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A preliminary hydrogeological characterization of landslides at Selsstaðir, East Iceland

SIT ICELAND: CLIMATE CHANGE AND THE ARCTIC

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Artificial Intelligence (AI) Use Statement

Artificial Intelligence tools, specifically ChatGPT, were employed during this research for:

- Troubleshooting GIS-related tasks in ArcGIS Pro, including dataset formatting and uploading.
- Assisting with R Studio code writing and troubleshooting error messages.
- Sourcing relevant literature and scientific resources on perched aquifers, debris flow mechanics, and landslide modeling.
- Refining scientific discussion sections to ensure clarity, coherence, and consistency with academic standards.

Acknowledgements

Thank you to my academic director, Dr. Christine Palmer and assistant director, Sadie Ainsworth, for their advice and encouragement. To Vivian, whose expertise in field work and soil science was key to completing the field study. Thank you to Bjarki Borgþórsson, who shared his knowledge and experience of the weather and landslide cycles in the area. He and Nelson provided transportation to the field site throughout the project. I extend my gratitude to Dr. Nathan Young, a professor at the SUNY College of Environmental Science and Forestry, whose valuable advice improved project design. I truly appreciate the assistance from Jón Kristinn Helgason, a landslide specialist at the Icelandic Meteorological Office, for the meaningful research idea to improve the development of landslide research in Iceland. I couldn’t go without thanking my parents, because I wouldn’t have had this opportunity if it weren’t for their constant love and support.

Abstract

This study investigates the hydrologic and geomorphic conditions contributing to landslide hazards on the north slopes of Seyðisfjörður, East Iceland, with a focus on the emergence of new springs following the 2020 landslide sequence. Field observations, soil profiling, and flow rate measurements reveal the likely presence of a perched aquifer system, formed where groundwater accumulates above a compact, impermeable subsurface layer. The emergence of multiple springs at about 261 meters above sea level marks a hydrologically active zone strongly correlated with landslide source areas. These findings suggest that subsurface water buildup plays a key role in slope saturation, structural weakening, and debris flow initiation. The implications are critical under a changing climate, as increasing rainfall intensity and frequency accelerate aquifer recharge and reduce slope stability. By identifying spring elevation as a tool for hazard mapping, this research provides a foundation for improved landslide risk assessment and climate-adaptive monitoring strategies in Iceland's fjord landscapes.

Introduction

Landslides and debris flows pose a persistent threat to fjord communities in East Iceland, particularly in Seyðisfjörður, where steep glacially carved slopes, layered geology, and high precipitation converge to create conditions conducive to mass movement. Despite decades of documented landslide events, systematic monitoring and detailed hydrological studies have been limited to the south side of the fjord, leaving the south-facing slopes comparatively under-researched. The December 2020 landslide cycle—triggered by a 10-day storm that brought over 750 mm of rain—highlighted the urgency of understanding the geomorphic and hydrologic dynamics of this area.

The complex interaction between rainfall, snowmelt, and soil permeability is increasingly important in the context of climate change. Warming trends in the North Atlantic region are expected to intensify precipitation and alter seasonal water inputs, which in turn affect slope saturation and landslide timing (Björnsson et al., 2023). However, the subsurface processes that control water accumulation and mobilization remain poorly constrained in Icelandic fjord environments.

This study focuses on a known landslide source area above the farm Selsstaðir, where new spring emergence points observed after the 2020 event raised questions about the underlying hydrologic structure. By characterizing soil texture, flow rates, and vegetation at and around the spring locations, this research aims to assess the role of perched aquifers in slope instability. The findings contribute to a growing body of research on climate-sensitive hazard prediction and offer a practical framework for future landslide monitoring efforts in Iceland. All photos and maps were taken and created by the author (Stahl, 2025).

Environmental Setting

Seyðisfjörður is a glacially carved U-shaped fjord formed during the last deglaciation (12,000–10,000 years ago). The mountains flanking the fjord consist of steep cliffs and slopes composed mainly of Tertiary basalt flows interbedded with sedimentary layers, including clayey silts, sandstone, and lignite (Figure 1). These interbedded horizons have become increasingly impermeable over time due to compaction, influencing both surface hydrology and slope stability. The lower slopes are covered with unconsolidated, permeable glacial and colluvial material that can store large volumes of water (Einarsson, 1994; Saemundsson et al., 2003; Beylich, 2000; Santamarta et al., 2014; Portier et al., 2023).

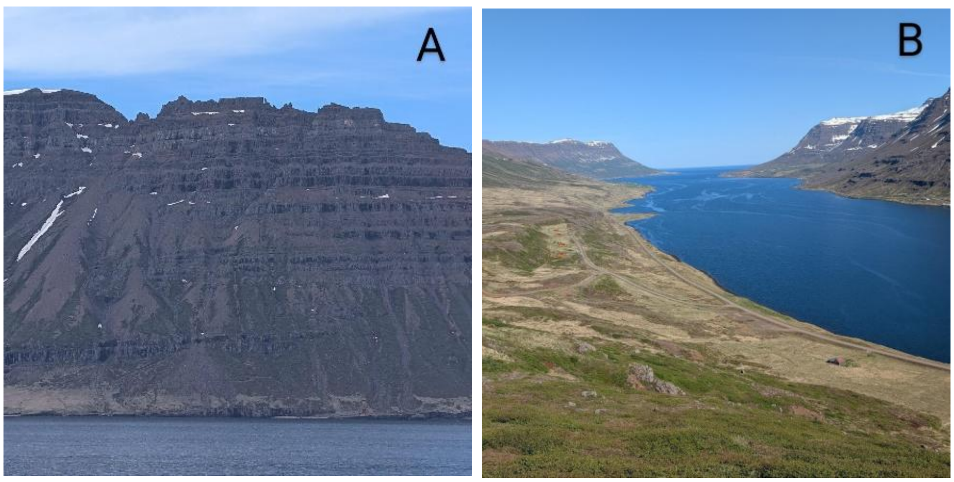

Figure 1. A) The vertical cliffs and unconsolidated lower slopes on the north side of Seyðisfjörður. B) A view of the glacially carved U-shaped valley of Seyðisfjörður.

The interbedded mid-layer is almost impermeable for three main reasons, explained in a modelling experiment by Liu et al: 1) Fine grained soils have higher specific surface area and smaller pore sizes, with many non-connected micropores. The high specific surface area enables strong adhesive forces in the pores that reduce permeability. 2) The disconnected pores prohibit flow channel establishment. 3) The electric repulsion from the charges carried by the fine-grained particles increases the resistance to water flow through the pores (2025). When water percolating down from the surface is trapped by a relatively impermeable layer, it accumulates in the soil or rock, creating a perched aquifer. This sits above the regional water table and its extent is usually related to seasonal rain or runoff. If there is no outlet, like a stream, it saturates all unfilled pores. Knowing the depth of the mid-layer is crucial for future estimation of the volume of a future slide in the area, and therefore the hazard associated with it. The amount of time it takes for the slope to become oversaturated depends on the climate and amount of rain the area receives.

The climate is maritime and tundra-classified (Köppen-Geiger), with high precipitation driven by Iceland's position beneath the Icelandic Low (the main low-pressure pathway over the North Atlantic Ocean). Mean annual precipitation is typically higher in the southern and eastern regions due to the wind patterns (Einarsson 1984; Saemundsson et al. 2003; Knutsson 2008; Bartsch 2024).

The eastern fjords, especially the north-facing slopes, receive intensified rainfall due to topographic effects. Due to the orientation of the fjord, easterly winds can bring rain that pelts the north side and dissipates before reaching the town (Seyðisfjörður Resident, 2025). This contributes to seasonal oversaturation of slopes and increases the likelihood of slope failures. Additionally, south-facing slopes receive more sunlight, which contributed to faster deglaciation and potential destabilization (Portier et al., 2023).

Mass Movements

The steep, glacially carved slopes of the East Fjords make the region highly susceptible to mass movements, particularly debris flows, landslides, and avalanches. These processes are primarily driven by gravity but often triggered by meteorological events (Decaulne & Sæmundsson, 2007; Portier et al., 2023). Long lasting rainfall controls almost 50% of debris-flow events and intense rainfall represents more than 30% of debris flow causes in East Iceland (Decaulne & Sæmundsson, 2007) (Figure 2).

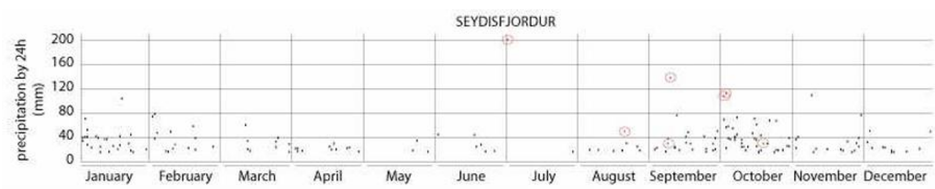

Figure 2. Monthly high rainfall distribution and related debris-flow releases in eastern Iceland. The debris-flow events are circled in red (Saemundsson & Decaulne 2008).

Debris flows are initiated when water-saturated, poorly sorted sediments lose cohesion and begin to move downslope. Once mobilized, they behave like a dense slurry, capable of transporting both fine particles and large boulders (Iverson, 1997). This transformation is particularly likely during rainfall exceeding local infiltration capacity, causing water to accumulate in soil and reduce internal friction. Historical data show that debris flows in East Iceland most frequently occur during September to November, after the summer snowmelt and rain (Decaulne & Sæmundsson, 2007) (Figure 3).

The landslides in December, 2020 were notable for extreme rainfall rates (up to 60 mm/hr), which led to over saturation and fluid-like debris flows. From the 10th to the 19th of December 2020, Seyðisfjörður received about 750 mm of cumulative rain, sometimes coming in at 250 mm/day, one third of the annual rainfall the area usually receives. Several landslides hit the town between the 15th and 18th of December, destroying or damaging more than 10 buildings. The largest landslide occurred on December 15th, and it ranks as the most damaging landslide to have affected an urban area in Iceland (Icelandic Met Office, 2021).

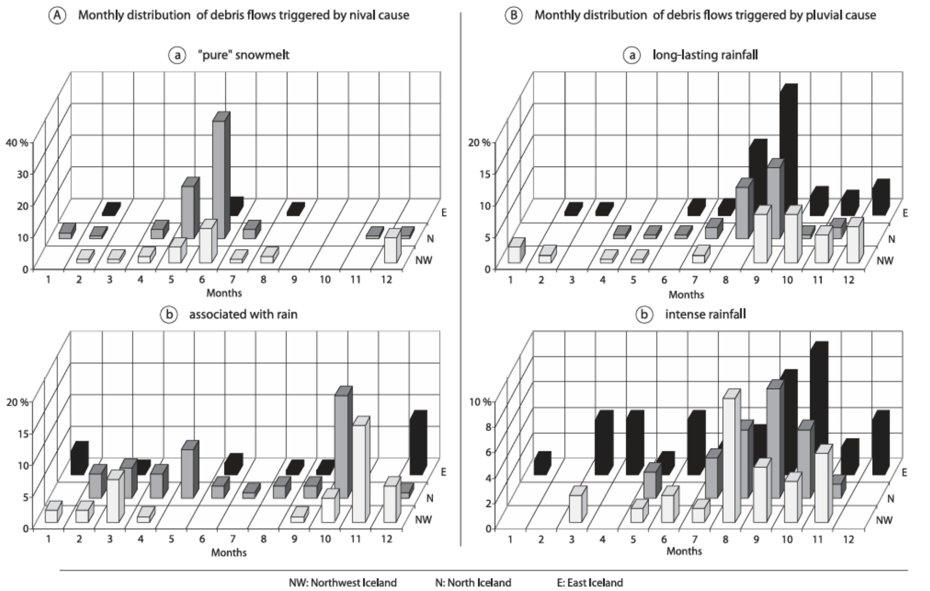

Figure 3. Monthly distribution of (a) nival and (b) pluvial controls of documented debris flows in the Icelandic fjords (1900–2003) (Decaulne & Sæmundsson, 2007).

The December 2020 landslide cycle revealed the emergence of springs at approximately 261 meters above sea level (m a.s.l.), suggesting a perched aquifer system above an impermeable subsurface layer. This study aims to characterize that system through field observations, soil profiling, and flow rate measurements. Knowing the depth of the spring emergence allows for more accurate hazard assessments by the Icelandic Meteorological Office (IMO).

Site description

The study area lies above the farm Selsstaðir on the north side of Seyðisfjörður which has historically received less monitoring than the south side, despite repeated slope failures. The specific landslide source area sits around 200–282 m a.s.l., below the plateau Skógarhjallar. The fjord is mostly oriented ESE–WSW but the innermost section is in the NNE–SSW direction. By local convention, the opposite sides of the fjord are referred to as the south and north side irrespective of the actual compass direction (Illmer et al., 2016). This report adopts this convention. The history of landslides in Seyðisfjörður dates to the 18th century and has a more complete record than many other towns in Iceland (Bartsch, 2024).

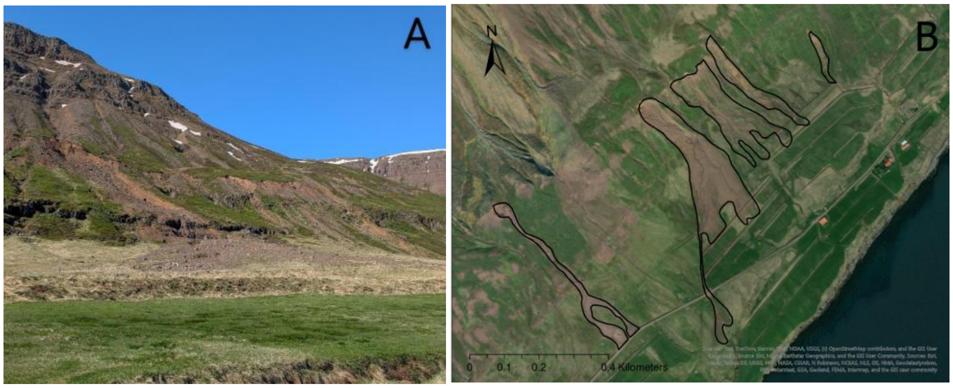

Figure 4. A) Image of the study site above the farm Selsstaðir. B) 2020 landslide cycle outlines.

Inventory

IMO has a record of at least 10 landslide events in this area between 1901 and 2020. The end of the 19th century marks the beginning of economic and social developments in the Icelandic fjords, correlated with increased damages from landslides (Decaulne & Sæmundsson, 2007). While the nature of rainfall varied through these events, all were triggered by heavy or prolonged precipitation. Below is a summary of those events:

Sept 21, 1901: Triggered by sustained rainfall from Sept 16–23. Specific damage unknown.

Aug 5–7, 1946: Damaged fields, barns, telephone poles, and sheep. Associated with multi-day storms and strong winds across the East Fjords.

Aug 19, 1950: Damaged fields and outbuildings at Selsstaðir following intense overnight rain.

June 15–16, 1962: Multiple slides from Grýta killed at least 20 sheep. Triggered by heavy rain and snowfall in higher elevations.

1975: Landslide at Selsstaðir recorded; no details on weather or damage.

Oct 4, 1985: Large slide reached the sea, destroying a cattle ranch and multiple hectares of land. Occurred during heavy East Fjord rainfall. A chunk of ice was observed in the mountain after the slide (Seyðisfjörður Resident, 2025).

Aug 27, 1994: Landslide at Dvergasteinn blocked road and damaged property. 150 mm of rain recorded per day for two days at Dalatangi weather station.

Oct 2, 2001: Slide covered road near Sunnuholt; smaller debris flows above Selsstaðir.

Nov 11, 2002: Small slide near Selsstaðir. Preceded by observation of an 80 m crack in Skógarhjallar.

Dec 2020: Multiple slides above Selsstaðir and on the south side of the fjord during a 750 mm, 10-day rainfall event. One slide destroyed fences and pastures and crossed the road into the sea.

These events illustrate the strong connection between pluvial (rain) triggers and landslide frequency in the area. While slope steepness and geology are important background information for mass movement, it is the timing and intensity of rainfall that determines when failures occur. The repeated involvement of the Selsstaðir area underscores its vulnerability.

Ethics Statement

Fieldwork was conducted in accordance with ethical and environmental standards for geoscientific research. Permission to access and sample the landslide site was granted by local authorities. Site selection was performed with consideration for both safety and ecological sensitivity, and no excavation occurred within protected or undisturbed habitats.

The digital tools used to support this research, including artificial intelligence (AI), carry an associated carbon footprint. Their energy use was considered, and their application was limited to essential tasks that directly supported the project's goals. Where feasible, open-access software was used to reduce duplication of effort and resource consumption.

Local input from residents and Icelandic specialists helped contextualize the findings within the region's climatic history. The project aimed to contribute positively to community resilience by improving understanding of landslide risks and informing future hazard mapping efforts in Seyðisfjörður and similar fjord environments.

Methods

Site Selection and General Observations

Fieldwork was conducted near Selsstaðir on a mountainside affected by a debris flow from the 2020 landslide cycle. Three locations were selected: one at each side of the debris flow and one in the center. Site selection was based on accessibility, safety, visible variation in slope, similar elevation, grain size, and the ability to excavate shallow soil pits.

The following data was recorded at each site:

- GPS coordinates, slope aspect and elevation (verified using ArcticDEM Layer and "GPS Status & Toolbox" app)
- Slope angle (0–90°, measured with "Clinometer bubble + level" app)
- Grain size distribution and vegetation cover including grasses, mosses, and roots via quadrats.
- Photographs documenting surface conditions.

Quadrat Sampling Procedure

- Quadrat size: (0.5 m × 0.5 m) with a foldable 2-meter stick
- Three quadrats per site (Source, Path, Deposit)
- Selection aimed at capturing variation in material and vegetation
- Visual grain size estimated using Udden-Wentworth scale (Wentworth, 1922). Grain sizes 2mm or less were recorded as Sand/Matrix.
- Vegetation cover estimated in 25% increment ranges from 0-100% (except for 0-10% and 10-25%)

Table 1. Udden-Wentworth Size Classifications (Wentworth, 1922)

Class	**Size Range**
Clay	< 0.0039 mm
Silt	0.0039 – 0.0625 mm
Sand	0.0625 – 2 mm
Granule	2 – 4 mm
Pebble	4 – 64 mm
Cobble	64 – 256 mm
Boulder	> 256 mm

Soil Pit Excavation Procedure

One soil pit was dug per site, except for the source location, which has two pits. Soil pits were dug to a minimum depth of 20 cm and recorded based on depth, width, texture, color, and notable inclusions. a small and large flat-faced shovel, as well as rocks and hands when necessary (see Figure 5). A summary is provided below.

A modified soil texture by feel and ribbon test was used to identify layers with high clay content (Theis, 1979, Brady & Weil, 2016; USDA NRCS, 2022). (Figure 6)

1. Ball formation: Does soil shape into a ball when moist?
2. Ribbon test: Does it form ribbons when squeezed upward between thumb and forefinger?
3. Texture by feel: When wetted in palm, does it feel gritty or smooth?

Flow Rate Measurement procedure

- 1-liter Nalgene bottle and stopwatch were used
- Timer started at submersion and stopped at backflow
- Flow calculated from 3–6 trials

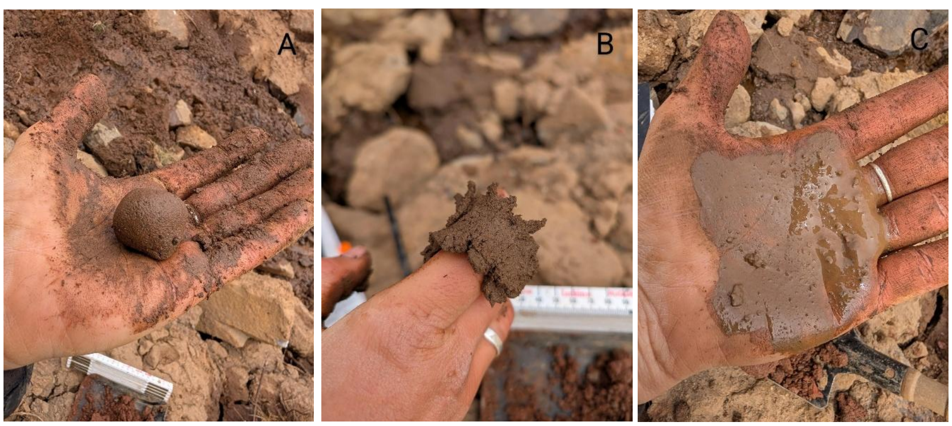

Figure 5. Soil texture by feel test using the methods presented by Theis (1979). A) Ball formation. B) Ribbon test C) Texture by feel.

Figure 6. A) Materials used. B) Rock types throughout landslide scar C) Flow rate collection.

Data Processing

Percent cover values for vegetation and grain sizes were converted to midpoint values to facilitate plotting (Table 2). These midpoints were then averaged across quadrats at each site. These averages were normalized in R, so that they added up to 100% for better interpretation and visualization. For further simplification, the grain sizes were categorized into coarse (Boulder, Cobble, Pebble) and fine (Granule, Sand/Matrix) materials. The results were then analyzed in R Studio, a program for statistical computing and graphing. Attached is the link to the GitHub repository with the R files. bbstahl/Selsstadir.SoilDistribution: Analyzes soil distribution and vegetation cover at the Selsstaðir 2020 landslide in Seyðisfjörður

Table 2. Converted percent ranges to midpoint values.

Percent Range	Midpoint Value
0-10	5
10-25	17.5
25-50	37.5
50-75	62.5

75-100	87.5

These combined field methods provide both plan-view (surface) data through quadrats and depth-oriented data from the soil pits, offering a preliminary 2D and 3D characterization of the mountain slope. This multi-scalar approach aims to identify layering patterns, hydrologic behavior, and post-landslide sediment dynamics. Further investigation is needed for more definitive subsurface characterization.

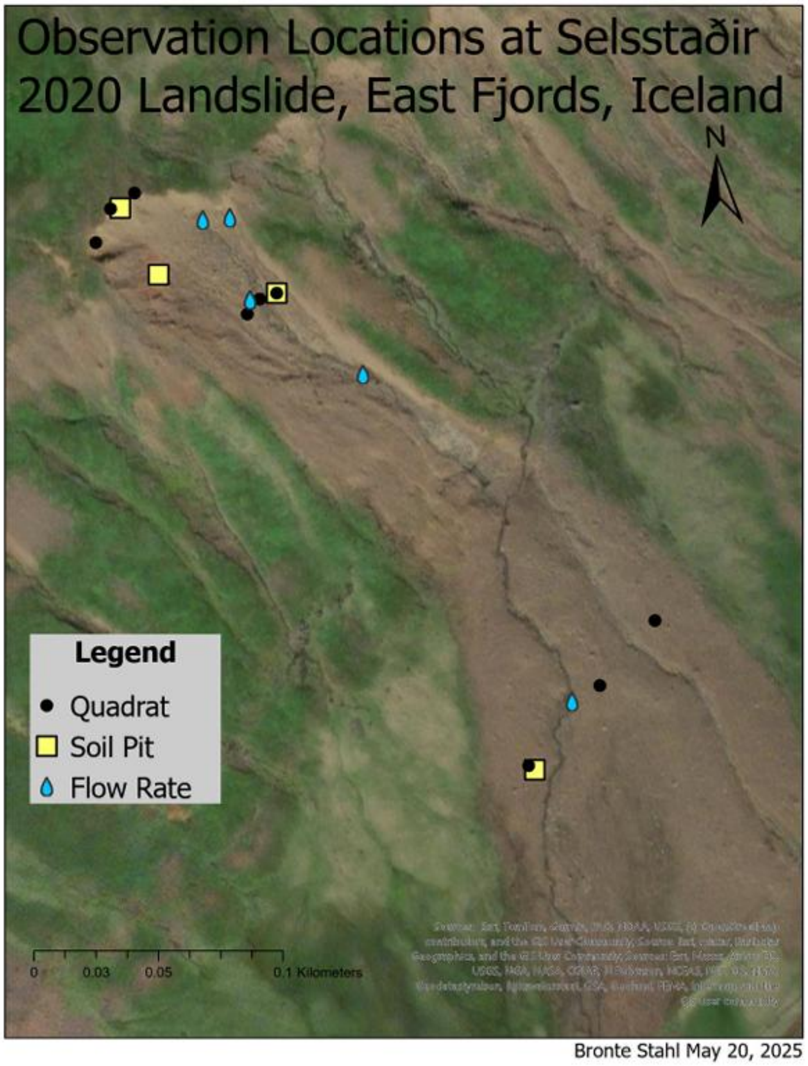

Figure 7. Map of sampling points on 16 and 20 May 2025.

Results

The results section is organized by sample location (source, path, deposit). Within these are sections for soil pit descriptions (e.g. 1.1), quadrat and surface conditions (e.g 1.2), and a visual summary of figures relating to the previous two sections (e.g.1.3).

1. **Source Area Observations**

1.1 Soil Pit Description

The source of the landslide is connected to Skógarhjallar which is vegetated with grasses, shrubs and mosses. The slope was dusty, blowing the fine sediment away in a light breeze due to the dry conditions this April and May. The soil pit was dug 50 cm deep and 20 cm long, next to quadrat 3. There was a reddish oxidized upper layer and a brown/grey bottom layer in the horizon. Fine roots exuded out of the soil throughout the pit (Figure 8).

A second soil pit (soil pit 4) was dug on the west side of the scar, 267 m a.s.l. There were large patches of red colored sediment spread throughout the orange-colored slope. The pit was 43 cm deep and 20 cm wide. There were faint horizons present, and the soil texture is sandy clay loam; when rolled into a ball, it was sticky to the touch. There were sand and gravel sized rocks mixed with the red-colored fine particles, making it very gritty (Figure 9).

1.2 Quadrat and Surface Conditions

The quadrats at the source area were dominated by fine grained material (granule or smaller). Quadrat 1 and 2 had vegetation and pebbles, but quadrat 1 only had sand or smaller (Figure 10).

Table 2. Location properties of the quadrats at the source area.

Name	Location	Elevation (m.a.s.l.)	Slope Angle (°)	Slope Aspect (°)
Q1 Source	West	282	55	86 E
Q2 Source	Middle	282	46	116 ESE
Q3 Source	East	281	64	163 SSE

A crack was observed between the source of the study site landslide and the one to the east, heading out of the fjord. The west side had an eight-meter-long crack, the width of which varied from 10-25 cm in width. The crack on the east side is four meters long, the widest separation being 45cm thick and 75 cm deep. The crack wasn't visible from the surface in the 8 meters between the side cracks, but there was a depression that connected the two. There is creeping in that area and another crack is forming closer to the edge of the drop off (Figure 10).

There is a series of six spring emergence points at 261 m a.s.l. across the scar of the landslide shown in figure 10. The east side of the scar (towards the farm) is more saturated, with a higher flow than the western side, where water is slowly seeping out. These springs form a stream that travels down the slope and promotes vegetation such as mosses and grasses. There is a horizontal line of vegetation at 265 and 273 m a.s.l. Flows 1 and 2 were measured at two spring emergence points. The others were measured from the stream downslope. Flow 4 and 5 were in the deposit areas and had a more level slope angle. The soil at each type was clay loam, but the surface cover was much different. (Figure 12, 13)

Table 3. Properties of the location that flow rates were measured.

Name	Elevation (m.a.s.l.)	Flow Direction	Soil test (Theis, 1979)	Flow Rate (L/min)	Surface Condition
Flow 1	203.4	159 SSE	Clay Loam	2.341	Sludgy wet. Acts as a fluid when disturbed.
Flow 2	204.4	175 S	NA	16.129	Mix of rock sizes with sparse grasses.
Flow 3	186.4	159 SSE	NA	51.282	Mix of rock sizes, unconsolidated, unstable.
Flow 4	152.4	122 ESE	Clay Loam	37.736	Unstable cobbles and boulders, minimal vegetation.
Flow 5	93.4	193 SSW	Clay Loam	40.541	Gravelly with boulders in the stream bed and walls 1-2m tall of mixed rock.

1.3 Visual Summary

Figure 8. A) Soil pit 1 B) View of source area scar and reddish horizon about 20 cm deep.

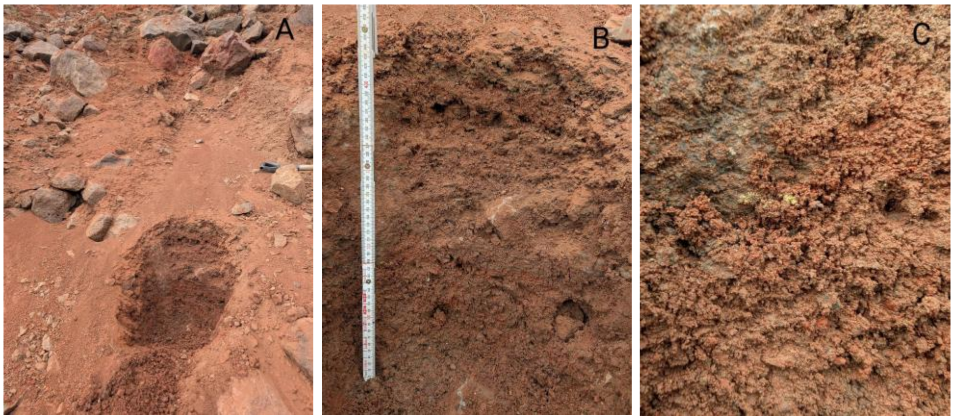

Figure 9. Soil pit 4 below source area. A) Surroundings of the pit. B) Pit wall C) Close up of the yellow spots in the middle and grey boulder embedded in the top left.

Figure 10. Map of observation locations of the spring emergence points, cracks, and vegetation line at the source area of the study site.

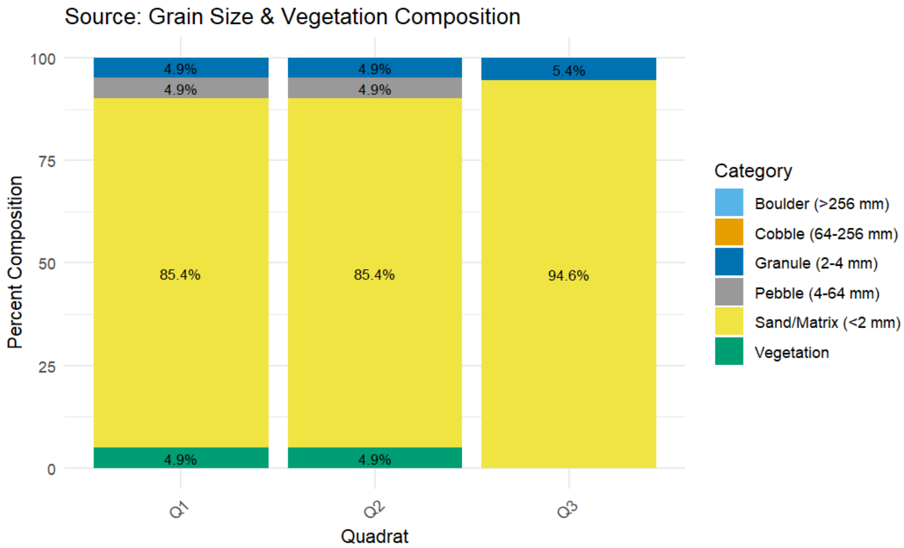

Figure 11. Stacked bar chart showing the grain size and vegetation composition. of quadrats 1, 2 and 3 at the source area.

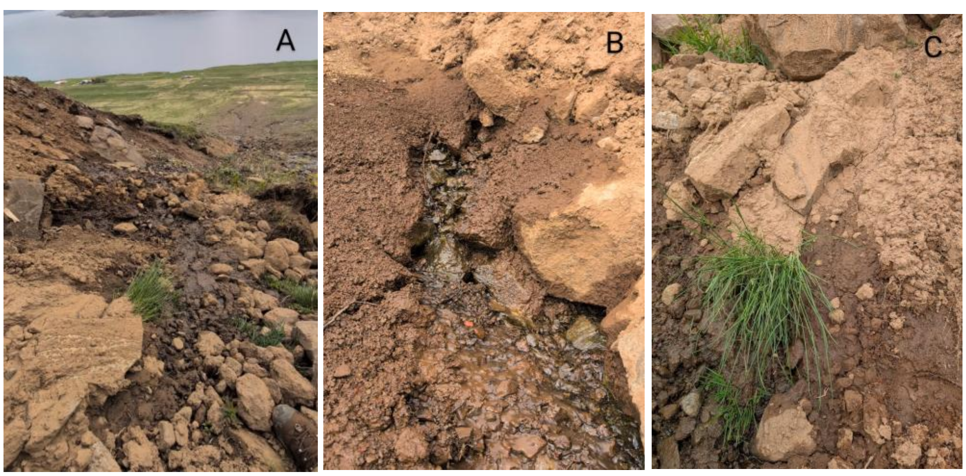

Figure 12. Images of Spring 1. A) View from the landslide path looking out towards Selsstaðir. B) Spring emergence point saturating the surrounding sediment. C) Seeping and vegetation coverage.

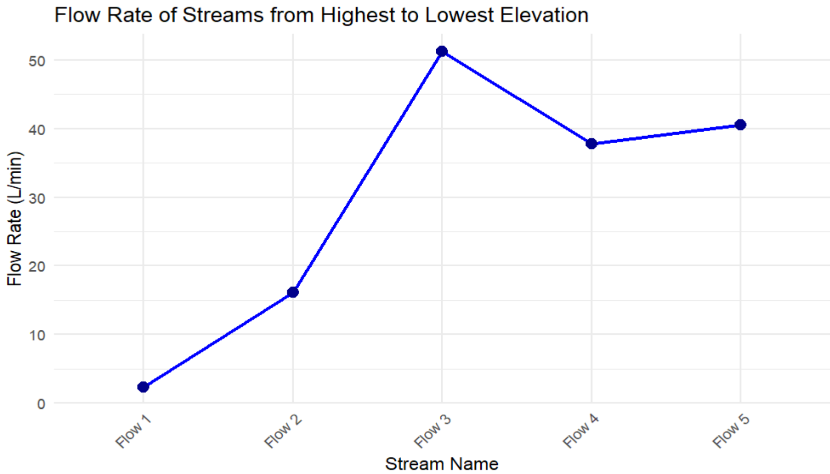

Figure 13. The flow rate in liters per minute of each spring fed stream. The flow number increases with a decrease in elevation.

Debris Flow Path Observations

2.1 Soil Pit Description

The surface cover of the quadrats at the path site varies greatly due to two streams running through them that formed from springs. A soil pit was dug next to quadrat 1, a depth of 22 cm and a length of 20 cm. The wall of the soil pit showed no horizons, but there was red and yellow/green mottling. There was wet clay-like sediment surrounding gravel sized rocks and the texture is clay loam. There was visible iron oxidation and a few spots about 5mm wide of light green that may be copper. (Figure 13)

2.1 Quadrat and Surface Conditions

The surface conditions of the general area were unstable because of loose rocks and unconsolidated fine sediment but varied across the width of the path because of the streams. (Figures 14, 15)

Table 4. Location properties of quadrats in the debris flow path.

Name	Location	Elevation (m.a.s.l.)	Slope Angle (°)	Slope Aspect (°)	Surface Condition
Q1	West	236	28	110 ESE	Dry, rocky, unstable
Q2	Middle	236	23	151 SSE	Wet, mossy, saturated, streams on either side.
Q3	East	237	16	125 SE	Rocky slope with many kinds of rocks.

2.3 Visual Summary

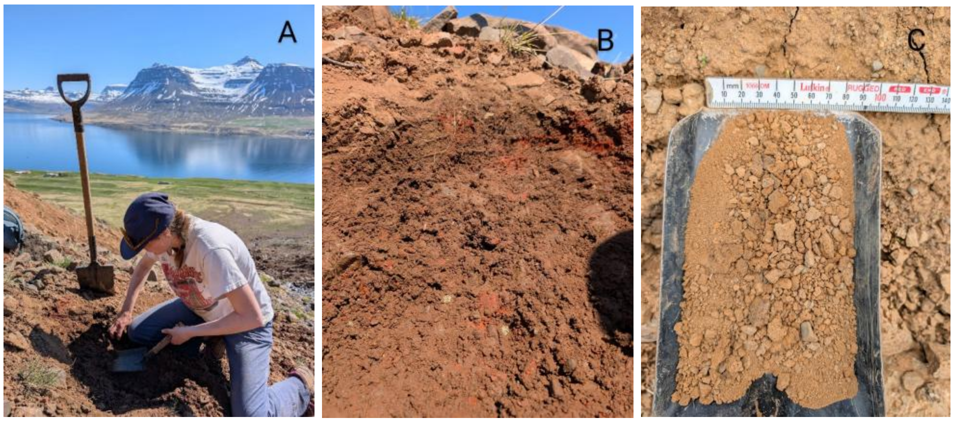

Figure 13. A) View from soil pit 2 B) Wall of soil pit 2 C) Grain size distribution of finer sediment at path location.

Figure 14. Quadrats at the path location.

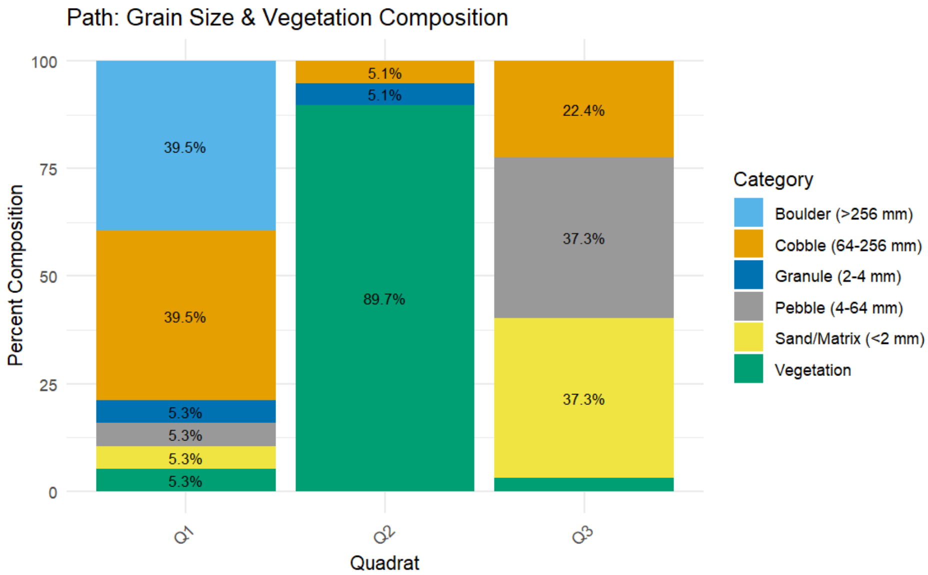

Figure 15. Stacked bar chart showing the grain size and vegetation composition of quadrats 1, 2 and 3 at the path location.

Deposition Zone Observations

3.1 Soil Pit Description

The deposit area of the debris flow flattens out into a wide tongue, highlighting the fluidity of it. Soil pit 3 was dug near quadrat 3 at 147 m a.s.l. and a 5 cm layer of vegetation was dug through before reaching the bare soil. The pit was 20 cm deep by 20 cm long. It contained fine grained sediment that was uniform with no layers. The soil texture was clay loam. There was decomposed organic material within the soil, and it was mixed with cobble sized rocks that ranged from 64-174 mm. (Figure 16)

3.2 Quadrat and Surface Conditions

Surface conditions greatly varied. The quadrats were on mostly level ground. The narrow stream channel that the debris flow followed has many person sized boulders in its banks (Figure 17, 18, 19).

Table 5. Location properties of quadrats in the deposition zone.

Name	Location	Elevation (m.a.s.l.)	Slope Angle (°)	Slope Aspect (°)	Surface Condition
Q1	West	146	9	148 SSE	Horsetails (grass), dead grass, different types of rocks about 170mm wide. There are mostly boulders around the area, foot sized rocks. Some are loose some are stuck
Q2	Middle	154	4	145 SE	Rocky with uneven pebbles, grasses emerging.
Q3	East	155	14	134 SE	Rocky, gravelly, they are more cemented in, more stable and level but still uneven terrain. Some grasses emerging.

3.3 Visual Summary

Figure 16. Soil properties at the deposition zone A) Soil pit 3 B) Fine sediment size distribution.

Figure 17. Quadrats at the deposition zone.

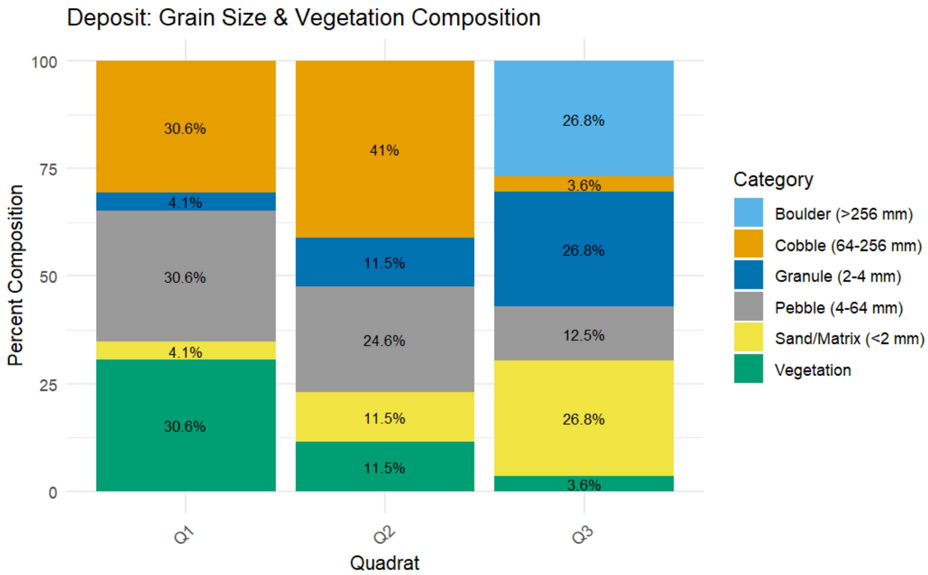

Figure 18. Stacked bar chart showing the grain size and vegetation composition. of quadrats 1, 2 and 3 at the deposition zone.

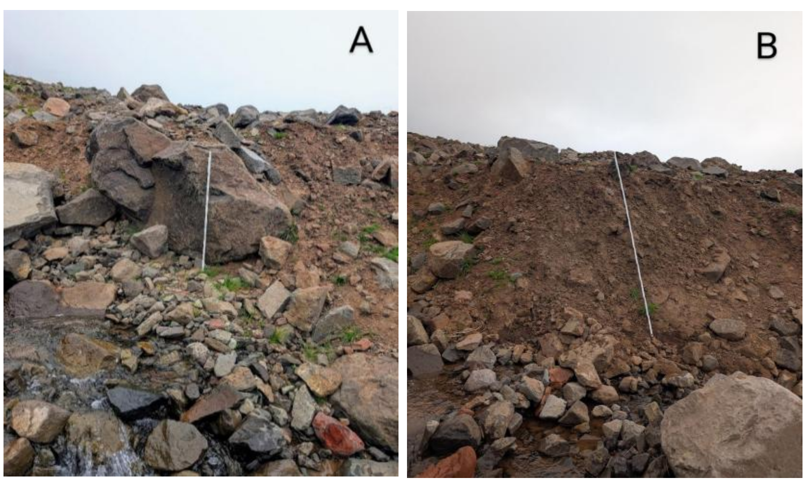

Figure 19. A) A 1-meter-tall boulder along the path of the stream, like many others. B) A 2-meter bank of sediment, carved out by the debris flow in 2020.

Summary

Figure 20 illustrates how coarse materials increase as slope angle decreases. The source area had a high percentage of fine materials because gravity caused the coarse material to fall away. The greater vegetation at the path location is related to the moist conditions of the slope from the spring fed streams. These patterns suggest that saturated fine materials from the source transition into higher energy flows capable of mobilizing large boulders into the lower elevations.

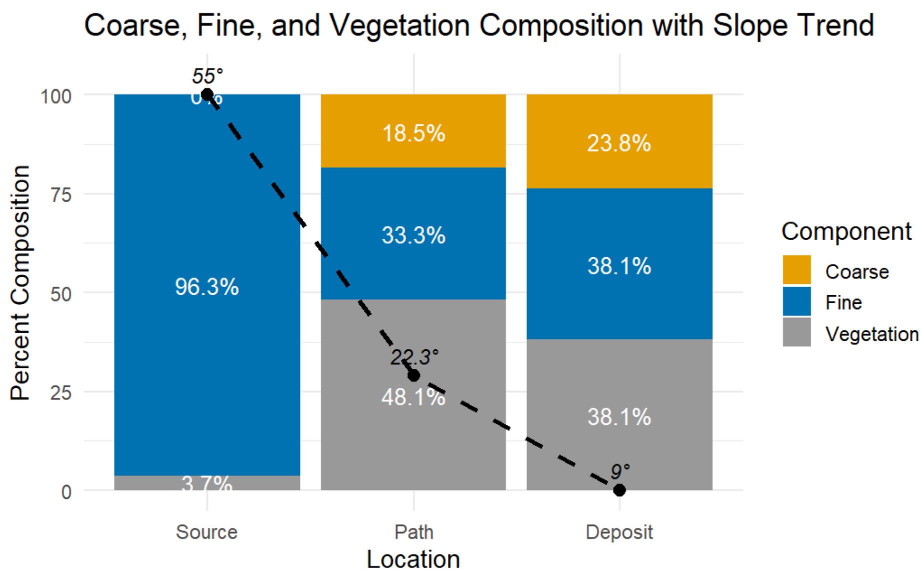

Figure 20. Stacked bar chart showing the distribution of vegetation, fine, and coarse materials at each location, related to slope angle.

Figure 21 shows the aggregation of sediment and vegetation distribution for each sample location. It provides a more specific breakdown of the fine and coarse sediment distribution. The path and deposition zones have similar presence of pebbles, cobbles and boulders. The path location has the most vegetation cover, according to the quadrats, possibly due to water infiltrating the area from the spring fed streams. The streams at the deposition zone run in deep channels armored with large boulders, preventing infiltration out (Figure 19).

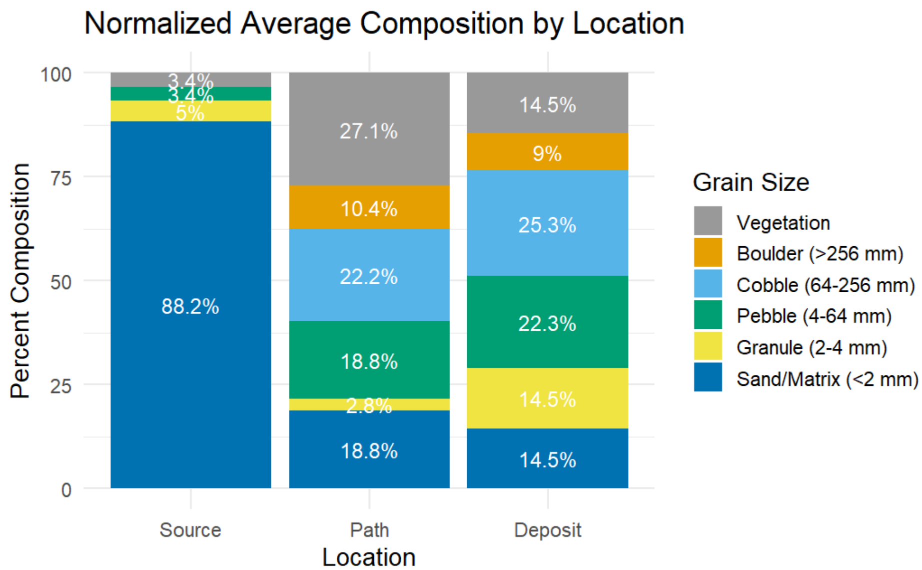

Figure 21. The normalized average soil size distribution and vegetation cover for each location.

Discussion

Findings

The field observations and soil analyses conducted at the Selsstaðir landslide scar strongly indicate the presence of a perched aquifer system controlled by a subsurface impermeable layer. The soil profiles, especially at the landslide source, exhibit a grey lower horizon indicative of sustained saturation and anoxic conditions, consistent with low-permeability, water-retaining substrates (Major & Iverson, 1999). The upper oxidized orange-brown layer, by contrast, marks fluctuating redox conditions likely tied to seasonal wetting and drying. These alternating saturation states may weaken the soil structure over time, increasing landslide susceptibility (Jakob & Hungr, 2005). Each soil texture by feel resulted in clay loam, besides soil pit 4 (sandy clay loam). Clay loam has a high-water storage capacity because the fine particles have a high surface area and strong ability to attract and hold water (Liu et al, 2025). This further shows the ability for the slope to retain a lot of water, allowing it to build up and eventually fail when it reaches capacity. The slope angle trends in figure 20 support the theory that sediment entrainment and deposition are governed by slope gradient and water content (Coussot & Meunier, 1996).

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These results help tell a story about the behavior of previous activity in the area. The new observations of springs add to that story, providing more information about what's below the surface in this region. The consistent emergence of springs along the scar at approximately 261 m a.s.l., particularly where clay loam dominates the soil texture, suggests a hydrologic barrier impeding vertical infiltration. This condition results in the accumulation and lateral movement of groundwater, a classic indicator of a perched water table (Coussot & Meunier, 1996; Iverson, 1997).

Flow rate measurements reinforce this hydrological interpretation. The two primary springs (Flow 1 and Flow 2) had distinct textures and flow characteristics, with Flow 2 exhibiting higher discharge (16.13 L/min) and coarser clasts (including boulders), while Flow 1 had finer, looser sediment that behaved fluidly when disturbed. These differences in flow rates suggest variability in flow resistance and sediment mobilization, which are key parameters in modeling debris flow behavior and volume estimation (Iverson, 1997). There have been similar observations of springs across a single elevation, and saturated sediments moving fluidly on the south mountain as well (Helgason, 2025). The flow of saturated material, pictured in Figure 12, mimicked the behavior of a density-driven flow, in which interstitial water significantly reduces friction and increases mobility (Iverson, 1997; Major & Iverson, 1999).

Observations of cracks and creeping near the landslide headwall in figure 11 show the ongoing instability of this slope. These features are early warning signs of either active movement or a reactivating landslide system, especially under continued hydrological loading (e.g., rainfall or snowmelt). The variation in crack size, depth, and progression across the headwall points to differential stress and strain along a failure plane, which may be closely tied to subsurface water buildup above an impermeable layer (van Asch et al., 1999; Highland & Bobrowsky, 2008).

In the Icelandic context, perched aquifers commonly develop where permeable volcanic materials are interbedded with impermeable clay or compacted tephra layers (Decaulne et al., 2005). Similar hydrogeologic structures have been documented in northern Iceland, where the Móafellshyrna landslide was partially attributed to water accumulation above a low-permeability stratum, combined with seasonal thawing (Morino et al., 2019). The landscape in Seyðisfjörður, characterized by steep slopes and stratified soil horizons, aligns with this model.

Implications for Landslide Hazard Analysis

Determining the depth and extent of springs is essential for quantifying landslide hazard potential:

- Volume estimation: The elevation of water emergence helps identify the maximum depth of saturated, potentially mobilizable material, which is central to estimating future debris flow volume.

- Return period prediction: If saturation above this layer occurs annually during snowmelt or heavy rain, landslide return intervals may correlate with climatic cycles.
- Hazard mapping: The springs delineate hydrologically active zones, helping to map areas of persistent instability for land use planning and risk mitigation.

Hazard Implications for Local Infrastructure and Residents

The potential for future debris flow events poses tangible risks to both infrastructure and residents downslope of the observed scar. Notably, the house at Selsstaðir lies in the projected path of potential flow trajectories and represents a stationary, long-duration exposure point, thereby increasing its relative risk. In contrast, the roadway below the scar is associated with lower exposure, as the probability of a vehicle being present during a debris flow is temporally limited. However, any obstruction or damage to the road could disrupt critical access and emergency response. Additionally, livestock such as sheep, which graze in the lower elevations, could also be affected during peak hazard periods.

Improving our understanding of the hydrologic and geotechnical conditions that lead to debris flows reaching inhabited areas is essential for refining hazard maps and mitigation planning. Specifically, identifying the saturation thresholds and timing of aquifer recharge above the impermeable layer can inform risk assessments tailored to vulnerable structures like Selsstaðir.

Recommendations for Future Research

Several key areas of investigation are recommended to build upon the findings of this study:

- **Hydraulic Conductivity Assessment**: Conducting formal soil pits and applying methods such as the Hazen formula could provide quantitative estimates of soil permeability and pore water transmission rates (Das, 2010). This empirical formula assumes relatively uniform, clean sand and does not perform well in clayey or silty soils. For Icelandic clay loam, additional lab methods (e.g., falling head permeameter) or field infiltration tests are recommended for validation.
- **Subsurface Characterization**: Determining the depth, lateral extent, and continuity of the mid-layer is crucial. Geotechnical drilling or geophysical techniques such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) are recommended for non-invasive subsurface mapping (Reynolds, 2011; Chamber et al. 2014).

  Storage Capacity and Saturation Timing: A fundamental question remains: how much water can the slope retain before failing? Estimating the volumetric water capacity above the mid-layer and the rate of recharge during precipitation or snowmelt events will allow for better predictive modeling.

- **Spring Temperature Monitoring**: Measuring the temperature of spring outflows could provide insights into source depth, flow path, and seasonal variations, enhancing the understanding of groundwater dynamics within the slope.
- **Event Modelling**: With an estimated elevation for spring emergence, historical debris flow records and rainfall data can be used to model the return period of similar landslide events and assess climatic triggers. Back tracking the 2020 debris flows in r.avaflow could help create experimental models for future debris flows in the region (Helgason, 2025).
- **Continuing the Landslide Inventory:** Gaining more information about the previous landslides on the north mountain would help with the modelling. For example, using historical weather station data to determine how much rain or snow Seydisfjordur received leading up to an event; and comparing images from the aerial photo gallery on atlas.lmi.is overtime to investigate the landslide extents and relate them to the weather conditions.

Limitations

Five weeks is a short time frame for a research project. With more time, I could have mapped the historical landslides as polygons by georeferencing old aerial images, and possibly modeled the 2020 debris flows in r.avaflow, a basic and free modeling platform geared towards hydrological models, to estimate their speed and flow paths. This would have synthesized the field observations more meaningfully and given IMO a more complete product. A water flow meter and thermometer would have provided more accurate flow rates and characterized the springs more definitely. Since random or grid-based selection for quadrats was not used, this was a biased selection, and a more scientific method should be used in the future. The quadrat was small compared to some of the boulders, and subconsciously, no large boulders were selected to be in the quadrats, which would have changed the distribution shown in figure 21. The quadrats at the deposit location could have been done further downslope, or an additional location observed to account for the revegetated pastures that were in the landslide path. Similar methods and the ones recommended for future research should be carried out on the other landslide scars from 2020 to paint a better picture of the event and confirm the findings presented in this report.\

Conclusion

The field component of this study revealed that spring locations around 261 m a.s.l. act as key geomorphic indicators for slope saturation and potential landslide activity. These springs appear to form where water accumulates above a subsurface impermeable layer—likely a compacted clay-rich horizon or bedrock interface—suggesting the presence of a perched aquifer. The spring elevation can serve as a reference layer in hydrological models or landslide susceptibility maps. Integrating this elevation data with return period estimates, climate projections, and field-based permeability measurements would be a logical next step. With continued monitoring and more comprehensive subsurface profiling, this site could serve as a testbed for understanding how water mobility and slope structure interact in landslide-prone fjord landscapes.

Despite the relatively short timeframe, this project covered a wide scope—from field data collection to spatial and statistical analysis. I was able to gather meaningful results while also developing technical skills in both ArcGIS Pro and R Studio. By the end, I was able to manage spatial datasets, run custom visualizations, troubleshoot coordinate mismatches, and script data transformations and normalizations for vegetation and grain size interpretation. These skills are not only essential for future geospatial work but were directly relevant to processing and visualizing the field data collected at Selsstaðir.

This project highlights that even a focused, time-limited study can uncover critical insights—especially when field observations are backed by spatial and statistical tools. It also reinforced the value of adaptability, both in the field and in the analysis stage, when data availability or project scope shifts. There's much more to explore, but this is a strong step forward.

Project Development and Insight for Future Students

The original goal for this project was to build a conceptual hydrological model of the south side of the fjord, specifically in an area called Neðri Botnar. I spent the first half of the timeline searching for datasets that I could upload into ArcGIS. I explored using MODFLOW and QGIS, but eventually returned to ArcGIS since that's what I'm most comfortable with.

The biggest challenge was finding usable data. I had expected more would be available from the IMO. The most useful sources were Lýsigagnagátt, the INSPIRE Geoportal, and Landmælingar Íslands. Lýsigagnagátt had a lot of downloadable data, but it only worked if I copied the URL of the XML file and uploaded it directly into ArcGIS. Even then, it only worked when ArcGIS recognized the file's "Source." If it showed up as "Automatic," the path was considered invalid.

Landmælingar Íslands offered a map with layer options and linked metadata for downloads. Access required submitting a name, email, and purpose of use—but the system was responsive and allowed me to reapply for additional access. INSPIRE Geoportal covers all of Europe and has valuable data but requires a lot of digging to find downloadable layers.

There was a delay early in the project to get in touch with an IMO employee who specializes in landslides and hazard mapping. Once we connected—about halfway through the project—they gave me helpful feedback and suggested focusing on the north side of Seyðisfjörður, which has no prior research, but is high on the to-do list. We agreed that it would be valuable to do a hazard analysis of that area and characterize its geomorphological and hydrological conditions.

My greatest suggestions for future students would be to pursue a topic you are interested in, get in contact with someone in that field, and ask if they or the organization has projects and research for a student of your caliber. Be open-minded and don't give up! The first two weeks of the independent study project are often spent designing and redirecting the research goals, a critical step. The research is important but get involved in the community you live in. That was the most memorable part of this program. I met a lot of inspiring people in Seyðisfjörður who have influenced how I will lead my life. Relish the Icelandic ways and get outside!

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