The formation process is important to understand as certain houses in Nybyen, located further into the Longyear Valley, are located on an avalanche plain. Cornices form on the lee side of the eastern side of the valley due to the southeasterly winds and heavy precipitation in the form of snow, as can be seen in Figure 3. With climate change, which may bring changes to wind, melting, and precipitation patterns, the direction of avalanche sedimentation will also change. This may lead to changes not only in how it is deposited in the areas already affected by this kind of sedimentation, but also in where they may occur overall (Eckerstorfer et al., 2013).

Figure 3. Accumulation of cornices on the eastern side of the Longyear Valley. Photographed 02.05.2023. Source: Authors’ own (2023).

Figur 3. Ackumulering av överhängande snötungor på den östra sidan av Longyeardalen. Fotograferad 02.05.2023. Källa: Författarnas egna (2023).

2.8 City planning and densification of Longyearbyen

A new revised area plan was adopted in February 2017 and encompasses the years 2016-2026. This plan is based on the local community plan, assembling the long-term and overarching goals for the community of the town. These goals clearly state the transition into a tourist-focused town, where they state the importance of making the town attractive and safe for residents and visitors. With these goals in mind, the plan sets out a comprehensive investment in infrastructure and the prioritisation of future growth as a travel destination. Due to the settlement being located in a valley with natural limitations on expansion where few areas with low exposure or risk of hazards are left unused, densification in existing building areas is occurring and is part of the adopted area plan. Housing is being added in Gruvedalen in the northeastern part of Longyearbyen, and the plans are discussing converting parts of the current harbour into housing areas. This would require current industrial buildings in the area to relocate, with talks of moving them closer to the airport. Certain industries could be moved further south in the Longyear Valley towards Nybyen, though this would require new risk assessments as the area is considered a hazard zone for avalanches (Longyearbyen Lokalstyre, 2019).

The population of Svalbard is being described as slowly increasing by Longyearbyen Lokalstyre (2019), but it is difficult to know the exact number due to certain complications. These include registration of residency, where people moving back to the mainland do not change their address as they earn more income if they are registered on Svalbard according to Norwegian law. As of 2023, 2 530 people are registered in Longyearbyen and Ny-Ålesund (Statistik sentralbyrå, 2023). Statistisk sentralbyrå (2023) shows the ongoing demographic change in Longyearbyen, where the net migration in 2022 of mainland Norwegians is negative, while net migration for residents from abroad is increasing on the island. However, since 2011, a positive trend can be seen for both residents from Norway and abroad.

3. Study area

The site for this study is the Longyear Valley, a valley located in Svalbard with its geographical position shown in Figure 4.

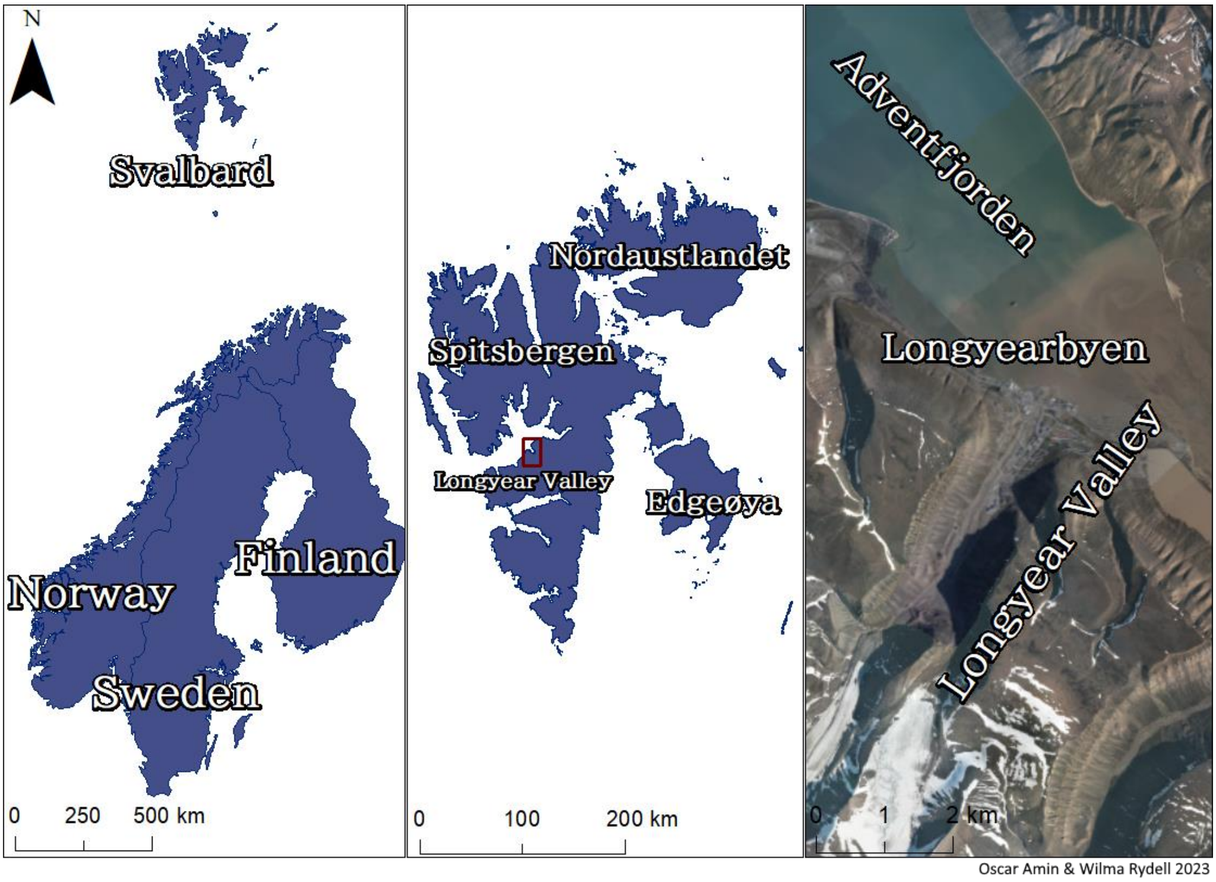

Figure 4. The location of the Longyear Valley and Longyearbyen in Svalbard, Norway. Source: Authors' own (2023). Data source: Basemap Europe, Efrainmaps; Basemap Svalbard and Svalbard Orthofoto 2014, Norwegian Polar Institute.

Figur 4. Lokaliseringen av Longyeardalen och Longyearbyen på Svalbard, Norway. Källa: Författarnas egna (2023). Datakälla: Baskarta Europa, Efrainmaps; Baskarta Svalbard och Svalbard Ortofoto 2014, Norska Polarinstitutet.

The topography of Svalbard was largely formed due to tectonic faulting occurring millions of years ago. The Longyear Valley has, like most fjords and valleys in Spitsbergen, been affected by the continuous erosion by surges and retreats of glaciers on land, along with different types of weathering (Umbreit, 2008:11).

The geology of the Longyear Valley consists of layers of shale, sandstone, and siltstone from the Jurassic and Cretaceous, but mainly sandstones and shales from the Tertiary and Quaternary periods (Elvevold, Dallman, & Blomeier, 2007).

These softer rocks produce mineral soil by disintegrating, though most of the areas on Svalbard lack soil in significant amounts. The soil that does exist is mainly locked in the permafrost, with the active layer usually thawing between 1 to 1.5 meters during the summer months (Elvevold et al., 2007). This depth however is steadily increasing with climate change. As cited by Isaksen et al. (2022), permafrost is one of the indicators of global climate change, particularly near-surface permafrost which is often highly sensitive as it depends on air temperatures and precipitation. Thawing permafrost also poses a high risk of further reinforcing climate change as permafrost has acted as a carbon sink for thousands of years, locking carbon and methane in the frozen ground.

The town of Longyearbyen was founded and established as a mining site by the American businessman John Munroe Longyear in 1906. The town and company were handed over to Store Norske Spitsbergen Kullkompani in 1916 and the Svalbard Treaty was signed five years later, officially recognising Norwegian sovereignty over the islands with certain rights for citizens of the signatories (Visit Svalbard, n.d.). The island of Spitsbergen is thus inhabited by many nationalities, many of whom were workers in the mines until the town transitioned during the 1990s from being solely a mining site to becoming a recreational town (Hestnes et al., 2016).

The coal deposits within Longyeardalen were mainly formed during the Tertiary period when deep layers of peatlands formed over thousands of years and were later covered by sedimentary deposits (Umbreit, 2008:7). The location of the establishment of the town was dictated by these deposits, as it was only intended to be a site for mining and not for a proper settlement. Due to the narrow valley nestled between steep scree slopes with a river running through from the glacier down to the fjord, Longyearbyen has been described as one of the worst places on the island to maintain and develop a town (Meyer, 2022). As the town was not intended to grow and densify into a long-term society, the exposure to avalanches and landslides did not pose a threat to urban development historically. Today, many of the existing neighbourhoods, most notoriously Lia, are built on avalanche paths and are thus exposed to geomorphological hazards.

4. Method

This section details the methodology chosen for this study and a description of how it was conducted, along with the use of data. The data used in this study consists of aerial imagery, elevation models, and on-site ground truth images.

When categorizing physical activity and changes, the method used to identify these was similar to previous studies with similar goals (Bernhardt et al., 2017). By comparing hillshade modules and aerial imagery, identifications of mass movements such as debris flows could be seen in the study area. In addition, data such as NIR data was used to identify vegetation growth to detect debris flow activity. The movement and disruption of vegetation leave detectable observations in the *false color IR* visualization.

4.1 Data sources

The data used in this study consists of aerial imagery, elevation models, and on-site ground truth images, which were further used to execute remote sensing analysis through ArcMap. The choice of software was primarily based on existing knowledge of its various tools and experience in how to operate it. All data used in this study can be seen in Table 1.

Table 1. Data used to conduct results of remote sensing analysis, showing format, source, resolution, and sensor.

Tabell 1. Använd data för att utföra resultat av fjärranalys, med format, källa, resolution, och sensor.

Dataset	*Format*	*Source*	*Sensor*
World map, 2020	Raster	EfrainMaps	
Svalbard geology, 2016	Raster	DLR	
Svalbard Orthophoto, 2014	Raster	NPI	Aerial
Svalbard Basemap, 2012	Vector	NPI	Aerial
Svalbard Orthophoto, 1936	Raster	Geyman et al.	Aerial
Svalbard aerial photo (false-color infrared), 2008	Raster	Hauber et al.	HRSC-AX
Svalbard aerial photo (false-color infrared), 2011	Raster	Hauber et al.	HRSC-AX
DEM 2008	Raster	Hauber et al.	HRSC-AX
DEM 2018	Raster	PGC	Worldview-1

The aerial imagery was acquired with sensors used to intercept different forms of radiation through wavelengths, which showcases the variations among the data. Through an expedition over Svalbard to capture aerial imagery in 1936/1938, data has been collected and georeferenced for usage (Geyman, van Pelt, Maloof, Aas, & Kohler, 2021). The data over Svalbard and its infrastructure, geology, and orthophotos have been collected by NGI for usage in various studies. Aerial photo imagery from 2008 and 2011 was collected with an airborne HRSC- (High-Resolution Stereo Camera) AX camera (Hauber et al., 2011), along with the DEM data of 2008. DEM data from 2018 were acquired from the PGC and collected using satellite imagery from Worldview-1 during summertime. The datasets used from 1936 were in the shape of single band (*gray*) visualization, along with the DEM data, while images from 2008 and 2011 could be visualized in RGB and NIR wavelengths.

4.2 Analysis methods

To map and highlight geomorphological activity, comparisons between orthophotos and NIR data were made to visually confirm different forms of mass movements. These were inspected and confirmed by comparing them to each other and previous studies that highlight similar mass movements. The coastline and river were mapped using lines that spread across the sediment of the coastline, along with the shape of the Longyear River through summertime. By creating transects, the coastline retreat or propagation could be measured in 2008 and 2014, with positive values indicating propagation and negative values indicating retreat, and added to an *Excel* sheet later for visualization. The flood width area was calculated with the use of ArcMap geometry calculator to present accordingly.

Infrastructure mapping was done with basemap comparisons from NPI that show active building plans, which were later cross-referenced with Google Maps and Google Streetview to compare and assert the accuracy of these images. As they were offered in the shape of .lyr filer, steps were taken to create shapefiles for further analysis. To verify these results further, an excursion was also undertaken to Longyearbyen in May 2023. The primary focus during this excursion was to collect ground truth pictures, which were used to verify the status of current infrastructure, visualise the safeguards put in place for landslide risk management, and obtain visual material for further analysis. GPS points were also taken in accordance using *SW Maps* to create a layer that could be replicated in ArcGIS upon return from the excursion.

The methodology to produce results for the conditions of possible avalanches was formed by establishing different parameters that have a noticeable effect and act as underlying reasons to create favourable conditions. Cornice falls in particular were the focus due to the established majority of avalanches in the Longyear Valley being triggered by cornice falls (Adakudlu et al., 2019). As discussed there, landslides in the form of avalanches are most likely to occur on slopes with a gradient between 28° to 55° as these slopes allow snow to accumulate and then be carried away during an avalanche. Debris flows also have a possibility of occurring on low slopes due to permafrost in Arctic areas, so this form of avalanche was also classified as a possible risk.

Other important parameters were established to be height and wind direction, due to the accumulation of snow from cornice fall avalanches. As most of the wind over the Longyear Valley comes from the eastern direction, this was established as an important factor to consider (Adakudlu et al., 2019). As the amount of snow that can accumulate on slopes is also influenced by the shape of the slope, a layer of curvature was classified, which produces three layers showing the shape of the slope. Only the profile of the result was of interest, as it shows how concave or convex a slope is. The amount of snow on concave slopes is often more stable and less likely to be carried away during an avalanche compared to convex slopes, which was the basis for the classification.

To ascertain which rock types are most susceptible to landslides, a search was made for the rock types categorised in the geology repository to assign them a value for their risk of causing a landslide. Mudstone and shale were considered to be at the highest risk, as they are classified as weak sedimentary rocks (Lawrence & Shiels., 2013). A study examining a different site but with the same soil types as those mapped in the Longyear Valley, clarified that mudstone and shale are most susceptible to landslides due to their porosity (Eldin et al., 2013). Sandstone and siltstone on the other hand have lower porosity, where other chemical factors can increase or decrease their susceptibility to landslides.

Maps of each parameter were produced using tools in ArcMap which are highlighted in Table 2, and different values were assigned to them to highlight their importance as parameters that may affect avalanche conditions. Once these results were produced, they were combined through *Weighted Sum,* and Figure 5 highlights the work process through ModelBuilder.

Table 2. Parameters and their values assigned for Weighted Sum analysis.

Tabell 2. Parametrar och deras tilldelade värden för Weighted Sum-analys.

Parameter	*Assigned value*
Incline	0,4
Height	0,3
Curvature	0,2
Wind	0,2
Vegetation	0,1
Geology	0,1

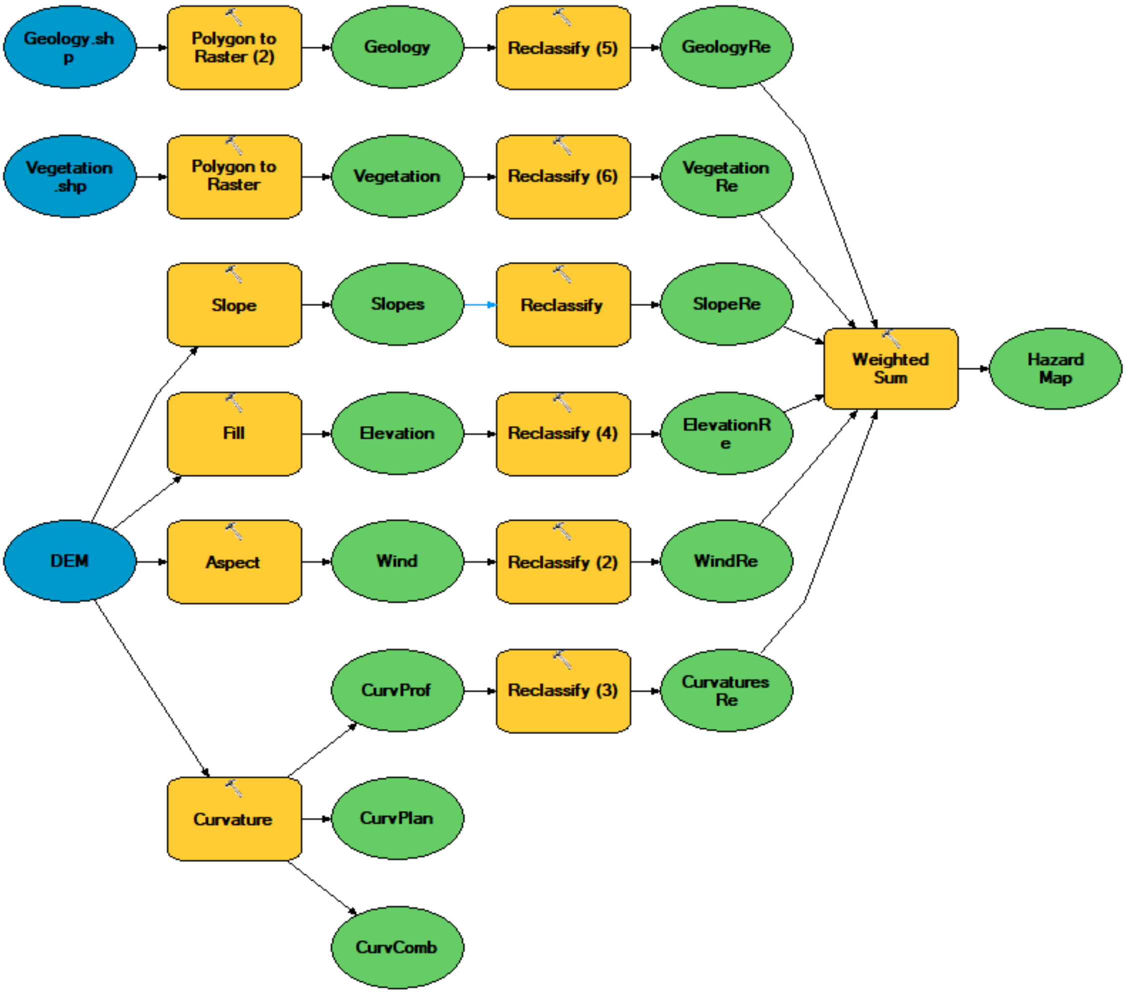

Figure 5. A visualisation of the work process to produce finalized hazard map. Source: Authors' own (2023).

Figur 5. En visualisering av arbetsprocessen för att producera den slutgiltiga farokarta. Källa: Författarnas egna (2023).

5. Results

This section presents the results of the spatial and geographical analysis of different geomorphological features and infrastructure in relation to conditions for avalanches.

5.1 Geomorphological activity

A noticeable spread of geomorphological activity can be observed in Figure 6, where five forms of clear geomorphological processes have been marked out. The NIR data in particular highlights signs of erosion and accumulation of sediment which have been mapped out accordingly. The data also visualizes the re-establishment of vegetation on top of old colluvial fans, where newer fans lack vegetation as seen in Figure 7. These forms of mass movements have been marked out as origin points but the slopes on both sides of the Longyear Valley mean that said processes can travel towards Longyearbyen, depending on the activity in question. A noticeable amount of debris flows and drainage systems, specifically fluvial channels, can be seen on the eastern side of the Longyear Valley, largely located near the southern side of the town, Nybyen. An abundance of observed activity also falls under the forms of debris flows, colluvial fans, and drainage systems, with only one clear example of an alluvial fan and solifluction visible.

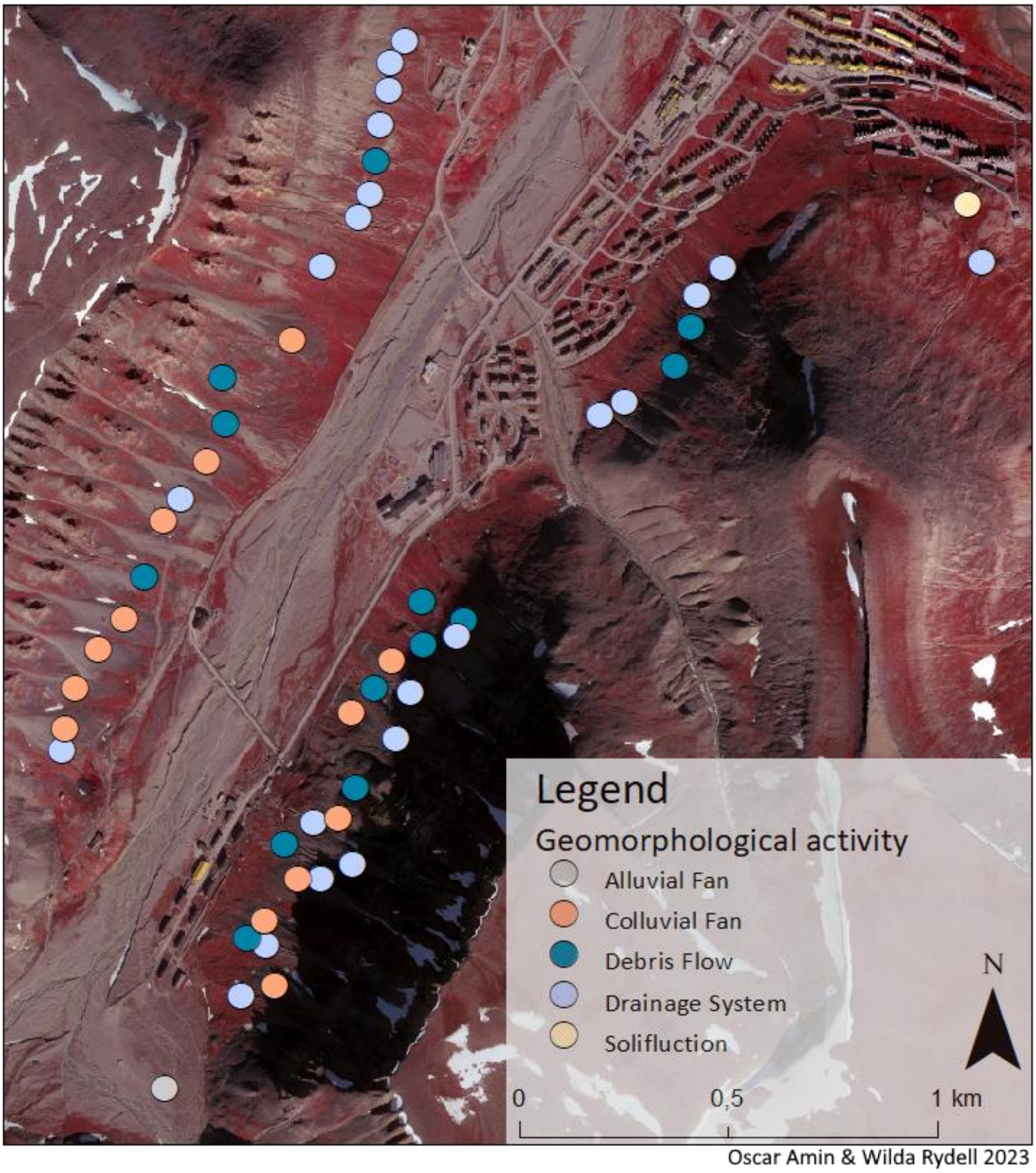

Figure 6. The different amounts of geomorphological activity in the Longyear Valley, highlighted with NIR data from 2011. Source: Authors’ own (2023.) Data source: HRSC-AX, MACS-Polar, Hauber et al. (2011).

Figur 6. De olika formerna av geomorfologiska aktivitet i Longyeardalen, markerade över NIR data från 2011. Källa: Författarnas egna (2023.) Datakälla: HRSC-AX, MACS-Polar, Hauber et al. (2011).

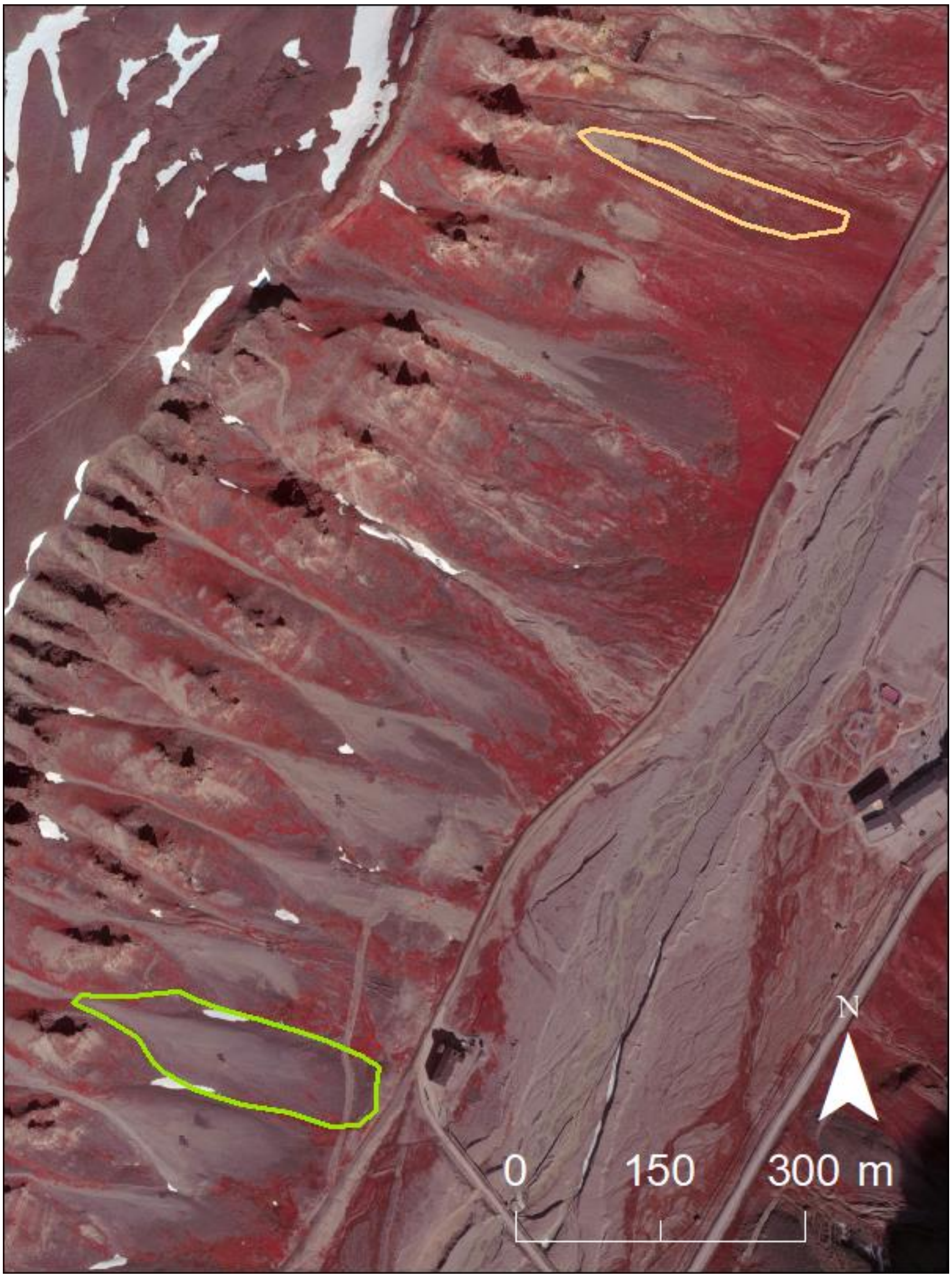

Figure 7. An example of the re-establishment of vegetation near colluvial fans. The orange-marked area highlights an older colluvial fan due to the darker red signifying vegetation, while the green-marked area shows sparse vegetation, suggesting a more recently formed colluvial fan. Source: Authors' own (2023.) Data source: HRSC-AX, MACS-Polar, Hauber et al. (2011).

Figur 7. Ett exempel på återetablering av vegetation nära kolluviala avlagringar. Det orange markerade området visar en äldre kolluvial avlagring på grund av den mörkare röda området som visar vegetationen, medan det grönmarkerade området visar gles vegetation, vilket tyder på en nyare bildad kolluvial avlagring. Källa: Författarnas egna (2023.) Datakälla: HRSC-AX, MACS-Polar, Hauber et al. (2011).

5.2 Coastline and the Longyear River

Regarding the coastline, there are clear variations from 1936 up to 2014. For a large portion of the coastline, starting from the western side, a clear and pronounced transgression into Adventfjorden can be observed in Figure 8.

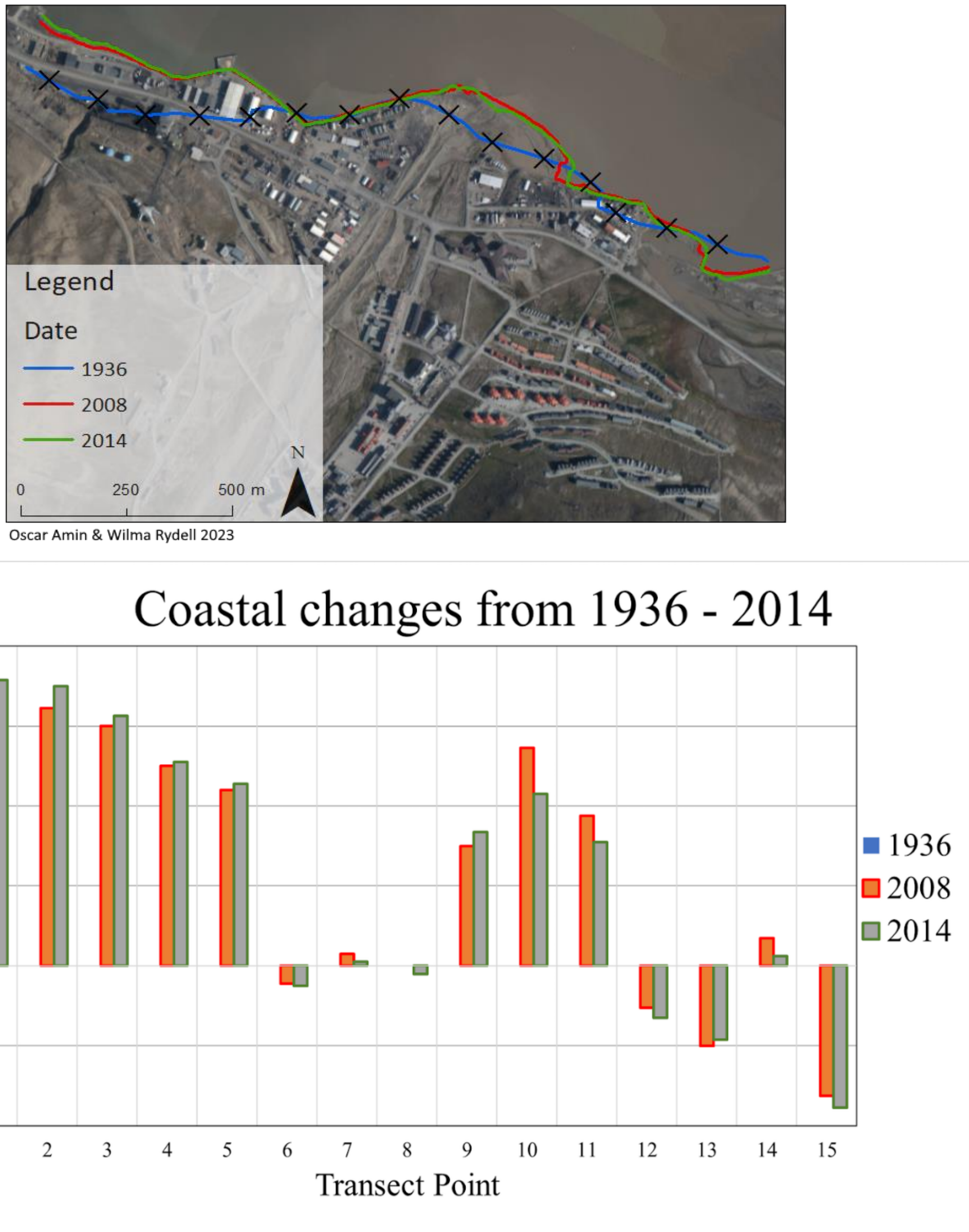

Figure 8. An orthophoto on Longyearbyen in 2014 and its coast, mapped out with respective years as a label, along with the results of each transect point and the coastal propagation and retreat (m) in 2008 and 2014, with 1936 as a baseline. Source: Authors' own (2023.) Data source: Geyman et al. (2021), NPI, Hauber et al. (2011).

Figur 8. Ett ortofoto av Longyearbyen 2014 och dess kust, kartlagd med respektive år som etikett, tillsammans med resultaten för varje transektpunkt och kustens utbredning och tillbakagång (m) 2008 och 2014, med 1936 som baslinje. Källa: Författarnas egna (2023.) Datakälla: Geyman et al. (2021), NPI, Hauber et al. (2011).

Beginning from *Transect* 1, going from left to right, where the strongest positive trend can be observed in both 2008 and 2014, the positive trend becomes less pronounced until *Transects* 6-8, which is located where the Longyear River connects to Adventfjorden. As *Transects* 1-5 are located where most of the harbour activity takes place in Longyearbyen, the noticeable increase which appears to be a positive trend between the recorded years can be attributed to a combination of sediment transportation and accumulation, in combination with further harbour activity.

This positive trend continues between *Transects* 9-11, but there are signs of erosion between 2008 and 2014 as the positive values decrease between the timespan, along with a general negative trend forming between *Transects* 12-15, suggesting that sediment accumulation largely travels alongside the western side of the Longyear Valley while erosion has a stronger effect on the eastern coastline. This is consistent with the stronger harbour activity as noted before.

5.3 Avalanche conditions

Through a combined analysis of the parameters commonly connected with avalanches in the Longyear Valley, a result could be produced in which areas of the Longyear Valley were divided into five different categories, highlighting areas where geological activity that may produce avalanches have the strongest conditions to do so, in Figure 9. As wind direction in particular plays a large part in the formation of avalanches in periglacial environments due to the existence of cornice falls, the strong presence of winds towards the western direction largely impacts the conditions of where avalanches can form, which is consistent with earlier studies showing that a large portion of them have occurred on the eastern side of Longyearbyen.

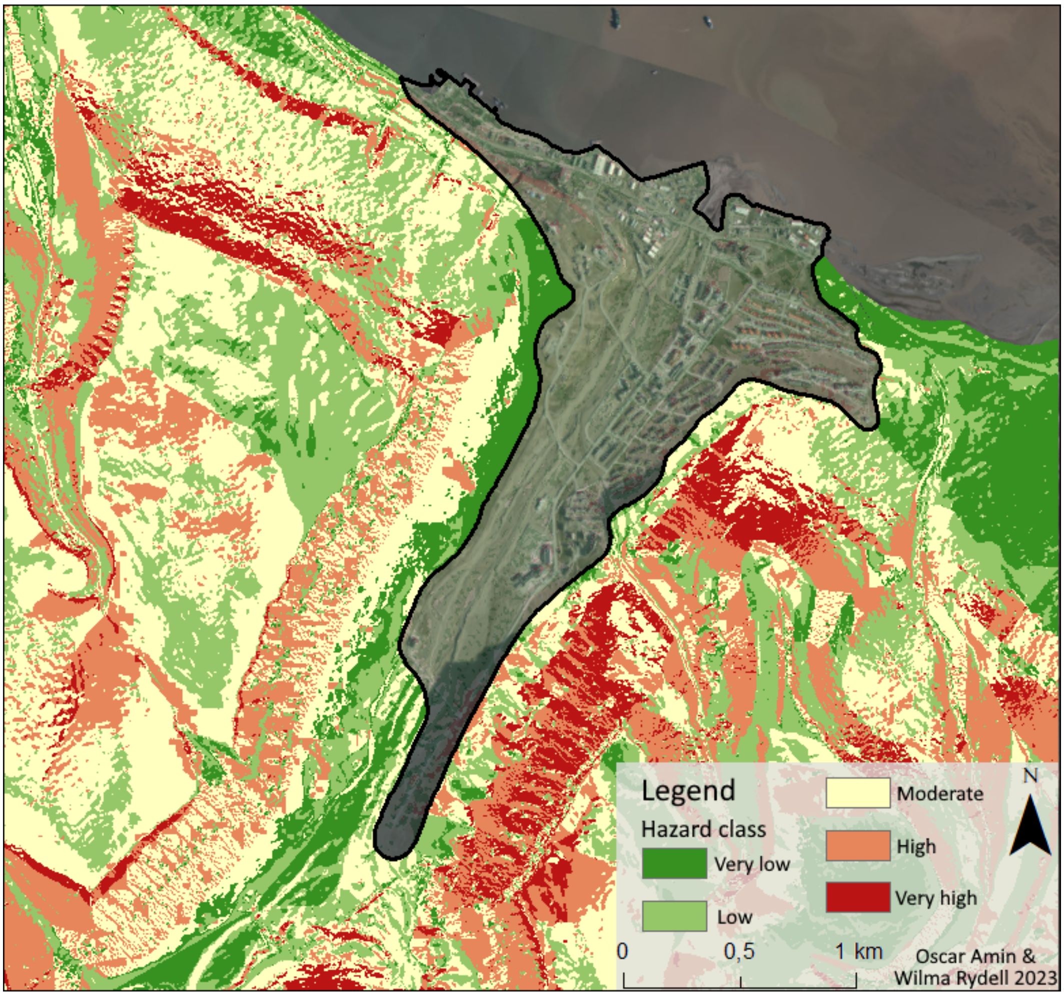

Figure 9. A hazard map of favourable conditions for avalanches, divided into five different classes, with an orthophoto of Longyearbyen in 2014 serving as a backdrop. Source: Authors' own (2023). Data source: NPI, PGC.

Figur 9. En karta över gynnsamma förhållanden för laviner, indelad i fem olika klasser, med ett ortofoto av Longyearbyen 2014 som bakgrund. Källa: Författarnas egna (2023). Datakälla: NPI, PGC.

While the results are based on geological parameters over multiple years, the aspects such as wind direction and slope curvature stay consistent throughout a large timeframe. It can be observed that a large portion of the eastern side has conditions that are very favourable for the formation of avalanches. While these areas do not extend fully into Longyearbyen, it is important to acknowledge that the map only highlights areas in which avalanches may form, while they can and often do travel further than their origin point. Very high, to moderate conditions for avalanches exist on both sides of the Longyear Valley, pointing towards Longyearbyen, with a majority on the eastern side being geographically close to residential areas.

This presents a threat to existing buildings and continues to be a hazard concerning plans for further expansion.

5.4 Infrastructure

In terms of infrastructure in Longyearbyen, comparisons show that buildings near the northeastern portion of the town have been either demolished or abandoned by today, as Figure 10 shows.

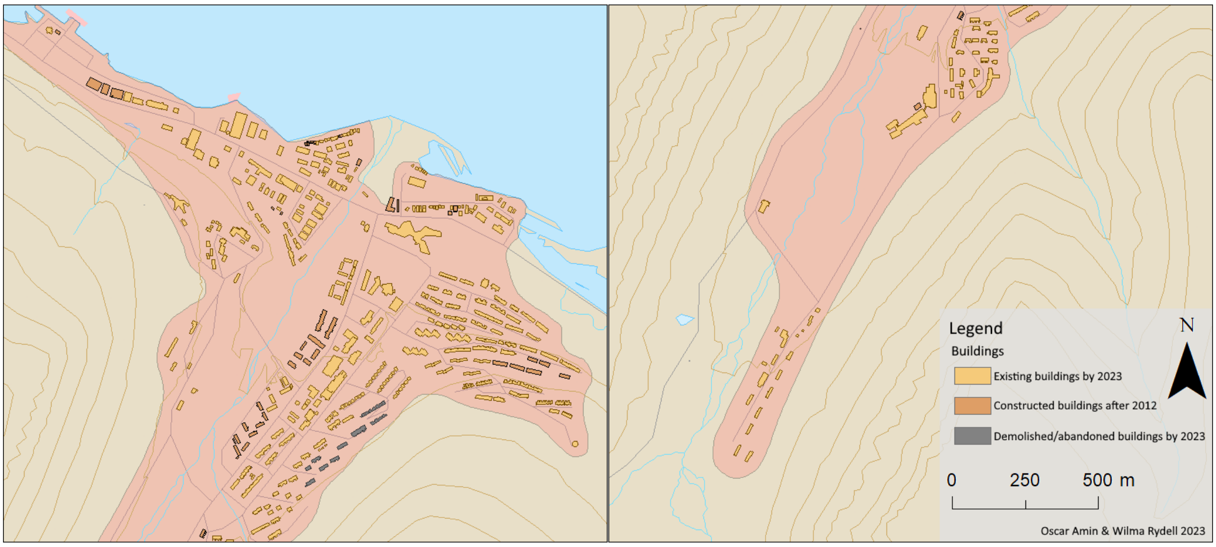

Figure 10. Map detailing the infrastructure of Longyearbyen, showcasing buildings built after 2012 and demolished by 2023. Data: Authors' own (2023). Data source: NPI, own data (2023).

Figur 10. Karta som visar Longyearbyens infrastruktur, med byggnader som uppförts efter 2012 och rivits senast 2023. Data: Författarnas egna (2023). Datakälla: NPI, egen data (2023).

A portion of these buildings were part of those destroyed by the observed avalanches in 2015 and 2017 and have therefore not been rebuilt due to the inherent conditions of further avalanches in this region of the town. However, the densification of the town and the continued change for tourism has created a higher demand for residential areas, and the efforts to accommodate this demand can be observed to be localized within the centre of the town, as well as the portion described as Gruvedalen, which is largely a residential district. On the western side of the town, a church and a preschool are located within an area with favourable conditions for avalanches, but the preschool has been relocated to the centre of town, likely in response to the possible threat.

To further investigate areas of interest, ground truth pictures were taken at areas of interest to produce an accurate understanding of Longyearbyen today. Figure 11 details Gruvedalen where a large portion of the town's residents live today.

Figure 11. Ground truth image taken of the northeastern region of Longyearbyen. Data: Authors' own (2023). Data source: NPI, own data (2023).

Figur 11. Bild tagen på plats av den nordöstra delen av Longyearbyen. Data: Författarnas egna (2023). Datakälla: NPI, egen data (2023).

Buildings and structures appear to be largely intact and plots for further densification could be observed. Construction work was also apparent in the centre of town, where residential areas for research students and tourists are heavily located, as shown in Figure 12. Further town densification appeared to be located and scheduled within this portion of Longyearbyen, which has a lower risk of being affected by geological activity.

Figure 12. Ground truth image taken of the construction work in the centre of Longyearbyen. Data: Authors' own (2023). Data source: NPI, own data (2023).

Figur 12. Bild tagen på plats av byggnadsarbetet i Longyearbyens centrum. Data: Författarnas egna (2023). Datakälla: NPI, egen data (2023).

The section of Longyearbyen where previous avalanches have taken place was observed to have demolished buildings, and appeared abandoned in some way, shown in Figure 13. In addition, multiple rows of fences had been placed across the hill in sets of rows, with observed collections of snow having formed on each row. These are a continuous project set to hinder snow avalanches, as each row slows down the accumulation of snow and hinders the ability for avalanches to drag down enough material to present a danger.

In case these fail or in the case of a slush or debris flow, a stone wall up to 5 meters high and 200 meters wide has been constructed, running across the residential buildings closest to the existing area previously affected in 2015 and 2017.

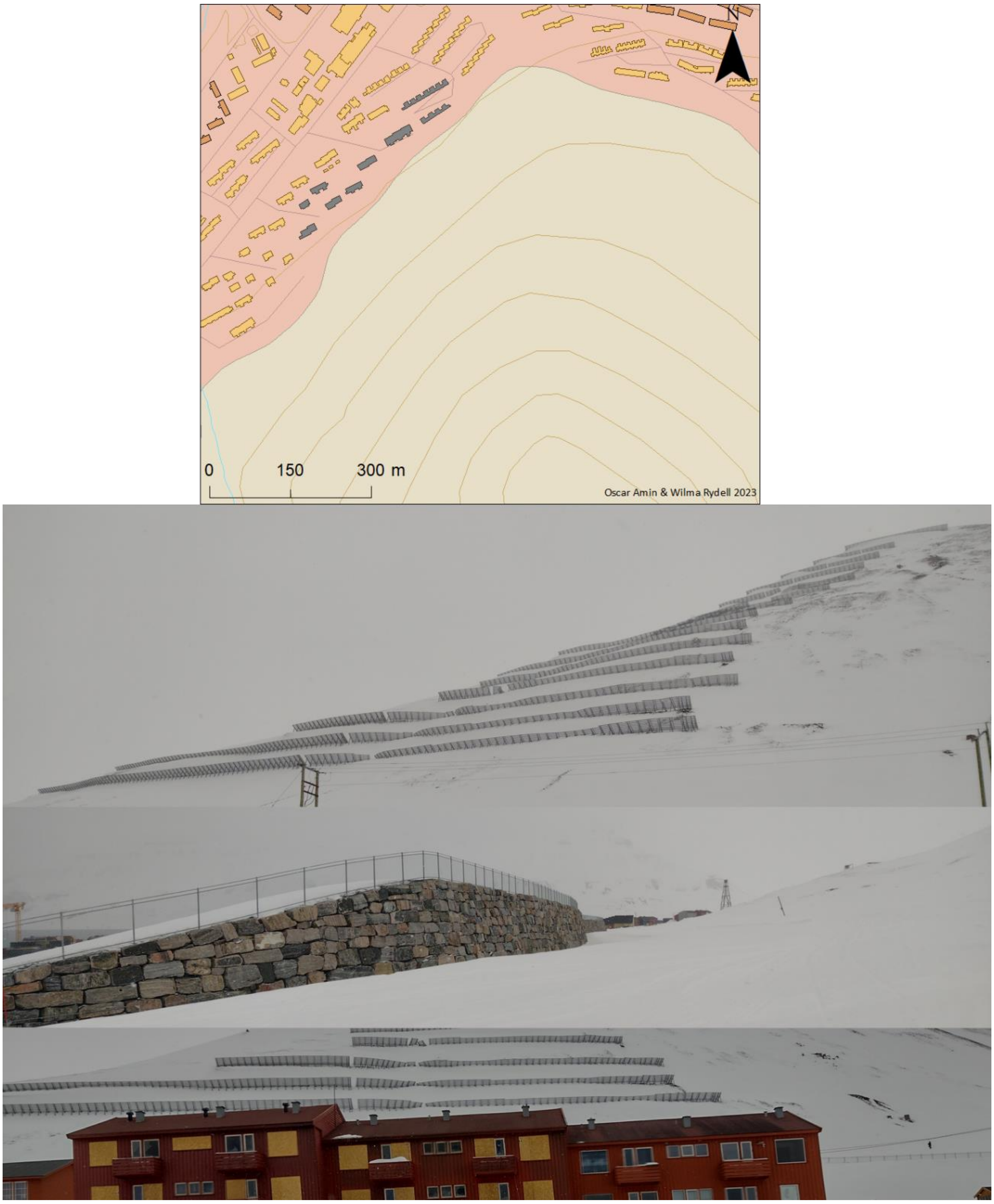

Figure 13. Ground truth image taken of the abandoned buildings and avalanche protection structures in the eastern part of Longyearbyen. Data: Authors' own (2023). Data source: NPI, own data (2023).

Figur 13. Bild tagen på plats av de övergivna byggnaderna och lavinskyddskonstruktionerna i den östra delen av Longyearbyen. Data: Författarnas egna (2023). Datakälla: NPI, egna data (2023).

6. Discussion

As previous studies have concluded (Hancock et al., 2018; Hestnes et al., 2016; Jónsson et al., 2019; Sydnes et al., 2021) the Longyear Valley is an active hazard zone for geomorphological mass movement, with a strong prevalence along the eastern side as Figure 7 and Figure 11 show. From the observations made in Figure 12 with data from 2014 and the lack of comparison with ground truth pictures from 2023, it is difficult to determine how much the valley has changed from 2014 up until the conduction of this study. It is also difficult to determine how frequently these events occur, as data with intervals between 1936 and 2008 could not be retrieved. The aerial images from 1936 were also taken during the winter season, which makes comparing geomorphological changes between the years difficult. This study could thus only conclude what processes occur within the valley and in proximation to infrastructure, and which processes are the most prevalent.

It can be observed that the amount of sediment has increased alongside the coastline and may continue to do so as a positive trend can be seen through the results. This suggests that a continued amount of sediment travels alongside the Longyear Valley towards the coastline because of continued thawing and geomorphological activity. This is further supported by studies that suggest that the climate changes in effect will continue to increase the severity of these movements and how often they occur (Eckerstorfer et al., 2013). The shift of residential areas towards the centre of town along with the continued increase of avalanches and mass movement protection structures suggest that Longyearbyen is aware of these challenges and therefore is relocating many residential areas to minimize future damages. While this presents a temporary solution and possible protection against future destructive geomorphological activities, the increase in sediment transportation increases the chance of slush flows, debris flows and damages caused by the Longyear River, leaving the town in a position where further steps must be taken to protect infrastructure if the warming climate continues as predictions show (Bekele & Sinitsyn, 2020).

The coastline can also be compared to Hanaskogdalen due to the geomorphological similarities between the two areas. It can be observed that the coastline in Hanaskogdalen shows stronger signs of retreat compared to the Longyear Valley. However, the human activity in Longyearbyen extends to the harbour area and the effect this has on the coastline could influence how it shapes and where sedimentation spreads alongside the coast.

In addition, due to the geographical layout, Hanaskogdalen may be in a position where it is affected by coastal erosion in a stronger matter than the Longyear Valley, due to the decreased amount of sea ice allowing coastal processes to reach further inland. As Longyearbyen is constantly monitored to reduce the impact of these coastal processes, this is likely the underlying reason for the differences between the two areas.

When analysing avalanches, it is important to highlight the proportion of factors behind the conditions for them, especially in Arctic areas where climate change and factors such as snow, permafrost, and ice further influence mass movement. In these areas, only the active layer and the snow that may be on top of it are affected when ground movements occur.

Slope stability is affected by changes in temperature and precipitation, with projected changes in the future affecting the depth of the active layer above the permafrost. This may increase the risk of a type of landslide that can only occur in Arctic areas, where the active layer moves on top of the stable permafrost (Abakudlu et al., 2019). Other factors that may affect active layer soil movements are various thawing processes, whose cycles have already started to change due to the impact of climate change on Arctic temperatures and weather cycles.

6.1 Discussion of method

The data used in this study focuses largely on the 21st century and beyond, which presents a result that highlights recent changes and portrays the current state of the Longyear Valley. These changes are not considered in terms of time however, and further data over the area that ranges further back in time could be of interest to investigate and draw conclusions about the geomorphological state of the Longyear Valley in the past. As much of the data is also produced through remote sensing and interpretation, said results are also built on a high degree of subjectivity from the researchers. Tools such as the W*eighted Sum* are based on the values determined by those conducting the study, which means that the results are strongly influenced by the knowledge of those doing the work. The classification of factors can be adapted depending on the accuracy of the data one is working with and the level of knowledge one has regarding wind, geology, permafrost, etc. The same principle applies to the tools for combining layers as great emphasis is placed on the influence between each layer. This process means that the results produced are initially influenced by the knowledge of those working on the study.

The excursion undertaken as part of the research for this study was used to mainly collect ground truth data firsthand regarding mass movements and observe the current mitigation strategies that have recently been implemented and are ongoing. These observations were then used to compare with and complement the results procured from aerial imagery. With that being said, to further assess the changes in geomorphological activities, additional excursions would be of great interest during summertime conditions to inspect the ground layer and the permafrost to detect possible changes and the effects that this may have on further activity in Longyearbyen.

This study does not consider the increase in human activity in Longyearbyen as the gradual change from a mining town to a tourist spot has been in effect in recent years. Further studies could investigate this change and how the increase in human movements around the Longyear Valley can affect future development in the region. In addition, due to the focus on densification and growth to accommodate this, it may be of interest to conduct a study of the effects this has on the residents along with the current political understanding of the challenges ahead.

7. Conclusions

To conclude, this study has highlighted the types of geomorphological activity in the Longyear Valley that influence the community of Longyearbyen. It has also presented areas of considerable danger where favourable conditions of snow avalanches may exist and highlighted the structural mitigation strategies taken in mitigating risks when it comes to infrastructure and town densification. The geomorphological activity is of specific concern regarding the eastern parts of the Longyear Valley, in which multiple forms of debris flows and colluvial fans are apparent. It is on this side where most mitigation structures have been implemented. New buildings can be observed at the bottom of the North-facing mountainside of Sukkertoppen, where solifluction can be documented. Even though this form of mass movement is slow, it may pose a threat to infrastructure in its path in the future.

An increase in permafrost degradation and sediment transportation can be observed through the changes in the Longyear River and the coastline of Longyeardalen. Ground truth images have visually confirmed the changes and structures built in response within the town, both to mitigate damages caused by possible snow avalanches and to facilitate further expansion in the future.

As Longyearbyen today exists as a tourism community and will continue to do so, the situation in which human activity continues to increase along with residential areas having to be built to accommodate for this, this study is of interest as the results showcase the lessening areas of which buildings can safely be put without risking damages from further geomorphological activity. This, in addition to the changes in Earth’s climate and how this relates to the Arctic, will continue to be a connection that should be closely monitored and considered for the town as a whole to safely coexist in a region with continuously changing landscapes.

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