Eirini Makopoulou is a physical geographer who completed her doctoral research at the Geography Research Unit, University of Oulu, Finland. In her doctoral thesis, she investigates the spatial distribution and environmental controls of retrogressive thaw slumps and active-layer detachment failures — two dominant landforms of permafrost degradation under a warming climate — using statistical susceptibility modelling across multiple scales. At the circumpolar scale, she maps the occurrence and environmental drivers of retrogressive thaw slumps across the Northern Hemisphere permafrost domain. Her research further examines how these hazards intersect with critical infrastructure in Alaska and northwestern Canada, quantifying the vulnerability of roads and pipelines to slope instability. She also explores how these permafrost hazards are perceived and managed within nature-based tourism and protected-area governance in the Yukon. Through her work, she seeks to advance an integrated understanding of permafrost thaw as a coupled socioenvironmental process in rapidly changing northern regions.

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Contents

Appendices are available in the printed version of this publication.

Abstract

In recent decades, the Arctic has warmed at a rate that significantly exceeds the global mean, a phenomenon commonly referred to as Arctic amplification. Studies consistently show that Arctic temperatures are increasing at a rate roughly two to four times the global average, highlighting the exceptional sensitivity of northern environments to ongoing climatic change. Permafrost thaw is increasingly destabilizing high-latitude and high-altitude landscapes, giving rise to a range of slope failures with growing implications for ecosystems, infrastructure, and human activity. This dissertation examines thaw-driven mass-wasting processes across multiple spatial scales, focusing on retrogressive thaw slumps (RTSs) and active-layer detachment failures (ALDs) as dominant expressions of permafrost degradation under a warming climate. Integrating circumpolar susceptibility modeling, regional comparative analysis, applied infrastructure exposure assessment, and a tourism-focused case study, the thesis develops a multiscale framework for understanding where thaw-related slope instability is likely to occur, how controlling factors vary among permafrost landscapes, and why these processes matter for society.

At the circumpolar scale, statistical susceptibility modeling identifies consistent hemispheric patterns in RTS occurrence associated with climatic conditions and terrain settings commonly linked to ice-rich permafrost. Comparative regional analyses demonstrate that RTSs occupy distinct environmental envelopes throughout cold regions, highlighting pronounced environmental heterogeneity between regions. Regional-scale modeling of ALDs across Alaska and northwestern Canada reveals strong associations with slope morphology, cold-climate conditions, and fine-grained soils and shows extensive overlap between susceptible terrain and critical infrastructure networks. A local-scale synthesis in Yukon protected areas further illustrates that thaw-driven geomorphic hazards intersect with tourism, heritage, and governance, extending permafrost risk beyond infrastructure and settlements to transient human presence.

Collectively, the results show that thaw-related slope failures are governed by consistent classes of environmental controls, such as climate and topography, whose expression and consequences are fundamentally scale-dependent. By linking physical susceptibility with environmental heterogeneity and patterns of human use, this dissertation advances an integrated perspective on permafrost thaw as a coupled socioenvironmental phenomenon. The findings provide a scientific basis for anticipated impacts of accelerating permafrost degradation and support the development of multiscale adaptation strategies in rapidly changing cryospheric environments.

Keywords: retrogressive thaw slumps, active layer detachment failures, slope hazards, statistical modeling, susceptibility modeling, permafrost disturbances

List of original publications

Article I Makopoulou E, Karjalainen O, Elia L, Blais-Stevens A, Lantz T, Lipovsky P, Lombardo L, Nicu CI, Rubensdotter, Rudy AC & Hjort J (2024) Retrogressive thaw slump susceptibility in the northern hemisphere permafrost region. *Earth Surface Processes and Landforms* 49(11): 3319–3331. https://doi.org/10.1002/esp.5890

Article II Makopoulou E, Hjort J, Lantz T & Karjalainen O (Submitted manuscript) Regional contrasts in environmental factors of retrogressive thaw slumps across the Arctic and the Tibetan Plateau.

Article III Makopoulou E, Karjalainen O, Lipovsky P, Blais-Stevens A & Hjort J (2025) Susceptibility of active-layer detachment failures and vulnerability of infrastructure in Alaska and northwestern Canada. *Landslides* 22: 3561–3575. https://doi.org/10.1007/s10346-025-02603-x

Article IV Makopoulou E & Varnajot A (2025) Permafrost degradation-induced risks for nature-based tourism in the Arctic – case from the Yukon. *Climatic Change* 178(93). https://doi.org/10.1007/s10584-025-03942-3

Contributions

In Article I, Makopoulou, Karjalainen, and Hjort conceptualized the research idea. Makopoulou collected the data with help from Elia and Rubensdotter with data contributions from Lantz, Lipovsky, Lombardo, Nicu, Blais-Stevens, and Rudy. Karjalainen led the geospatial processing with Makopoulou and Hjort. Makopoulou and Karjalainen performed the statistical analysis with contributions from Hjort. Makopoulou wrote the original manuscript with contributions from all the authors.

In Article II, Makopoulou, Karjalainen, and Hjort conceptualized the research idea. Makopoulou collected the data with contributions from Lantz. Makopoulou performed the statistical analysis with contributions from Karjalainen and Hjort. Makopoulou wrote the original manuscript with contributions from all the authors.

In Article III, Makopoulou, Karjalainen, and Hjort conceptualized the research idea. Makopoulou collected the data with contributions from Lipovsky and Blais-Stevens. Makopoulou performed the statistical analysis with contributions from Karjalainen and Hjort. Makopoulou wrote the original manuscript with contributions from all the authors.

In Article IV, Makopoulou and Varnajot contributed to the study conception, design, writing, and editing. Makopoulou was responsible for the data visualizations.

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Frozen Debris Lobes (2020) *Downslope slump* [Video]. Produced by Frozen Debris Lobes, University of Alaska Fairbanks. YouTube. https://youtu.be/FSdb-T_9f-I

List of abbreviations

ALD .... active-layer detachment failure
AUC .... area under the curve
CHELSA .... Climatologies at High Resolution for the Earth's Land Surface Areas
CH_4 .... methane
CO_2 .... carbon dioxide
CTI .... compound topographic index
DEM .... digital elevation model
FDD .... freezing degree days
GBM .... generalized boosting modeling
GLM .... generalized linear model
GAM .... generalized additive model
MaxEnt .... maximum entropy
PERMANOVA .... permutational multivariate analysis of variance
ROC .... receiver operating characteristic
RTS .... retrogressive thaw slump
SCAI .... seed cell area index
SWB .... site water balance
TDD .... thawing degree days
TSS .... true skill statistic

1 Introduction

The Arctic and high-altitude regions are warming at rates two to four times faster than the global average, a trend that has intensified over the past four decades (IPCC 2021; Rantanen et al. 2022). This accelerated warming is driving widespread permafrost degradation, which represents one of the most pronounced indicators of climate change in cold regions (Streletskiy et al. 2025). Permafrost, defined as ground that remains at or below 0 °C for at least two consecutive years (Lewkowicz et al. 2024), underlies approximately 15% of the Northern Hemisphere's land surface (Obu 2021). Rising air temperatures and increased precipitation deepen the active layer, defined as the near-surface soil layer that thaws seasonally above permafrost and refreezes during winter (Lewkowicz et al. 2024). Active layer deepening destabilizes ice-rich soils, while climatic extremes further accelerate thaw-driven geomorphic change and the release of previously frozen organic carbon through enhanced microbial decomposition and erosion of organic-rich permafrost sediments (Schuur et al. 2015; Turetsky et al. 2020). Together, these processes have cascading impacts on ecosystems, infrastructure, and global climate feedbacks.

Among the most dynamic indications of permafrost thaw are *retrogressive thaw slumps* (RTSs) and *active-layer detachment failures* (ALDs), which are the dominant forms of thaw-induced mass wasting across Arctic, sub-Arctic, and high-altitude permafrost landscapes, including major high-altitude upland regions such as the Tibetan Plateau. RTSs initiate when destabilized slopes expose ice-rich permafrost through erosion, mass wasting, wildfire, wave action, or anthropogenic disturbance, leading to ground-ice melt, headwall retreat, and sustained retrogressive growth that can persist for decades (Bartleman et al. 2001; Burn & Lewkowicz 1990). ALDs, in contrast, are shallow translational slides confined to the seasonally thawed active layer and are typically triggered by elevated pore-water pressure during peak thaw periods (Dyke 2004; Harris & Lewkowicz 1993, 2000; Lewkowicz & Harris 2005). Both RTSs and ALDs tend to occur in spatial clusters and exhibit strong sensitivity to summer temperature and precipitation regimes, which makes them effective indicators of permafrost landscape vulnerability.

The significance of RTSs and ALDs extends well beyond localized slope instability. At high densities, these disturbances reshape geomorphology, alter drainage networks, and increase sediment and solute fluxes into rivers and lakes, affecting hydrological and aquatic ecosystems at watershed scales (Kokelj et al. 2021a; Patton et al. 2021). Vegetation removal and soil disturbance promote early successional plant communities adapted to warmer and mineral-dominated soils with reduced organic matter, while displacing cold-adapted tundra species and altering ecosystem structure (Bartleman et al. 2001; Huebner & Bret-Harte 2019; Lantz et al. 2009). Both RTSs and ALDs expose previously frozen organic matter to microbial decomposition, which enhances carbon mobilization and contributes to positive climate feedbacks through increased CO_2 and CH_4 emissions (Dai et al. 2025; Ramage et al. 2018; Schuur et al. 2015; Turetsky et al. 2020).

From a societal perspective, thaw-driven slope failures pose increasing risks to northern infrastructure and human activities. Roads, pipelines, buildings, and access corridors (airports/airstrips) constructed on permafrost are increasingly destabilized by ground subsidence, debris deposition, and altered hydrological pathways (Hjort et al. 2018, 2022; Streletskiy et al. 2019). Beyond infrastructure, thaw-related hazards intersect with nature-based tourism, a rapidly growing economic sector in Arctic regions. Summer, the peak season for outdoor recreation and tourism, coincides with maximum thaw instability, exposing visitors to unfamiliar hazards in remote parks and protected areas (Saarinen & Varnajot 2019). In this broader context, recent transdisciplinary assessments emphasize that permafrost thaw generates interacting risks across physical, ecological, and socio-economic systems, including infrastructure disruption, water quality degradation, and food and supply insecurity, which underscores that thaw impacts extend well beyond geomorphic processes (Gartler et al. 2025). Despite this growing recognition, recent work shows that tourists constitute a distinct and largely overlooked risk group in permafrost regions. A gap therefore exists in adaptation and risk-governance frameworks, which remain focused primarily on infrastructure and local communities (Varnajot & Makopoulou 2025).

Research on thaw-induced slope failures has evolved substantially over recent decades. Previous work documented RTS morphology and dynamics in the Canadian Arctic (Burn & Lewkowicz 1990; Lacelle et al. 2015) and ALD processes in Yukon and the Mackenzie Valley (Lewkowicz & Harris 2005; Lipovsky et al. 2006). Swanson et al. (2021) documented ALDs and RTSs in Alaska's Arctic National Parks, while Jiao et al. (2022) examined RTS and ALD development along the Qinghai–Tibet Highway, highlighting the roles of ice content, slope gradient, and hydrological changes in slope instability. In West Siberian Arctic, a high-resolution inventory by Nesterova et al. (2025) revealed that over 75% of RTSs are concentrated along lakeshores. Ward Jones et al. (2019) demonstrated rapid RTS initiation in response to ice-wedge degradation and terrain controls in the Canadian High Arctic, while Lantz and Kokelj (2008) and Kokelj et al. (2017) provided regional analyses of thaw-slump processes linked to warming. More recently, Nesterova et al. (2024) provided a comprehensive review of RTS characteristics and terminology across Arctic and high-altitude environments, emphasizing geomorphic controls and process variability. Short-term RTS dynamics captured in high-frequency field observations by Ward Jones & Pollard (2021) complement the broader temporal and spatial patterns identified by van der Sluijs et al. (2023), who demonstrated that thaw slump growth follows consistent allometric scaling relationships across seasonal to decadal timescales. These studies established the importance of ice-rich sediments, slope gradients, and thawing degree days (TDD) as key controls on slope stability.

Research has increasingly adopted statistical and machine-learning approaches to predict the spatial distribution of thermokarst-related slope failures. Generalized linear model (GLM) approaches have been applied at local to regional scales (Elia et al. 2023; Nicu et al. 2023; Rudy et al. 2016; Yin et al. 2021), and they have identified RTS-prone regions and the potential impacts on Arctic landscapes. Large-scale inventories and advances in remote sensing have further transformed understanding of thaw-induced slope processes. High-resolution satellite imagery, interferometric synthetic aperture radar, and deep learning techniques now enable systematic detection and monitoring of RTS activity across vast and previously under-sampled regions (Ardelean et al. 2020; Bernhard et al. 2022b; Huang et al. 2020; Maier et al. 2025; Nitze et al. 2025; Yang et al. 2025; Ying et al. 2025). Additionally, Nicu et al. (2021, 2022) offered a case study of RTS hazard impacts on Arctic cultural heritage in Svalbard, underlining the societal implications of terrain instability. These datasets reveal an accelerating rate of slope activity in response to extreme summer warmth and precipitation, reinforcing earlier findings on climate sensitivity (Lewkowicz & Way 2019; Segal et al. 2016).

This thesis investigates thaw-induced slope processes in permafrost regions by examining the spatial distribution, environmental controls, and societal implications of RTSs and ALDs across multiple spatial scales. The work combines circumpolar-scale

susceptibility modeling, comparative regional analysis, regional infrastructure exposure assessment, and risk interpretation to address both fundamental geomorphic questions and the challenges associated with rapid permafrost degradation.
Specifically, the thesis has the following objectives:

1 **Quantify the circumpolar distribution and susceptibility of RTSs** under current climatic and environmental conditions and identify the dominant factors that control their spatial occurrence across the Northern Hemisphere permafrost domain (Article I).

2 **Assess regional contrasts in the environmental drivers of RTS occurrence** by comparing multiple Arctic and Tibetan Plateau high-altitude permafrost regions (Article II).

3 **Evaluate the susceptibility of ALDs and their spatial overlap with critical infrastructure,** with a focus on transportation and energy networks in Alaska and northwestern Canada, to identify regions of high vulnerability to thaw-induced slope instability (Article III).

4 **Examine how permafrost degradation and thaw-related geomorphic hazards are framed, perceived, and managed within nature-based tourism contexts.** The analysis synthesizes pathways through which physical permafrost processes translate into operational, safety, and governance challenges in Arctic protected areas (Article IV).

The four articles included in this thesis have complementary analytical approaches and spatial extents (Figure 1). Articles I and III apply large-scale spatial modeling to quantify susceptibility to RTSs and ALDs using harmonized geospatial datasets and statistical learning techniques. Article II compares the environmental distributions associated with RTS occurrence and evaluates the relative influence of climatic, topographic, and soil variables across Arctic and high-altitude permafrost regions. While the geomorphic and infrastructure-related impacts of permafrost thaw have received increasing attention, the implications of thaw-driven hazards for tourism, protected-area management, and visitor safety remain underrepresented in the permafrost hazard literature. This gap is particularly notable given that peak tourism activity coincides with periods of maximum thaw instability in Arctic environments. Article IV applies an integrative, risk-focused perspective to examine how permafrost-related slope hazards intersect with nature-based tourism and protected-area management at the regional scale. Together, these studies address thaw-related slope hazards from hemispheric to site-specific perspectives and link geomorphic process understanding with societal relevance.

This synthesis provides a comprehensive perspective on permafrost landscape dynamics in a rapidly warming Arctic. By linking understanding of geomorphic processes with applied hazard and risk considerations, the thesis advances both the fundamental and the practical knowledge needed to anticipate future changes in northern environments and to support adaptation strategies for communities, infrastructure operators, and park managers.

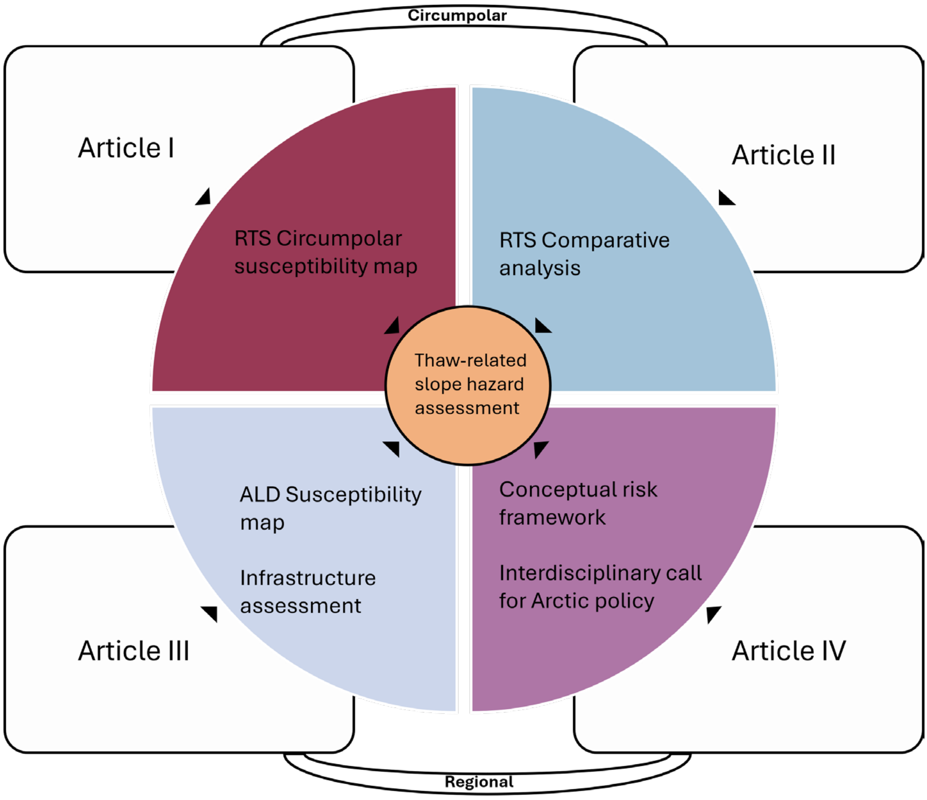

Figure 1. The theoretical framework of the thesis is presented across the four spatially and thematically distinct articles. This quadrant-based schematic illustrates the core structure and contributions of each article within the dissertation's overarching goal of assessing permafrost-related slope hazards (retrogressive thaw slumps [RTSs] and active-layer detachment failures [ALDs]). At the center lies the unifying focus.

2 Background

2.1 Permafrost landscapes

Permafrost landscapes are defined by the long-term presence of frozen ground, a condition that steers geomorphic, hydrological, and ecological processes across vast portions of Arctic, sub-Arctic, and high-altitude regions (French 2017; Lewkowicz et al. 2024). Permafrost underlies approximately 15% of the Northern Hemisphere's land surface and extends from continuous to sporadic zones, reflecting gradients in climate, vegetation, snow cover, and topography (Obu et al. 2021). Rather than being a static feature, permafrost is a dynamic component of the cryosphere that responds sensitively to changes in surface energy balance, hydrology, and vegetation, making it a key indicator of climate change in cold regions (Biskaborn et al. 2019).

A defining characteristic of permafrost landscapes is the presence of ground ice, which exerts a primary control on terrain stability and thaw sensitivity. Ground ice occurs in multiple forms, including pore ice, segregated ice, ice lenses, wedge ice, and massive ice bodies, and its abundance and spatial distribution vary widely among geological settings and permafrost zones (French & Shur 2010; Kokelj & Jorgenson 2013). Ice-rich permafrost, particularly in fine-grained sediments, stores large volumes of latent heat and undergoes substantial volume loss upon thaw, which leads to surface subsidence, slope instability, and thermokarst development (Shur & Jorgenson 2007). Recent syntheses emphasize that spatial heterogeneity in ground-ice content strongly modulates permafrost landscape responses to warming, producing highly uneven thaw impacts across regions subjected to similar climatic forcing (Gartler et al. 2025). Consequently, ground-ice distribution is increasingly recognized as a fundamental control on the magnitude, rate, and spatial clustering of permafrost-related disturbances.

Overlying the permafrost is the active layer, the near-surface zone that thaws seasonally during summer and refreezes in winter. Active-layer thickness varies spatially and temporally in response to air temperature, snow cover, vegetation, soil properties, and moisture conditions (Romanovsky & Osterkamp 2000; Shiklomanov et al. 2013). Warming air temperatures and increased precipitation have led to widespread active-layer thickening across Arctic and alpine regions, increasing the depth of seasonal thaw and altering subsurface hydrological pathways (Biskaborn et al. 2019; Nyland et al. 2021; Strand et al. 2021). Thickening of the active layer reduces the mechanical strength of near-surface soils, increases pore-water pressure during thaw, and enhances the transmission of heat to underlying permafrost, thereby preconditioning landscapes for slope failure and thermokarst processes (Lewkowicz & Harris 2005; Ward Jones et al. 2019).

Interaction between permafrost, ground ice, and the active layer forms the physical basis for many thaw-driven landscape disturbances. When warming or surface disturbance disrupts the thermal equilibrium of ice-rich permafrost, thaw can trigger abrupt and nonlinear geomorphic responses, including ground subsidence, thermokarst lake formation, and mass wasting (Turetsky et al. 2020). These processes are particularly pronounced where thick active layers overlie ice-rich permafrost, as seasonal thaw facilitates the exposure and melt of ground ice, leading to rapid landscape reorganization (Kokelj et al. 2021a). Such disturbances not only reshape terrain morphology but also alter hydrological connectivity, sediment transport, vegetation patterns, and biogeochemical cycling, reinforcing feedbacks between permafrost thaw and ecosystem change (Ramage et al. 2018; Schuur et al. 2015).

Permafrost landscapes therefore function as tightly coupled cryo-hydro-geomorphic systems in which small changes in climate or surface conditions can produce disproportionately large impacts (Kokelj et al. 2021b; Rowland et al. 2010). Understanding the spatial variability of permafrost thermal state, ground-ice content, and active-layer dynamics is essential for interpreting the distribution and behavior of the thaw-related hazards, such as RTSs and ALDs, examined in subsequent chapters of this thesis. By framing permafrost as a dynamic and heterogeneous landscape component rather than a uniform subsurface condition, this chapter provides the conceptual foundation for assessing susceptibility, impacts, and risk associated with thaw-driven geomorphic processes in a rapidly warming Arctic. Ground ice is a fundamental control on permafrost stability and thaw-related mass wasting and is introduced here to provide conceptual context for the processes examined in this dissertation. The diversity of geomorphic and infrastructural responses associated with permafrost degradation in Yukon, including slope failures, road deformation, and impacts on the built environment, is illustrated in Figure 2, which provides representative field examples of the disturbances discussed below.

Figure 2. Compilation of field photographs documenting impacts of permafrost degradation in Yukon. Panel a) shows roadside sign marking a high-risk slide area outside Dawson City in Yukon. Panels b) and c) illustrate active-layer detachment slides adjacent to Alaska and Dempster Highways respectively. Panel d) indicates the termination of a slide-affected road segment. Panels e) & f) show road deterioration of the Dempster and Haines Highways respectively. Panels g) & h) show buildings in Dawson City, affected by permafrost degradation. Panels i) & k) document cracking and subsidence. Panel j) presents an exposed retrogressive thaw slump scarp. Photos: Eirini Makopoulou.

2.2 Permafrost disturbances

Abrupt thaw-related slope disturbances are among the most transformative geomorphic processes in permafrost landscapes. RTSs and ALDs both result from the destabilization of ice-rich permafrost, yet they exhibit distinct morphologies, mechanisms, triggers, and environmental impacts. Together, these landforms play a pivotal role in reshaping Arctic and high-altitude terrain, accelerating biogeochemical fluxes, and intensifying climate-permafrost feedbacks.

2.2.1 Retrogressive thaw slumps (RTSs)

RTSs (Figure 3) are among the most distinctive and geomorphically transformative permafrost disturbances, reflecting the interaction between ice-rich permafrost, surface processes, and climatic forcing. RTSs initiate when erosion, mass wasting, wildfire, wave action, extreme rainfall, or anthropogenic disturbance exposes ground ice within ice-rich permafrost, triggering thaw, loss of structural support, and headwall collapse (Bartleman et al. 2001; Burn & Lewkowicz 1990). Once initiated, the exposed ice continues to melt, causing progressive upslope retreat of the headwall and sustained downslope transport of thawed sediments. This process links subsurface permafrost conditions directly to surface geomorphic change, making RTSs highly sensitive indicators of permafrost degradation.

Morphologically, RTSs are characterized by steep headwalls, extensive scar zones, and debris tongues that can extend tens to hundreds of meters downslope (Huebner & Bret-Harte 2019). They occur preferentially in fine-grained, ice-rich sediments such as glaciomarine, glaciofluvial, and loess-derived deposits, where the melting of excess ground-ice content generates subsidence that remains inherently unstable upon thawing (Lacelle et al. 2010). RTSs are commonly concentrated along riverbanks, lake shores, and coastal bluffs, where fluvial or coastal erosion provides the initial exposure necessary for ground-ice melt (Jones et al. 2015; Swanson 2014). These spatial patterns reflect the strong coupling between geomorphic setting and permafrost properties.

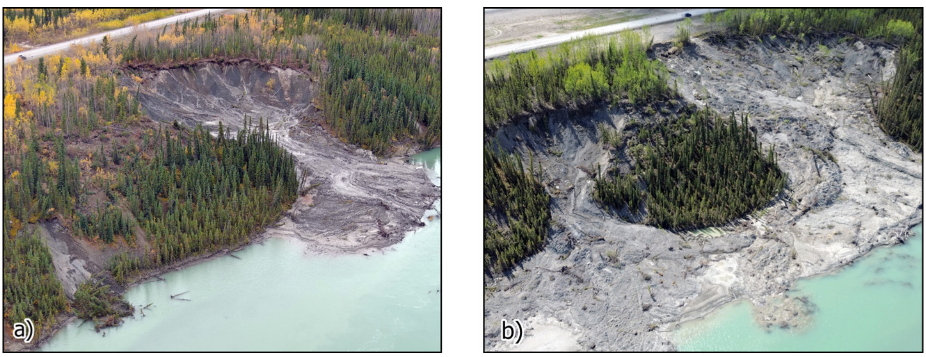

Figure 3. Oblique photos of retrogressive thaw slump (RTS) photos. Panel a) RTS in Takhini River, about 28 km NW of Whitehorse and a fresh active-layer detachment failure (ALD) in the lower left corner (photo taken in 2021); Panel b) same RTS in Takhini River and the ALD, which subsequently transformed into an RTS (photo taken in 2025). Photos: a) Peter Von Gaza, Sep. 2021; b) Eirini Makopoulou, Jun. 2025.

Climatic controls play a central role in both RTS initiation and acceleration. Warm and wet summers deepen the active layer, increase meltwater availability, and reduce slope stability, creating favorable conditions for slump initiation and rapid growth (Burn & Lewkowicz 1990; Kokelj et al. 2015; Lewkowicz & Way 2019). Recent studies have documented intensification and clustering of RTSs across the Arctic under contemporary warming, with many slumps remaining active for years to decades once initiated (Ardelean et al. 2020; Segal et al. 2016). Through vegetation removal, sediment redistribution, hydrological disruption, and carbon mobilization, RTSs represent a major mechanism by which permafrost thaw reshapes Arctic landscapes and contributes to broader environmental change.

2.2.2 Active-layer detachment failures (ALDs)

ALDs (Figure 4) represent a distinct yet closely related class of thaw-driven slope disturbances, one fundamentally linked to seasonal thaw dynamics. ALDs occur when the thawed active layer detaches and slides downslope over a relatively impermeable frozen substrate, typically in response to elevated pore-water pressure during peak thaw periods (Dyke 2004; Harris & Lewkowicz 1993, 2000). Unlike RTSs, ALDs are confined to the active layer and do not initially require the exposure of massive ground ice, which makes them particularly sensitive to short-term climatic variability and hydrological conditions.

ALDs often occur synchronously over large areas during exceptionally warm or wet summers, producing widespread shallow landsliding across hillslopes and valley sides (Kokelj & Jorgenson 2013; Lewkowicz & Harris 2005). Although individual ALDs are generally smaller and shorter lived than RTSs, their cumulative impact can be substantial. ALDs disturb vegetation, increase sediment and water fluxes to streams, and alter hillslope hydrology, with effects observed at watershed scales (Swanson 2021). In some cases, ALDs can dam streams or redirect flow paths, influencing sedimentation processes and aquatic habitats (Ackerson et al. 2021).

Importantly, ALDs can act as precursors to deeper thermokarst development by exposing underlying ice-rich permafrost layers to subsequent thaw (Clarke et al. 2024; Lipovsky et al. 2006). This process creates a functional linkage between ALDs and RTSs, positioning ALDs as early-stage indicators of permafrost instability in warming

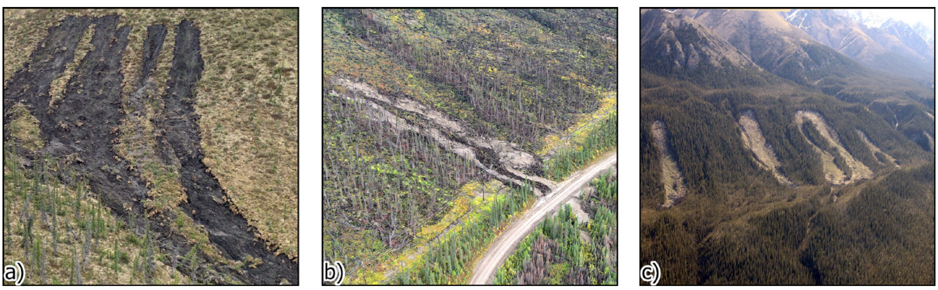

Figure 4. Active-layer detachment failure (ALD) photo compilation. Panel a) recent ALDs on the right side of Dempster Highway in Yukon at km 180-185 (photo taken Jun. 2025); Panel b) ALD that occurred after a 2023 forest fire adjacent to Haggart Creek Road, north of Mayo, Yukon, Canada (photo taken Aug. 2024); Panel c) ALDs on the side walls of the Donjek River Valley, Kluane Ranges, Yukon, Canada (photo taken in Jun. 2025). Photos: a) Eirini Makopoulou; b) Yukon Geological Survey 2024; c) Alix Varnajot.

landscapes. Most ALDs stabilize within months, which allows vegetation recovery relatively quickly and limits sediment export (Behnia & Blais-Stevens 2018). However, their geomorphic importance lies in their potential to expose deeper ice-rich material and create conditions for the transition toward RTS development (Figure 3). Observations from Yukon, the Mackenzie Delta region, and the Canadian Arctic Archipelago show that ALDs can act as precursors to larger, longer lived thaw slumps when failure scars cut into massive ground ice (Lewkowicz & Harris 2005; Lipovsky et al. 2006).

From a societal perspective, ALDs pose immediate risks to infrastructure and access corridors, as debris can be rapidly transported onto roads and other linear features, particularly following wildfire or extreme precipitation events (Clarke et al. 2024). Together, RTSs and ALDs represent complementary expressions of permafrost disturbance, operating at different depths and timescales. While both are influenced by climatic forcing and active-layer dynamics, they differ in their cryological requirements: excess ground ice is a fundamental necessity for the initiation of RTSs, whereas ALDs can occur in ice-poor substrates, where failures are instead driven by high pore-water pressure, such as during intense rainfall or rapid seasonal thaw.

2.3 Susceptibility modeling

Susceptibility mapping identifies terrain prone to thaw-related slope failures and is central to hazard management in permafrost regions. It assumes that conditions leading to past disturbances will also produce instability under similar circumstances (Carrara et al. 1991, 1995; Varnes et al. 1984). Susceptibility maps provide a spatial assessment of disturbance likelihood without specifying temporal probabilities (JTCI 2004). Susceptibility depends on terrain attributes such as lithology, soil properties, climate, hydrology, vegetation, and solar radiation (van Westen 2000), which are commonly grouped into intrinsic factors: slope, soil moisture, drainage, radiation, and extrinsic: for example, trigger factors like deep thaw or extreme precipitation (Atkinson & Massari 1998; Wu & Sidle 1995). While extrinsic factors are important, they are difficult to quantify and vary over short timescales, whereas intrinsic properties control long-term susceptibility patterns (Carrara et al. 1995; Siddle et al. 1991).

Early assessments were qualitative, relying on expert interpretation of slope morphology and surficial geology to derive ice-rich terrain (Jorgenson & Kreig 1988; Mackay 1971). With the advent of high-resolution imagery and digital elevation models, modeling evolved into quantitative approaches using disturbance inventories. Regression-based statistical models, such as generalized linear and additive models (GLM, GAM; Hastie & Tibshirani 1990) were widely applied to predict thaw-related slope failures, including ALDs and RTSs (Elia et al. 2023; Goetz et al. 2011; Petschko et al. 2014; Rudy et al. 2016). Recent work, including this dissertation, adopts advanced statistical modeling approaches that better handle nonlinearities and complex interactions. Generalized boosting modeling (GBM) efficiently captures threshold behaviors and multicollinearity among climatic, terrain, and soil predictors, offering predictive performance for large and heterogeneous landscapes (Friedman 2002; Karjalainen et al. 2020; Leppiniemi et al. 2023; Rudy et al. 2016; Segal et al. 2016). Presence-only algorithms such as MaxEnt remain valuable for biased inventories (Leppiniemi et al. 2025; O'Banion & Olsen 2014; Phillips et al. 2006; Popescu et al. 2024; Xu et al. 2025), while other frameworks (including decision trees and random forests) have shown strong performance in permafrost regions like the Qinghai–Tibet Plateau (Ran et al. 2022; Shen et al. 2024; Yin et al. 2021).

As Arctic regions continue to warm at accelerated rates (Rantanen et al. 2022), susceptibility modeling plays a crucial role in forecasting landscape reorganization, evaluating risks to infrastructure and communities, and supporting adaptation planning. By quantifying the spatial patterns and environmental controls of thaw-induced mass wasting, susceptibility models provide indispensable insights into the future trajectories of permafrost landscapes under rapid climate change. They move beyond simple observation to proactive hazard assessment, allowing nonlinear process interactions to be represented more realistically (Marmion et al. 2009). This predictive capacity is fundamental for evaluating the resilience and potential destabilization of periglacial landforms in response to continued permafrost warming.

3 Materials and methods

3.1 Study areas

This thesis examines permafrost disturbances at two interconnected spatial scales (Figure 5), circumpolar and regional, reflecting the environmental gradients that govern thaw-related slope hazards across the Northern Hemisphere. The circumpolar study (Article I; Figure 5a) spans the entire Northern Hemisphere permafrost region, following the permafrost extent established by Brown et al. (2002). This domain covers continuous, discontinuous, sporadic, and isolated permafrost extending across Alaska, Arctic Canada, Greenland, the Eurasian Arctic, and the high-elevation permafrost of the Tibetan Plateau. Mean annual air temperatures vary widely across this domain, from values near 0 °C in sub-Arctic transition zones to below -5 °C in the high Arctic (AMAP 2017; Biskaborn et al. 2019; Rantanen et al. 2022). Over the past four decades, large parts of this circumpolar region have warmed by approximately 2–4 °C, nearly four times the global average rate, which has substantially accelerated the thaw of ice-rich permafrost and amplified landscape sensitivity to geomorphic disturbance (AMAP 2017; Farquharson et al. 2019; Rantanen et al. 2022). This hemispheric scale captures the full breadth of environmental variability, including contrasts in ground-ice content, sediment types, terrain steepness, and hydrological regimes, and thus provides the foundation for assessing where and why thaw-driven slope failures occur in cold-region landscapes.

The circumpolar comparative study (Article II; Figure 5a) focuses on evaluating environmental differences among multiple cold-region RTS landscapes distributed across the Arctic and the Tibetan Plateau. The study area includes diverse geomorphic settings, such as lowland coastal plains, mountain foothills, upland tundra plateaus, and high-altitude permafrost terrain. These landscapes exhibit strong contrasts in precipitation, continentality, and snow cover persistence. Warming signals observed across these regions are consistent with broader Arctic climate trends and the substantial warming documented in high-elevation and mountain environments (Pepin et al. 2025; You et al. 2020). However, the magnitude and seasonal expression of recent warming, as well as associated active-layer deepening, vary among regions, creating distinct climatic contexts relevant for RTS occurrence (AMAP 2017; Biskaborn et al. 2019). By situating regions within a unified circumpolar framework, the comparative study examines how differing climatic and geomorphological conditions influence the occurrence of RTSs.

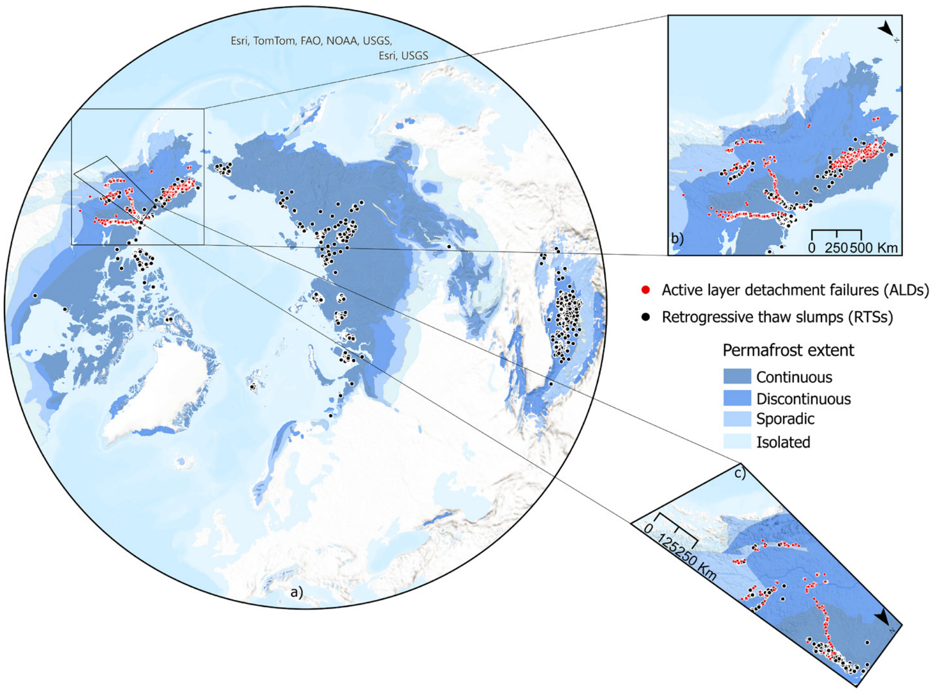

Figure 5. Overview of study areas, a) circumarctic and locations of the available retrogressive thaw slumps (RTSs) data used in Articles I & II; b) overview of the study area and the locations of active layer detachment failures (ALDs) used in Article III; c) overview of the Yukon region and the RTSs & ALDs used in Article IV. The permafrost zones are based on Brown et al. (2002).

The regional study (Article III; Figure 5b) is located in Alaska and northwestern Canada, an area underlain by continuous, discontinuous, sporadic, and isolated permafrost and characterized by rapid contemporary warming. Across this region, annual air temperatures range from near 0 °C in the southern discontinuous permafrost belt to below −10 °C in the northern mountains (AMAP 2017; NOAA 2023). Recent decades have seen marked thickening of the active layer, resulting in increased occurrence of shallow slope failures, particularly where thaw-sensitive sediments coincide with steep terrain or infrastructure (Farquharson et al. 2019; Lewkowicz & Way 2019). Intensifying summer rainfall events, documented across Alaska and the western Canadian Arctic, further destabilize weakening soils by increasing pore-water pressure and promoting slope saturation (AMAP 2017; Farquharson et al. 2019). The regional scale, therefore, enables investigation of high-resolution terrain-specific drivers of permafrost-related hazards in landscapes where warming, geomorphic sensitivity, and human activity intersect directly.

Finally, the regional study (Article IV; Figure 5c) examines the Yukon region as a key case in which pronounced geomorphic sensitivity, intensifying climate-driven permafrost degradation, and increasing human presence intersect. This combination creates a landscape in which environmental change directly intersects governance challenges and tourism exposure and makes the region especially well-suited for assessing risk management, decision-making frameworks, and adaptive capacity under conditions of rapid transformation.

3.2 Data

3.2.1 Retrogressive thaw slump and active-layer detachment failure observations

All four articles included in this thesis are based on a compilation of permafrost thaw-related slope failure datasets comprising RTSs and ALDs. Rather than constructing independent inventories for each study, a common, harmonized dataset was established for the specific objectives and scales of the individual articles. This approach ensures internal consistency across analyses while allowing methodological flexibility.

For Article I, a circumpolar RTS inventory (19,227 RTSs in total) was compiled by integrating published inventories, online geospatial databases, and visual interpretations of Arctic satellite imagery at 15 m resolution. For the visual interpretations, to ensure homogeneity at the hemispheric scale, only RTSs visible at a minimum mapping scale of 1:10,000 were retained. Article II uses the same RTS dataset but reorganizes it into 19 predefined study regions, 18 in the Arctic and 1 across the Tibetan Plateau.

The ALD dataset used in Article III was similarly compiled from previous inventories. A total of 4,398 ALD observations were compiled from published studies, geological survey reports across Alaska, Yukon, and parts of the Northwest Territories. An independent dataset of 142 ALDs from Siberia was incorporated exclusively for external model validation (Hjort & Luoto 2013). Article IV does not introduce new geomorphic inventories but instead draws directly on the RTS susceptibility output and RTS dataset from Article I and the ALD inventory from Article III. A full description of data sources, compilation procedures, and quality-control criteria is provided in the data section of each article.

3.2.2 Geospatial data

The geospatial datasets used in this thesis were selected to represent climatic, topographic, soil, and permafrost conditions across a multiscale set of study regions (Table 1). Owing to the varying spatial objectives of the four articles, the native resolutions and data

Table 1. Geospatial datasets used in the analysis of Articles I, II, and III. Abbreviations in the table refer to freezing and thawing degree days (FDD and TDD, respectively), site water balance (SWB), geomorphons (geom), profile curvature (pcurv), compound topographic index (CTI), and bulk density (bd).

Article	Climatic data	Topography data	Soil data	Modeling resolution
I	CHELSA v2.1 (FDD, TDD, rainfall), Karger et al. (2017)	Geomorpho90m (slope angle), Amatulli et al. (2020)	SoilGrids250m (fine sediments, bd), Poggio et al. (2021)	1 km
II	CHELSA v2.1 (FDD, TDD, rainfall, SWB), Karger et al. (2017)	Geomorpho90m (slope angle, geom, pcurv, CTI), Amatulli et al. (2020)	SoilGrids250m (fine sediments, bd), Poggio et al. (2021)	250 m
III	CHELSA v2.1 (FDD, TDD, rainfall, snowfall), Karger et al. (2017)	Geomorpho90m (slope angle, geom, pcurv), Amatulli et al. (2020)	SoilGrids250m (silt, bulk density), Poggio et al. (2021)	250 m

sources differ substantially among the circumpolar and regional domains. All datasets were harmonized to a consistent spatial resolution within each article to ensure compatibility among predictors.

For the circumpolar thaw-slump analysis (Article I), global climatologies from CHELSA v2.1 (Karger et al. 2017) provided temperature and precipitation variables at 1 km resolution, while terrain predictors were derived from Geomorpho90m (Amatulli et al. 2020). Soil properties from SoilGrids250m (Poggio et al. 2021) were similarly upscaled to 1 km resolution. In the circumpolar comparative study (Article II), a finer 250 m resolution was used to evaluate environmental differences among 19 distinct cold-region landscapes. Climatic variables were downscaled from CHELSA, terrain predictors were produced from Geomorpho90m derivatives, and soil properties were used at their native 250 m resolution. These harmonized datasets support consistent environmental comparisons of geomorphically diverse regions.

For the regional analysis of Alaska and northwestern Canada (Article III), terrain and climatic inputs were selected to match the 250 m modeling resolution required for ALD susceptibility mapping, a resolution sufficient to characterize fine-scale terrain controls. The 250 m resolution was selected as the optimal modeling scale for Article III because it provides the detail necessary to intersect geomorphic hazards with infrastructure while remaining consistent with the native resolution of the underlying soil and climatic datasets. This prevents the introduction of false precision through over-resampling and ensures that the model captures regional environmental gradients rather than local micro-topographic noise. Terrain predictors were obtained from Geomorpho90m (Amatulli et al. 2020), climatic variables from CHELSA v2.1 (Karger et al. 2017), and soil properties from SoilGrids250m (Poggio et al. 2021). Finally, for Article IV, national park and protected-area boundaries were obtained from GeoYukon Map Services (https://mapservices.gov.yk.ca/GeoYukon), which provides authoritative polygon layers for parks and conservation areas managed by the Yukon government.

3.2.3 Infrastructure data

In Article III, the regional-scale analysis of ALDs required spatially explicit and quality-controlled information on transportation and energy infrastructure across Alaska, Yukon, and the Northwest Territories. Linear infrastructure included the Trans-Alaska Pipeline, the Norman Wells Pipeline, and the primary and secondary road networks of Alaska and western Canada. Pipeline geometries were obtained from the State of Alaska Geoportal (2024) and the Government of Canada (2024), while road network data were acquired from the Alaska Department of Transportation and Public Facilities (2024) and the Government of Canada (2024). Representative examples of the linear infrastructure elements considered in the vulnerability analysis, including major highways and pipelines in Alaska and northwestern Canada, are shown in Figure 6.

In Article IV, the same road network in Article III is incorporated to reflect its central role in regional accessibility, as roads often constitute the primary terrestrial access option for visitors to reach remote parks, cultural heritage sites, and scenic destinations in the Yukon. In many areas, this ground-based access is the most feasible alternative to air travel, underscoring the dependence of tourism activity on transportation infrastructure that traverses permafrost terrain, which is increasingly affected by thaw-related slope instability.

Figure 6. Visualizations of infrastructure elements. Panels a) & b) Alaska Highway and Trans-Alaska Pipeline; panels c) & d) Norman Wells Pipeline and Dempster Highway, respectively. Photos: a) Alix Varnajot; b) Peter Prokosch (https://www.grida.no/resources/1651); c) Al Grillo, Associated Press File Photo; d) Eirini Makopoulou.

3.2.4 Other data

Distribution modeling requires absence or background data to provide an environmental contrast against presence observations (i.e., RTS and ALD locations). For Article I, an absence dataset of 17,000 points was generated in ArcGIS Pro using a random sampling strategy. To ensure spatial independence and minimize the risk of environmental overlap, a minimum distance threshold of 1,000 m was enforced between the sampled points and all presence locations. This dataset was verified using imagery available in ArcGIS PRO and Google Earth Pro to ensure an unbiased representation of the broad environmental gradients across the Northern Hemisphere permafrost domain.

Articles II & III utilized a presence-only modeling approach (MaxEnt); thus, background data were automated and produced by the MaxEnt software. In contrast with Articles I, II & III, Article IV incorporated visitor number datasets for the Kluane, Tombstone, Herschel Island–Qikiqtaruk, and Ni'iinlii'Njik parks (Government of Canada n.d.; Herschel Island–Qikiqtaruk Territorial Park Management Plan 2019; Yukon Parks Strategy 2020).

3.3 Methods

The methodological framework (Figure 7) applied in this dissertation integrates geomorphologic inventories, spatially harmonized environmental predictors, and a suite of predictive and exploratory statistical modeling techniques. Although each article addresses distinct research aims, the analytical logic is consistent: (1) detect: a) compilation of mass-wasting feature datasets, b) preparation and harmonization of environmental variables at appropriate spatial resolutions; (2) analyze: a) statistical modeling, b) evaluation of models' predictive skill; and (3) contextualize: integration of spatial data on infrastructure and protected areas to assess exposure to thaw-related hazards. Below, the methodological choices for each article are described in detail.

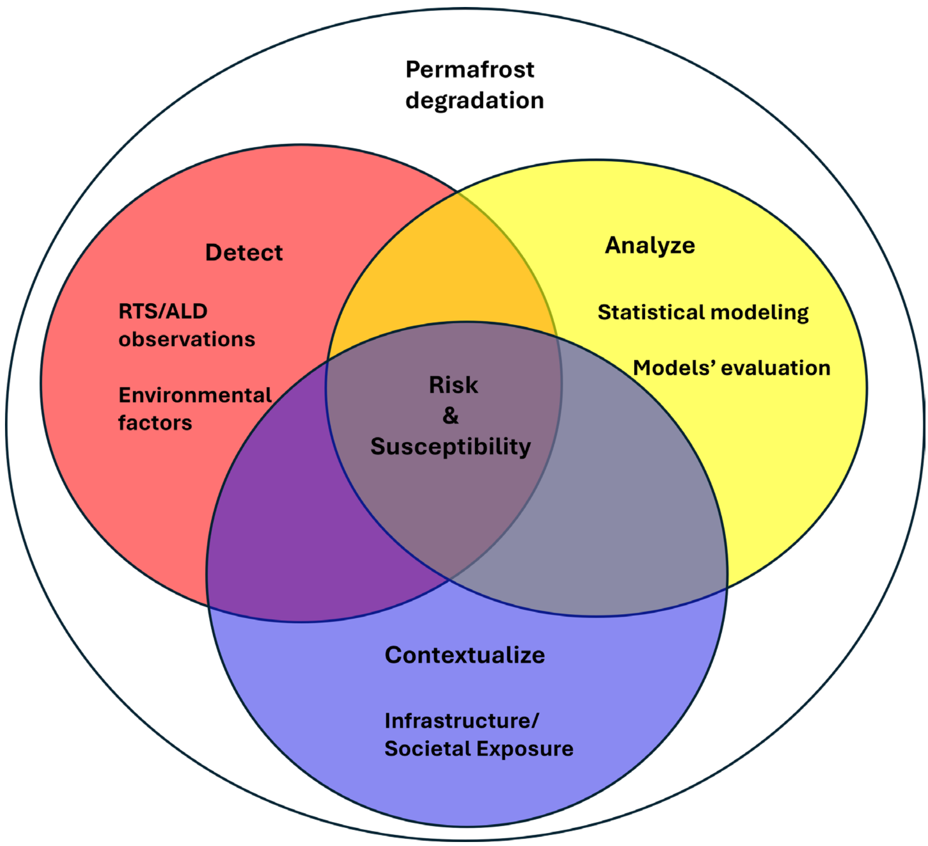

Figure 7. Conceptual framework of the methodology illustrating the integration of three core components: detection, analysis, and contextualization in the assessment of thaw-related slope hazards. Detection involves retrogressive thaw slump/active-layer detachment (RTS/ALD) observations and environmental variable extraction; analysis refers to statistical modeling of hazard potential; and contextualization involves overlaying societal exposure layers such as infrastructure and national parks.

In **Article I**, a circumpolar susceptibility model was developed to map the occurrence of RTSs across the permafrost domain. A primary methodological challenge in this scale modeling is the natural spatial clustering of RTS observations. When data points are geographically concentrated, standard statistical models can become over-fitted to local conditions, leading to an overestimation of performance (Schratz et al. 2019). To ensure the model captured broad environmental drivers, a repeated distance-based sampling strategy was employed. This approach involved running the model through multiple independent iterations to reduce residual spatial structure and ensure that the environmental characteristics of both presence and absence locations were represented fairly across the circumpolar region (Moreno et al. 2023). While the broad logic of this approach is described here, a more detailed breakdown of the specific methodology is provided in the Methods section of Article I.

To further ensure the integrity of the predictive results, the dataset underwent a rigorous spatial filtering process. By enforcing a minimum distance threshold between observations, the model was prevented from being over-influenced by high-density clusters in a single landscape. Furthermore, a strict spatial separation was maintained between the data used for model calibration and the data used for evaluation (Hao et al. 2020; Valavi et al. 2021). By testing the model on locations geographically distant from the training data, the study ensured that the model's predictive power was representative of its ability to generalize across the vast and varied Arctic region (Roberts et al. 2017).

The actual modeling was performed using GBM, a technique well-suited for capturing the complex, nonlinear relationships between permafrost landform occurrence and environmental factors. Beyond binary classification, this method enabled deeper exploration of the data through variable importance rankings and response curves. Response curves were used to visualize how the probability of an RTS changes as a specific environmental factor increases or decreases, providing insight into the physical thresholds that lead to terrain instability. The effectiveness of the models was evaluated using the area under the curve and true skill statistic (AUC & TSS, respectively), supported by sensitivity and specificity metrics (Allouche et al. 2006; Guisan et al. 2017).

Final susceptibility maps were produced by averaging predictions across ten runs and classifying probabilities using the 50th, 75th, 90th, and 95th percentiles, representing very low to very high susceptibility classes, following established practice (Goetz et al. 2015; Rudy et al. 2016; Yin et al. 2021).

Building on the circumpolar analysis from Article I, **Article II** investigates whether the environmental conditions driving RTS occurrence remain consistent for different geographic regions. This study examines whether RTSs in one part of the Arctic occupy a different "environmental envelope"-defined as specific climatic, topographic, and soil conditions-than those in another, or how they compare to high-altitude permafrost on the Tibetan Plateau. In it, the methodology shifted from a single global model to a comparative framework focused on regional distinctiveness and variability.

The analysis began by quantifying the extent to which these regions differ from one another using a multivariate dissimilarity index. By calculating an average environmental distance (mean Gower distance; Gower 1971) between regions, each landscape was ranked based on its unique characteristics. This allowed for identification of highly distinct tiers of RTS environments, ensuring that the subsequent modeling captured most of the environmental variability associated with RTS occurrence. To ensure that regions with more extensive data did not skew the results, a stratified random subsampling approach was used. By selecting a balanced number of observations from each study area, the analysis was forced to treat each landscape with equal importance, regardless of the density of documented RTSs, thereby reducing regional sampling bias. Subsequent analyses focused on high- and medium-tier regions, which capture the majority of environmental variability associated with RTS occurrence.

Beyond looking at the environment as a whole, the research examined differences between regions using Kruskal–Wallis tests for continuous variables, adjusted using the Benjamini–Hochberg procedure (Benjamini & Hochberg 1995; Hollander & Wolfe 1973). Differences in the categorical geomorphon variable were evaluated using chi-square tests and Cramer's V (Cohen 1988). To compare Arctic and Tibetan Plateau RTS environments, the same analyses were repeated under both balanced and unbalanced conditions.

To quantify regional environmental drivers of RTS occurrence, maximum entropy (MaxEnt) models (Phillips et al. 2006) were developed separately for each Arctic region and the Tibetan Plateau. To prevent the results from being biased by local data clusters, a spatial thinning technique was applied, and randomly sampled background points were used to characterize the broader environmental context of each region. Each regional model was calibrated using 80% of the available data, with the remaining data reserved for independent evaluation of the model's predictive accuracy. Finally, model performance was assessed using the AUC, with interpretative thresholds following Swets (1988) and Elith (2000). Predictor influence was quantified using permutation importance, which measures the reduction in model performance when predictor values are randomly permuted, providing an estimate of each variable's independent contribution to RTS suitability (Phillips et al. 2006; Phillips & Dudík 2008).

Article III shifts the focus to ALDs across Alaska, Yukon, and the Northwest Territories. To map these features, the study implemented MaxEnt modeling to generate probabilistic estimates of occurrence within the study area (Phillips et al. 2006). To reduce spatial autocorrelation associated with clustered ALD observations, a repeated tenfold distance-based resampling scheme was applied (Schratz et al. 2019).

Similarly to Articles I and II, ALD occurrences were split into training and evaluation datasets while a minimum distance was enforced to ensure spatial independence (Hao et al. 2020; Valavi et al. 2021). To capture the full range of environmental gradients across the western Arctic without overreaching the observed data, each model iteration combined presence points with a large number of background points (Roberts et al. 2017). Variable importance was assessed from each predictor's contribution to model gain and averaged across ten runs to obtain stable estimates of environmental control on ALD susceptibility (Thuiller et al. 2021). Model performance was evaluated using AUC (Elith 2000; Swets 1988) and the seed cell area index (SCAI). The SCAI was used for evaluation of potential predictive bias, specifically testing whether the model exhibits a tendency to overestimate landslide susceptibility (Rabby et al. 2023; Süzen & Doyuran 2004). Model transferability was tested using an independent ALD dataset from central Siberia (Kharuk et al. 2016), with identical predictors and evaluation metrics applied to assess predictive robustness beyond the calibration region (Phillips et al. 2006; Steger et al. 2022).

Final susceptibility maps were generated by averaging predictions across model runs and classifying probabilities using the 50th, 75th, 90th, and 95th percentiles, corresponding to very low to very high susceptibility classes (Goetz et al. 2015; Rudy et al. 2016; Yin et al. 2021). Beyond susceptibility modeling, Article III included an infrastructure vulnerability assessment. By intersecting the final ALD susceptibility maps with the road and pipeline networks, the study quantified the specific lengths of critical infrastructure, such as the Trans-Alaska and Norman Wells pipelines and the Alaskan and Dempster Highways, that traverse high-risk zones. This integrated approach translates physical susceptibility into a practical tool for hazard management by identifying where linear infrastructure is most at risk of slope failures.

Article IV employed a mixed qualitative–spatial analytical framework to contextualize permafrost degradation within tourism and protected areas. Rather than developing new statistical susceptibility models, the study synthesized environmental change processes with institutional and experiential dimensions to identify governance gaps and research needs. The methodological approach combined structured qualitative content analysis of policy and management documents, targeted literature synthesis on permafrost-related hazards, and spatial overlay analysis of thaw-sensitive terrain in relation to visitor access points and protected-area boundaries. This integrative design enabled a cross-disciplinary assessment of how geomorphic instability intersects with tourism practices and governance structures in Arctic environments.

Spatially, an overlay analysis was conducted between the RTS susceptibility map developed in Article I and the spatial boundaries of national parks in Yukon. Additionally, visitor numbers for national parks (Kluane, Tombstone, Herschel Island–Qikiqtaruk, and Ni'iinlii'Njik) were integrated to illustrate contrasting risk exposure scenarios. This analysis examined the spatial co-occurrence of susceptibility zones with protected areas, thereby contextualizing where geomorphic vulnerability intersects with park infrastructure and visitor routes. The overlay analysis did not involve new predictive modeling; instead, it served an interpretative function by highlighting spatial relationships relevant to exposure and governance.

4 Results and discussion

The four articles included in this dissertation collectively examine thaw-induced slope failures across circumpolar and regional spatial scales. Although each article addresses a distinct component of permafrost landscape dynamics, together they reveal consistent environmental controls, that is, emergent geographical patterns such as the concentration of RTSs in ice-rich permafrost and their topographic specificity. The findings, along with their societally significant implications for infrastructure and tourism, advance understanding of RTSs and ALDs. The results are organized below according to the four research objectives guiding this thesis.

4.1 Circumpolar susceptibility and environmental controls of retrogressive thaw slumps (Article I)

The circumpolar susceptibility model (Figure 8) developed in Article I demonstrates that RTS occurrence is governed by a coherent set of environmental drivers that operate across the Northern Hemisphere permafrost domain. Model results indicate that RTS occurrence at the circumpolar scale is primarily controlled by thaw-season climate conditions. TDD, freezing degree days (FDD), rainfall, and soil bulk density consistently ranked as the most influential predictors, while slope and fine sediment content played secondary roles. RTS probability peaked under intermediate ranges of summer warmth and precipitation, highlighting nonlinear climatic thresholds rather than monotonic responses. This pattern reflects the requirement that sufficient thaw energy and moisture that are needed to mobilize ice-rich sediments, yet excessive levels of these drivers can trigger a transition to alternative mass-wasting processes as rapid debris flows (Lacelle et al. 2015; Lewkowicz & Way 2019).

Terrain and substrate characteristics further constrained RTS susceptibility. Elevated probabilities were associated with gentle to moderate slopes, low to intermediate bulk density, and high fine sediment fractions, consistent with the distribution of ice-rich, fine-grained permafrost deposits prone to thaw-driven instability (French 2017; Kokelj et al. 2017). Soil properties act as critical modifiers by governing ground-ice content, drainage, and mechanical strength, thereby mediating the geomorphic response to climatic forcing (Hjort et al. 2014). The high importance of soil bulk density and fine sediment fractions corroborates the material-based susceptibility frameworks proposed by French (2017), emphasizing that ice-rich, glaciolacustrine, and fine-grained marine deposits are the primary substrates in thaw-driven instability (Lantz & Kokelj 2008). While the model does not explicitly account for excess ground ice or extreme events, the spatial patterns suggest that these unrepresented factors likely drive local deviations from predicted susceptibility (Obu et al. 2019; Ramage et al. 2021). In particular, the inclusion of soil bulk density serves as a crucial proxy for ground-ice potential. However, it is important to note that while fine-grained sediments are specifically required for the formation of segregated ice, low bulk density more broadly indicates high volumetric ice content across various soil types, including features as wedge ice (Castagner et al. 2022).

Model performance was robust under spatially constrained validation, with consistently high AUC values and stable sensitivity, although lower specificity indicates some overprediction, which is a common outcome in large-scale susceptibility modeling where true absences are uncertain (Goetz et al. 2015; Valavi et al. 2021).

The resulting susceptibility map highlights extensive zones of high to very high RTS susceptibility across continuous permafrost regions, particularly northern Alaska, northwestern Canada, eastern Siberia, Svalbard, and the Qinghai–Tibetan Plateau. These patterns align with documented RTS hotspots in Peel Plateau (Kokelj et al. 2015) and Taymyr Peninsula (Bernhard et al. 2022a; Nitze et al. 2017; Nitze et al. 2018) while identifying climatically suitable regions with sparse inventories, suggesting either under-mapping or emerging risk under current climate conditions.

In contrast, lower susceptibility in discontinuous and sporadic permafrost zones reflects lower ground-ice abundance and weaker thermal forcing. Although air temperatures are higher in these southern latitudes, the presence of ecosystem-protected permafrost, where thick organic layers and vegetation insulate the ground, muffles effective transfer of atmospheric heat to the frozen substrate (Shur & Jorgenson 2007). Furthermore, as noted by Castagner et al. (2022), the lack of massive, near-surface ice bodies in these zones means that available thermal energy typically

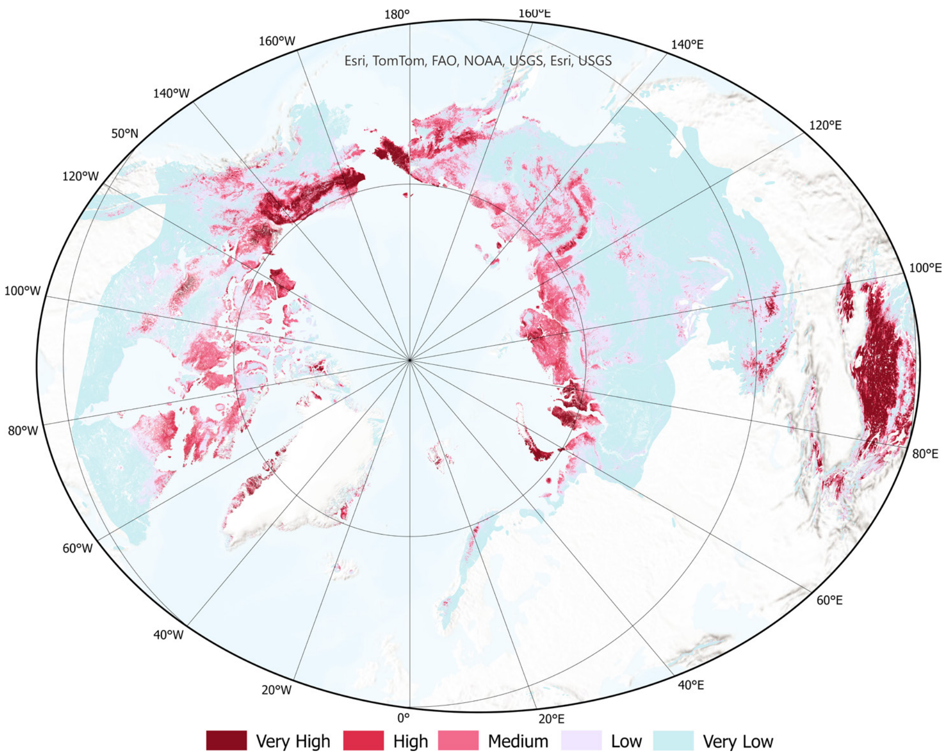

Figure 8. Susceptibility map for retrogressive thaw slump occurrences based on a generalized boosting model for the circumpolar permafrost area. Basemap: Esri, HERE, Garmin, USGS, FAO, NOAA, and others.

triggers generalized subsidence rather than the high-energy headwall retreat characteristic of an RTS. Despite inherent limitations (see section 4.5 Data and methodological limitations), the framework provides a transferable basis for identifying regions of elevated permafrost instability and supports broader assessments of infrastructure risk, ecosystem disturbance, and carbon-cycle feedbacks under continued climate change.

4.2 Regional variation and environmental distinctiveness among RTS-prone landscapes (Article II)

While Article I established circumpolar patterns, Article II demonstrated that the environmental envelopes associated with RTS occurrence vary substantially among Arctic regions and differ even more markedly between Arctic and high-altitude permafrost domains. Gower dissimilarity and PERMANOVA analyses revealed statistically significant difference among the 19 regions included in the comparative study, driven largely by contrasts in precipitation regimes, soil, and topographic context. The results confirm that although RTS occurrence depends on a shared suite of environmental factors, the relative strength and configuration of these drivers differ among landscapes (Figure 9; Kokelj et al. 2015; Rudy et al. 2016).

Climate variables dominate regional differentiation, as FDD and TDD account for most interregional contrasts, which underscores the primary role of thermal forcing in RTS development. Site water balance (SWB) further structures RTS environments by regulating moisture availability, while soil properties contribute a secondary but statistically significant influence. Terrain predictors, such as geomorphons and slope angle, play a modifying role, becoming more important in topographically complex regions. Differences in multivariate dispersion among regions indicate that environmental distinctiveness is not simply a function of internal variability but reflects region-specific combinations of controls (Anderson 2006). This implies that while regions like Lena exhibit high environmental dispersion, Yakutia displays low intraregional variability. This indicates that RTS initiation in Yakutia is constrained to a consistently unique and narrow environmental envelope, reflecting its distinct unglaciated history and the dominant role of ice-rich Yedoma deposits (Strauss et al. 2017).

Macro-regional comparison shows that RTS environments on the Tibetan Plateau (see Figure 6 in Article II) occupy a narrower and more constrained environmental space than those in the Arctic. PERMANOVA results indicate that macro-regional context alone explains a substantial share of total environmental variation; for example, Tibetan Plateau RTSs are characterized by steeper slopes, drier conditions, and distinct thermal regimes. Despite receiving nearly double the annual rainfall of the Arctic (~400 mm/yr vs. ~200 mm/yr), the Tibetan Plateau maintains a consistently negative SWB. This deficit is driven by intense solar radiation and extreme evapotranspiration rates typical of high-altitude environments, which rapidly deplete surface moisture during the summer months (Chen et al. 2023; Meng et al. 2024). Higher dispersion among Arctic RTSs reflects the greater climatic and geomorphic diversity of high-latitude permafrost landscapes.

Maximum entropy modeling corroborates these multivariate patterns. Across regions, TDD consistently emerge as the most influential predictor of RTS occurrence (Table 2), confirming the dominant role of summer conditions. Rainfall and SWB are important in many regions, while terrain variables gain prominence in mountainous settings. Model performance is generally good, although reduced AUC values in environmentally distinct regions likely reflects unrepresented controls, such as ground-ice

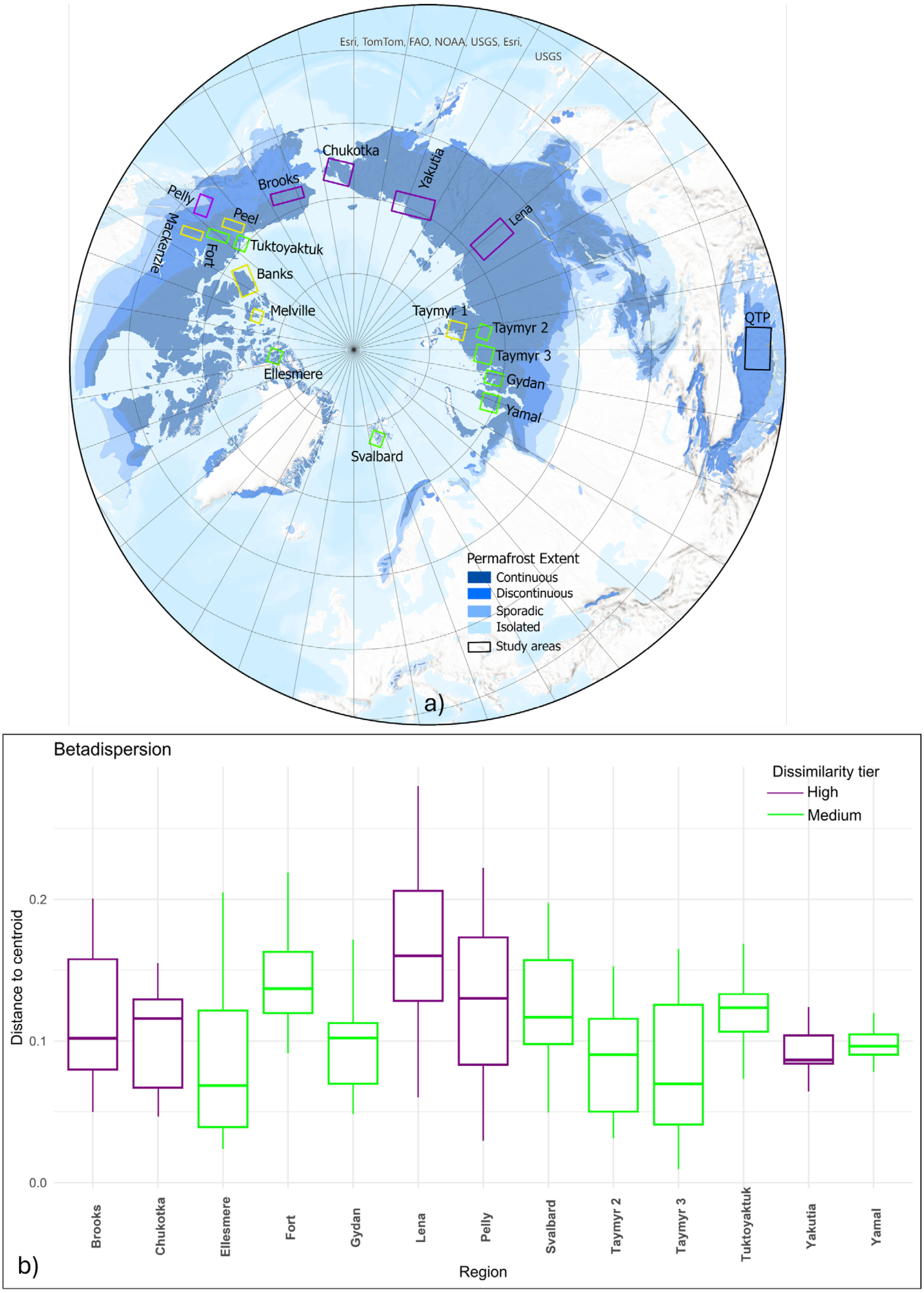

Figure 9. Geographic distribution and environmental distinctiveness of SCAI study regions across permafrost extent (Brown et al. 2002). Panel a) shows the distribution of the 19 study regions across the Arctic and the Tibetan Plateau, categorized by dissimilarity tiers after Gower dissimilarity (purple: high, green: medium, and yellow: low tier). Panel b) shows the multivariate dispersion for each region, categorized by dissimilarity tier.

Table 2. Average variable importance in percentages. The abbreviated predictors are thawing degree days (TDD), site water balance (SWB), geomorphons (Geom), freezing degree days (FDD), bulk density (Bd), compound topographic index (CTI), and profile curvature (Pcurv).

	TDD	SWB	Rainfall	Slope	Geom	FDD	Fine	Bd	CTI	Pcurv
Average %	22.4	16.6	16	10.9	10.8	8.9	5.6	5.5	2.75	0.56

distribution, erosion processes, and short-term climatic extremes. These limitations are consistent with the use of climate normals and harmonized predictors in large-domain susceptibility modeling (Artcile I; Phillips et al. 2006; Phillips & Dudík 2008; Rudy et al. 2016).

4.3 Environmental controls on active-layer detachment failure susceptibility and infrastructure vulnerability (Article III)

The MaxEnt-based susceptibility modeling identified clear and spatially coherent controls on ALDs across Alaska, Yukon, and the Northwest Territories. Topographic settings, expressed through geomorphons, emerged as the dominant predictor, FDD, indicating that ALDs preferentially occur on slopes in cold, ice-rich permafrost environments. This aligns with the established process understanding that sustained freezing conditions promote excess ground-ice accumulation, preconditioning slopes for detachment during thaw (Kokelj & Jorgenson 2013; Lewkowicz 2007). Soil properties, particularly silt content and bulk density, further reinforce this interpretation, reflecting the high frost susceptibility and low shear strength of fine-grained sediments commonly associated with ALDs (Blais-Stevens et al. 2010; Lipovsky & Huscroft 2007).

The resulting susceptibility map (Figure 10) highlights extensive zones of high to very high ALD susceptibility across the Brooks Range and Franklin Mountains in Alaska, central Yukon around Dawson City and Mayo, and along the Mackenzie River corridor in the Northwest Territories. These patterns are broadly consistent with earlier local and regional studies (Behnia & Blais-Stevens 2018; Couture & Riopel 2008; Elia et al. 2023) while extending susceptibility assessment to previously unmapped areas. Conversely, low relief regions such as the Alaskan Coastal Plain and southern Yukon are characterized by low susceptibility, which underscores the critical role of terrain steepness and geomorphic setting in ALD initiation (Wilson et al. 2015).

Regarding variable importance (Table 3), the geomorphon variable emerged as the most influential predictor in the model, indicating that geomorphon-based representations of topographic features are well-suited to capturing local-scale variability in ALD susceptibility. This is the first application of this dataset for ALD susceptibility modeling, although geomorphons have been widely employed in other landslide susceptibility studies (Luo & Liu 2018). The findings are consistent with previous work showing that ALDs occur across a broad range of slope gradients, from nearly flat to steep terrain, particularly in fine-silty materials (Behnia & Blais-Stevens 2018; Blais-Stevens et al. 2010; Elia et al. 2023; Lipovsky & Huscroft 2007; Rudy et al. 2016). In agreement with Behnia and Blais-Stevens (2018), profile and plan curvature display relatively low importance in the model.

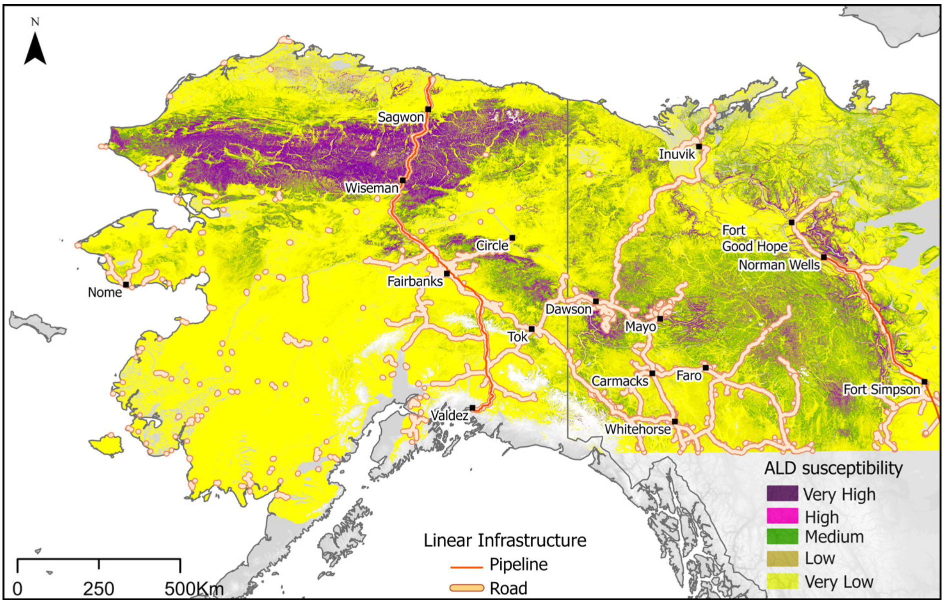

Figure 10. Infrastructure vulnerability assessment of active-layer detachment failure (ALD) susceptibility within 500 m distance from linear infrastructure (pipelines and roads) for the study area. Basemap: Digital Terrain Model (DTM) from Amatulli et al. (2019).

Table 3. Average variable importance in percentages. The abbreviated predictors are geomorphons (Geom), freezing degree days (FDD), bulk density (Bd), thawing degree days (TDD), and profile curvature (Pcurv).

	Geom	FDD	Silt	Slope angle	Bd	TDD	Rainfall	Pcurv	Snowfall
Average %	30.93	25.92	15.9	13.56	8.23	4.3	0.68	0.47	0.02

Precipitation variables exhibited relatively low importance in the model. This does not contradict field evidence linking ALDs to intense rainfall or wildfire disturbances (Lewkowicz & Harris 2005; Patton et al. 2021) but rather reflects the study's focus on long-term susceptibility under climate-normal conditions rather than event-based triggers. By prioritizing spatially consistent predictors, the model delineates environments prone to ALDs, even if it cannot explicitly capture short-lived disturbances such as extreme storms or post-fire slope failures. This trade-off is inherent in large-scale susceptibility mapping and is widely acknowledged in permafrost hazard assessments (Hjort et al. 2013; Rudy et al. 2016).

Model evaluation demonstrated good to excellent predictive performance, with AUC values near or above 0.9 for both the calibration area and an independent validation dataset in central Siberia. The good transferability indicates that the identified environmental controls are not regionally idiosyncratic but reflect broader permafrost–geomorphic relationships across the circumarctic domain (Hjort et al. 2013; Steger et al. 2022). Nevertheless, a subset of observed ALDs occurred in areas classified as low susceptibility, particularly along riverbanks and in regions affected by localized disturbances. These mismatches likely reflect limitations in spatial resolution, unrepresented ground-ice variability, and the inability of climate-normal predictors to capture episodic triggers such as heatwaves or wildfire-induced thaw (Clarke et al. 2024; Li et al. 2025).

Overlay analysis with linear infrastructure (Figure 10) revealed substantial exposure of roads and pipelines to ALD-prone terrain. Approximately 12% of the Trans-Alaska Pipeline and more than 20% of the Norman Wells pipeline traverse high to very high susceptibility zones, with similar patterns observed along major highways, including the Dalton, Dempster, and Mackenzie corridors. These findings underscore the growing vulnerability of Arctic infrastructure to permafrost-driven slope instability and are consistent with broader assessments of thaw-related infrastructure risk (Fatolahzadeh Gheysari & Maghoul 2024; Hjort et al. 2022). Importantly, the spatial variability in susceptibility suggests that risk is highly uneven, reinforcing the need for targeted monitoring and adaptive management rather than uniform mitigation strategies.

Overall, the (integrated) results demonstrate that ALD susceptibility is governed by a combination of cold-climate controls, fine-grained soils, and specific slope landforms and that these conditions intersect extensively with critical infrastructure networks. While the modeling framework is robust for regional-scale planning, further advances will depend on improved representation of active-layer thickness and on climate extremes. Such refinements are essential for translating susceptibility maps into operational risk assessments under accelerating Arctic warming (Burn et al. 2024; Patton et al. 2021).

Article III therefore extends the more process-oriented findings of Articles I and II into a societal domain, illustrating how geomorphic hazard potential interacts with essential human systems across the western Arctic. By situating geomorphic susceptibility within the context of infrastructure exposure and risk, Article III bridges process understanding with real-world implications. These cascading effects are particularly acute in Arctic communities, where infrastructure disruptions can compromise access to land-based hunting, fishing, and harvesting activities, thereby exacerbating food insecurity and increasing health vulnerability (Ford et al. 2006). This intersection of physical susceptibility with patterns of human use emphasizes the urgent need for proactive planning and targeted monitoring to mitigate permafrost-related hazards in high-use socio-economic systems.

4.4 Permafrost hazards and nature-based tourism vulnerability in Yukon protected areas (Article IV)

Whereas the first three articles focus on susceptibility modeling and environmental factors, Article IV examines how these thaw-driven geomorphic hazards intersect with tourism environments, management practices, and visitor experiences. Thaw-driven hazards increasingly coincide with the peak season for nature-based tourism, creating an emerging risk domain in Arctic wilderness areas. While permafrost-related hazards are well documented in relation to infrastructure and permanent settlements (Hjort et al. 2022; Streletskiy et al. 2019), their implications for transient human presence, including tourism, remain weakly represented in climate-risk research and policy (Kaján & Saarinen 2013; Varnajot & Makopoulou 2025).

Overlay analysis of circumpolar RTS susceptibility with protected-area boundaries in Yukon (Table 4) reveals substantial spatial overlap between highly susceptible areas and prominent tourism destinations. Northern Yukon, particularly the Arctic Coastal Plain, exhibits extensive zones of very high RTS susceptibility, reflecting ice-rich sediments, low relief, and strong coastal and fluvial controls (Kokelj et al. 2015; Lewkowicz & Way 2019). Parks such as Herschel Island–Qikiqtaruk and Ni'iinlii'Njik are almost entirely situated within high susceptibility zones. Although visitor numbers in these parks are relatively low due to their remoteness, the magnitude, unpredictability, and rapid evolution of RTS activity imply disproportionately high exposure for those who do visit (Bernhard et al. 2022a ; Lacelle et al. 2015).

In contrast, parks such as Tombstone Territorial Park and Kluane National Park and Reserve have substantially higher visitor numbers, with Kluane alone exceeding 47,000 visitors annually (Government of Canada n.d.), but display more heterogeneous susceptibility patterns, with generally low to moderate background susceptibility interspersed with localized hotspots. This contrast points to two distinct tourism risk profiles in a warming Arctic: infrequent but high-severity exposure in remote, highly unstable landscapes, and frequent exposure to localized hazards in more accessible destinations. In both contexts, risk emerges from the interaction between geomorphic susceptibility, accessibility, and visitor behavior rather than from hazard magnitude alone (Scott et al. 2019; Steiger et al. 2021).

The results highlight a growing mismatch between accelerating permafrost degradation and existing tourism governance frameworks. Current park management plans and tourism strategies in the Yukon, as well as in other permafrost regions across the Arctic and sub-Arctic, rarely explicitly address thaw-related geomorphic hazards, despite clear evidence of increasing permafrost instability under climate change (Obu et al. 2019; Ramage et al. 2021). Moreover, most Arctic tourists originate from outside the region and typically lack familiarity with permafrost terrain, which increases vulnerability through limited hazard awareness and risk literacy (Kaján & Saarinen 2013; Pashkevich et al. 2016). This gap suggests that climate-change adaptation in Arctic tourism has lagged behind infrastructure-focused adaptation, despite comparable exposure pathways (Hjort et al. 2022).

Table 4. Summary of retrogressive thaw slump (RTS) susceptibility, active-layer detachment failure (ALD) presence, and nature-based tourism exposure risk for key parks and reserves in the Yukon, Canada. Visitor numbers are categorized by annual density: High (>10,000 visitors), Low (100–1,000 visitors), and Very Low (<100 visitors).

Protected Area	**RTS Susceptibility**	**Visitor Numbers**	**Tourism Exposure Risk**
Tombstone Territorial Park	Localized hotspots with high susceptibility	High	High – frequent RTS/ALD exposure
Kluane National Park & Reserve	Localized hotspots for RTS but ALD-dominant	High	Moderate-High – ALD-prone trails
Herschel Island–Qikiqtaruk territorial park	Very High	Low	Low – severe hazards/ frequent RTS, few visitors
Ni'iinlii Njik ecological reserve	High	Very Low	Very Low – high susceptibility but few visitors

Conceptually, the analysis demonstrates the value of integrating susceptibility mapping with tourism and governance research to identify climate-driven risks to human presence in protected areas. Although RTS susceptibility maps cannot predict individual events, they provide a spatial framework for anticipating where tourism-hazard interactions are most likely to intensify as warming continues (Aalto et al. 2018; Goetz et al. 2015). Such approaches can support targeted risk communication, visitor management, and adaptive planning within protected areas.

Overall, the Yukon case illustrates a broader Arctic challenge. Climate-driven permafrost degradation is reshaping not only landscapes and ecosystems but also the safety and sustainability of nature-based tourism and the livelihoods of local and Indigenous communities who live on and travel across these lands. Addressing this challenge requires moving beyond infrastructure-centered risk assessments toward interdisciplinary frameworks that explicitly consider both transient human exposure and everyday local use in rapidly changing cryospheric environments (AMAP 2017; Gartler et al. 2025; Turetsky et al. 2020).

4.5 Data and methodological limitations

This dissertation is subject to data and methodological constraints inherent to large-scale permafrost research. Susceptibility modeling in Articles I–III relies on climatic, terrain, and soil proxies to infer conditions favorable for thaw-related slope failures. However, several critical limitations regarding data quality and statistical assumptions must be acknowledged. The absence of spatially explicit ground-ice and cryostratigraphic data limits process attribution and contributes to regional uncertainty, particularly in landscapes characterized by high internal environmental heterogeneity, for example, in areas with different ice content (Obu et al. 2019; Ramage et al. 2021).

Furthermore, the models are based on aggregated inventories and climate normals and therefore characterize long-term susceptibility rather than short-term triggering associated with individual events. Consequently, factors such as extreme rainfall, heatwaves, wildfire disturbance, and localized coastal or fluvial erosion are not explicitly represented, and model outputs should be interpreted as indicators of relative susceptibility rather than event-level predictions (Goetz et al. 2015; Lewkowicz & Way 2019).

Spatial resolution further constrains interpretation. Predictor variables were harmonized to coarse resolutions to ensure consistency across large domains, which smoothed fine-scale controls such as local hydrology and microtopography. Converting polygon-based observations to centroid points also reduces information on failure geometry. Inventory completeness and spatial heterogeneity in mapping efforts introduce additional uncertainty. Although distance-based and balanced resampling strategies were applied to reduce the influence of spatial clustering, the presence of spatial autocorrelation remains a persistent challenge. While these strategies ensure a degree of spatial independence, residual autocorrelation is an inherent property of geographically continuous environmental data (Legendre 1993) that can result in overly optimistic measures of model performance (Araújo et al. 2019).

The use of geospatial data also introduces risks of multicollinearity, where high correlation among climatic and terrain predictors can obscure the individual contribution of specific drivers and inflate the importance of certain variables (Hjort & Luoto 2013). Moreover, these models often assume spatial stationarity, but the physical processes governing thaw slumps may vary across vast Arctic domains, meaning a single statistical structure may not capture localized geomorphic sensitivities (Hjort & Luoto 2013).

Finally, the statistical and machine-learning approaches employed capture large-scale patterns but do not explicitly represent physical processes. Variable importance therefore reflects statistical association rather than causation, and model transferability depends on similarity in environmental space between regions (Anderson 2001; Phillips et al. 2006). Considering these constraints, the results presented here identify broad susceptibility patterns while highlighting the need for higher resolution, process-based validation.

5 Future research on thaw-related hazards

The articles included in this dissertation identify several priority directions for future research that emerge directly from their results and analytical scope. Across all studies, the identification of coherent large-scale susceptibility patterns highlights the need for improved representation of permafrost properties. While the use of climatic, terrain, and soil proxies is appropriate for large-domain analyses, integrating higher resolution and better-constrained datasets describing ground-ice content, sedimentary history, and soil physical properties would allow future studies to better resolve the subsurface controls on thaw-driven mass wasting and reduce regional uncertainty.

Current global products, such as SoilGrids (Poggio et al. 2021), provide spatially continuous information on soil texture and organic carbon but remain limited in their representation of the vertical structure of permafrost-affected soils (Hengl et al. 2017). Integrating borehole syntheses, geophysical observations, and emerging circumpolar ground-ice products would allow future studies to better resolve subsurface controls on thaw-related hazards (Lacelle et al. 2015; Lewkowicz & Way 2019). Specifically, the distribution of massive ice and Yedoma deposits is a fundamental control on the initiation and magnitude of RTSs, but these remain difficult to map at hemispheric scales (Kokelj et al. 2017; Nesterova et al. 2025).

A second key research direction concerns the temporal dimension of permafrost slope instability. By design, the modeling frameworks applied in Articles I–III characterize long-term susceptibility rather than event triggering. Building on their results, future research should focus on time-resolved inventories and explicit incorporation of climatic extremes, such as anomalously warm summers, intense rainfall events, and wildfire disturbance (Farquharson et al. 2019; Huscroft et al. 2004; Segal et al. 2016). These episodic triggers should be analyzed further with more persistent and cumulative geomorphic drives, such as coastal or fluvial erosion, for better understanding of the initiation mechanisms. Furthermore, integrating data on near-historical bioclimatic trends would significantly enhance the predictive capacity of RTS and ALD models, as these trends capture the intensification of Arctic environmental extremes that often lead mass-wasting events (Aalto et al. 2026). While RTSs are often driven by cumulative thermal denudation**,** ALDs are more directly linked to short-lived extremes and disturbances like wildfire, which remove insulating organic layers and trigger rapid failure (Jones et al. 2015; Lantz & Kokelj 2008; Patton et al. 2021). Linking susceptibility patterns to time series of climatic forcing and disturbance history represents a critical step toward dynamic assessments of permafrost-related risk.

Closely related to this temporal dimension is the issue of organic carbon and nutrient mobilization. Thaw-driven mass wasting can rapidly expose deep, previously frozen organic material, acting as efficient pathways for carbon export to aquatic systems and the atmosphere (Abbott et al. 2016; Turetsky et al. 2020; Vonk et al. 2012). Although individual thaw slumps have been identified as local hotspots of biogeochemical fluxes, the cumulative regional contribution of expanding mass-wasting activity to Arctic carbon budgets remains poorly constrained (Kokelj et al. 2021a; Ramage et al. 2017). Increasing sediment delivery to river systems also carries implications for water quality and downstream communities located along fluvial corridors (Lamoureux & Lafrenière 2018).

Crucially, these geomorphic changes translate into significant socioenvironmental risks. Increasing sediment delivery from thaw-affected slopes to river systems alters water quality and channel morphology, threatening the food security and water safety of communities located along fluvial corridors (Lamoureux & Lafrenière 2018). Furthermore, the intersection of thaw-related hazards with existing and planned infrastructure, such as pipelines, roads, and buildings, poses a direct threat to Arctic economic stability and safety (Hjort et al. 2018, 2022). Future studies should not only identify where hazards occur but also quantify who and what is at risk by integrating engineering perspectives on material strength with indigenous knowledge and local governance to support effective adaptation and resilience strategies (Chen et al. 2023; Swanson 2021).

Taken together, these directions point toward the need for integrated, multiscale research frameworks that combine improved subsurface characterization, temporal process understanding, and modeling innovation with socioenvironmental perspectives (Gartler et al. 2025; Varnajot & Makopoulou 2025). Advancing along these lines will be essential for anticipating the evolution of rapidly changing permafrost landscapes and supporting effective adaptation and resilience strategies in northern and high-altitude regions.

6 Conclusions

This dissertation demonstrates that thaw-driven slope failures are governed by coherent environmental constraints that manifest differently and carry different implications depending on spatial scale. By integrating circumpolar susceptibility modeling, regional comparative analysis, applied infrastructure assessments, and a tourism-focused synthesis, the thesis shows that scale is not merely a matter of spatial extent but a critical analytical dimension shaping how permafrost degradation is detected, interpreted, and managed.

More specifically, at the circumpolar scale, RTSs are primarily controlled by climatic conditions such as TDD, FDD, and rainfall in combination with soil properties such as bulk density. The comparative regional analysis further shows that RTSs occupy distinct environmental envelopes across Arctic regions and high-altitude permafrost on the Tibetan Plateau. While climate remains the dominant driver, the relative importance of topographic and soil properties varies regionally. At the regional scale, susceptibility modeling of ALDs reveals extensive areas of high susceptibility across Alaska and northwestern Canada, with substantial spatial overlap between thaw-prone terrain and critical transportation and energy infrastructure.

Collectively, the first three articles establish that RTSs and ALDs are associated with consistent environmental controls, particularly climatic conditions and terrain context, while exhibiting pronounced regional variability. This variability may limit the universal transferability of susceptibility relationships, as modeled process–response linkages may differ by climatic, geomorphic, and permafrost setting. This underscores the need to interpret large-scale models within their environmental and geographical contexts. The results confirm that susceptibility modeling is effective for identifying where thaw-related instability is likely to intensify, even as local expression and impacts remain highly heterogeneous.

Beyond geomorphic patterns, Article IV of this dissertation demonstrates that permafrost degradation is increasingly a socioenvironmental issue. The intersection of thaw-prone terrain with infrastructure networks and protected areas shows that thaw-driven mass wasting affects not only landscapes and ecosystems but also transportation systems, tourism, cultural values, and governance practices. Risk emerges through the interaction of physical susceptibility, spatial context, and patterns of human use, rather than from hazard magnitude alone. Thaw-related hazards intersect with protected areas and visitor access routes, yet they remain weakly addressed in current tourism management frameworks, indicating a gap between accelerating environmental change and institutional risk awareness.

By linking physical susceptibility with regional heterogeneity and human exposure across scales, this dissertation provides an integrated framework for understanding permafrost thaw as a coupled socioenvironmental process under continued climate warming. In doing so, it advances the scientific basis for anticipating and managing the consequences of rapid permafrost change in northern and high-altitude regions.

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