A Planning-Scale Permafrost Hazard Susceptibility Framework for Municipal Development Review in Iqaluit

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Abstract

Permafrost conditions strongly influence ground performance in Arctic communities, yet thaw-related land information is not always available in a form City planning and development review staff can readily use. In Iqaluit, development review occurs within a context shaped by housing pressure, servicing constraints, climate change, and spatially variable permafrost. This thesis addresses the need for a planning-scale spatial reference that helps staff consider permafrost thaw-related susceptibility as proposals are assessed against planning policies, by-laws, City objectives, and technical and safety requirements.

The thesis develops a planning-oriented framework for producing a Permafrost Hazard Susceptibility Index (PHSI) and displaying the resulting classes through a planner-facing overlay for the populated area of Iqaluit, Nunavut. Using an applied, qualitative, single-case design and document analysis, it brings together literature on permafrost processes, susceptibility mapping, engineering standards and guidance, and Iqaluit's policy and development review context. The review considers subsurface physical, thermal, and mechanical conditions together with snow, vegetation, surficial geology, topography, drainage, and hydrology.

The framework distinguishes thaw potential from thaw impact. The Thermal Response Index (TRI) and Ground Thermal State (GTS) form a Thaw Potential Index (TPI), which is combined with a Thaw Impact Index (TII) to produce the PHSI. It explains how mapped and local technical evidence can be rated, combined, classified, calibrated, and validated. It also distinguishes baseline and future ground conditions, sets minimum evidence requirements, reports confidence separately, and retains Unknown / Insufficient Data where a class cannot be supported.

An illustrative application shows how baseline and future PHSI classes could inform discussions during the City's planning and development review process concerning height and density, servicing, development intensity, further geotechnical investigation, and mitigation. The study does not produce a calibrated operational map or replace site-specific investigation, engineering design, expert judgement, or decisions made through that process. Rather, it provides a transparent planning-scale framework for translating scientific, engineering, and planning knowledge into a practical reference for a thaw-sensitive northern city.

Acknowledgments

I want to express my utmost gratitude to Professor Beatriz Martin-Perez for guiding me through the research and completion of this thesis. I am especially grateful for her patience and support during moments of uncertainty and pivoting, and for connecting me with professors whose expertise informed this interdisciplinary work at the intersection of geotechnical and permafrost engineering, climate change, and municipal planning and zoning in the Arctic.

I also want to extend my sincere thanks to my co-supervisors, Professor Di Wang and Professor Yunesh Saulick for providing their expertise, guidance, feedback and support that helped inform the geotechnical, arctic science and climate change dimensions of this research.

I want to offer special thanks to the City of Iqaluit's Director of Planning and Development, Mathew Dodds and City Planner Reiko Kobayashi, who offered their time to meet with me and discuss challenges faced by Planners in practice in a permafrost setting. Their insights informed the foundation for this research and helped ground it in realities of municipal planning, zoning, and development review in Iqaluit. Their contribution helped position this work within broader academic discussions of risk-informed planning in the Canadian Arctic.

I want to thank Professor Collin Rennie, who is the lead of the National Indigenous Climate Compass (NICC) project, for providing me with the opportunity to conduct collaborative research with Wiikwemkong First Nation. Through this work, I learned principles of consent, collaborative and ethical research practices, and data governance. This experience influenced the ethical lens through which I approached research in an Inuit context.

I am also grateful to my examiners, Professors Jackie Dawson and Sai Vanapalli, for their encouraging feedback and constructive critiques, which helped strengthen the final version of this thesis and inform the direction for future academic work.

I am appreciative of the financial support I received from the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Canada Graduate Scholarships - Master's (CGS-M) program, which supported me during the completion of this research.

I would like to offer special thanks to Mic Liu who has been my mentor since my undergraduate studies. Mic encouraged me to pursue graduate studies and supported my entry into the University of Ottawa's Master's program at the intersection of Civil Engineering and Policy and has continued to be a mentor for both my academic and professional journey. Their mentorship helped me understand that meaningful research is not only about technical knowledge, but also about who conducts the research, whose perspectives are included, and whom the work is intended to serve. I am grateful for their continued support.

Last but not least, I want to thank my family for their patience, compassion, and unconditional support throughout this process.

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Chapter 1: Introduction

1.1 Background

Permafrost is a defining feature of many Arctic and subarctic environments and plays an important role in the stability of natural and built systems. In engineering terms, permafrost is ground that remains at or below 0°C for at least two consecutive years (Canadian Standard Association [CSA] Group, 2021c). In many northern settlements, infrastructure is therefore constructed not simply on soil or rock, but on terrain whose behavior is directly influenced by frozen ground conditions, the presence of ground ice, and the seasonal dynamics of freezing and thawing (Harris et al., 1988; Couture et al., 2003). The long-term performance of buildings, transportation corridors, water and sewer systems, and other municipal assets is closely tied to the thermal and mechanical stability of this terrain.

In recent decades, the Arctic has warmed at rates that exceed the global average, with corresponding changes in permafrost temperature, Active Layer Thickness (ALT), and the stability of previously frozen ground (Arctic Monitoring and Assessment Programme [AMAP], 2017; Intergovernmental Panel on Climate Change [IPCC], 2021; Romanovsky et al., 2010). As ground ice thaws, soils may lose volume and strength, leading to thaw settlement, differential movement, thermokarst development, altered drainage, and other forms of terrain instability. These changes create direct challenges for the siting, design, maintenance, and long-term serviceability of infrastructure in northern communities.

The engineering implications of permafrost degradation are well established. Frozen soils can provide a stable bearing medium where thermal conditions remain relatively constant. However, where warming causes ice-rich soils to thaw, the resulting loss of strength and increase in deformation can affect foundations, pavements, pipelines, airfields, and municipal service systems (Andersland and Ladanyi, 2004; Doré and Zubeck, 2009). In built environments, these effects rarely occur in isolation. Changes in ground temperature may be accompanied by increasing ALT, altered moisture and drainage conditions, and changes in snow or vegetation, all of which influence how thaw-related ground effects develop.

These concerns are especially important in Arctic urban communities where development pressure, infrastructure demand, and climate change intersect. Northern regions of Canada face persistent housing shortages, population growth, and increasing demand for public, residential, and service infrastructure. Within this context, Iqaluit is an important case. As the capital of Nunavut and a regional service centre, Iqaluit is experiencing continued pressure for housing, infrastructure, servicing, and urban development. Decisions concerning land use, building height and density, site layout, servicing, and overall development intensity are therefore influenced not only by planning policy, but also by the ground conditions beneath the city.

Planning documents and technical guidance for Arctic communities increasingly recognize that climate change and permafrost degradation must be considered in long-term land-use and infrastructure decisions. City planning and development review staff require a practical way to consider thaw-sensitive ground conditions while proposals are assessed and refined. This includes understanding whether mapped ground conditions may affect a proposal, whether additional technical information is needed, and whether changes or mitigation measures should be considered before a Development Permit is issued. This need is particularly important in Iqaluit, where development pressure and servicing constraints must be considered alongside variable permafrost, terrain, and drainage conditions.

1.2 Problem Statement

Extensive research has examined the physical, thermal, and mechanical behavior of permafrost soils. This work has contributed to understanding thaw settlement, frost heave, bearing-capacity loss, active-layer dynamics, ground-temperature response, and the influence of surface conditions such as snow, vegetation, terrain, and drainage. Engineering standards, technical guidance, and hazard-mapping approaches have also been developed to support site investigation, project design, infrastructure assessment, and regional climate adaptation.

Despite this substantial body of knowledge, an important gap remains at the planning scale. Existing approaches are generally oriented toward detailed site-specific engineering, broad regional or national characterization of permafrost conditions, or assessments of infrastructure exposure and vulnerability. These approaches serve important purposes, but they do not, on their own, provide City planning and development review staff with a consistent spatial reference for considering thaw-related land susceptibility during the review process.

The City's planning and development review process is iterative, through which a development proposal submitted by an applicant is assessed for conformity with applicable planning policies and by-laws, consistency with City objectives, and compliance with relevant technical and safety requirements. Depending on the nature and scale of the proposal, the submission may include architectural and site plans, civil and utility plans, transportation and geotechnical studies, and other technical drawings or reports required for review. The process includes completeness review, coordinated technical and statutory review, applicant revisions, resubmissions, and re-review. During these stages, City planning and development review staff may identify concerns, request additional information, and assess whether changes, mitigation measures, or possible conditions are needed before the proposal can be supported.

Within this process, the significance of permafrost extends beyond whether land is technically developable in principle. Staff may need to consider whether mapped ground conditions are compatible with the proposed building form, height, density, servicing, drainage, and overall development intensity. They may also need to determine whether the submitted technical studies adequately address baseline and future permafrost thaw conditions and whether further geotechnical investigation is required.

The planning challenge is therefore not simply to understand permafrost as a physical condition. It is to translate existing scientific and engineering knowledge into information that can support the assessment of development proposals, the review of supporting technical information, and any revisions, mitigation measures, or conditions considered through the City's planning and development review process.

This thesis responds to that gap. It proposes a planning-scale framework for organizing relevant evidence and producing a Permafrost Hazard Susceptibility Index (PHSI). The resulting Low, Moderate, High, or Unknown / Insufficient Data classes would be displayed through a planner-facing overlay. The framework separates the analytical process used to produce the classes from the mapped output through which City planning and development review staff would view them. The framework must account for different forms of evidence, including mapped surface and terrain information, ground thermal data, and local borehole, geophysical, monitoring, and laboratory evidence. It must also distinguish thaw potential from thaw impact, support both baseline and future ground conditions, establish minimum evidence requirements, and communicate confidence without implying more certainty than the available information can support.

The research gap addressed in this thesis can therefore be stated as follows: "Although substantial knowledge exists regarding permafrost thaw and ground response, existing research and guidance do not yet provide a planning-oriented framework for translating that knowledge into a transparent PHSI and planner-facing overlay that can support the City's planning and development review process in Iqaluit."

This gap is both practical and conceptual. Practically, it limits the ability of City planning and development review staff to consider thaw-related land susceptibility using a consistent internal spatial reference. Conceptually, it reflects the incomplete translation of scientific and engineering knowledge into a form suited to planning-scale review.

Figure 1.1 summarizes the research logic. It shows how Arctic warming, permafrost conditions, and development pressure create a planning-scale gap between broad regional information and site-specific geotechnical assessment. It also shows how the thesis responds through the development of the proposed framework, PHSI, and overlay.

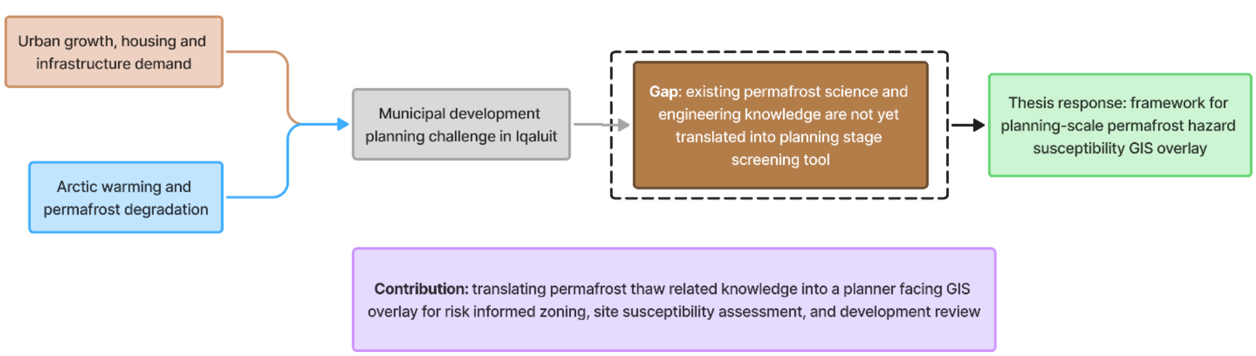

Figure 1.1. Research logic for the thesis

1.3 Research Objectives

The overall aim of this research is to develop a planning-oriented framework for producing a Permafrost Hazard Susceptibility Index and presenting the resulting classes through a planner-facing overlay for the populated area of Iqaluit, Nunavut. The framework is intended to support the City's planning and development review process without replacing site-specific investigation, engineering design, or the City's decision-making authority.

The framework defines the analytical process used to select, rate, combine, classify, calibrate, and validate the relevant evidence. The PHSI is the classified analytical result produced through that process. The overlay is the mapped output through which City planning and development review staff would view the PHSI class for a selected location and planning horizon.

The thesis also describes how the overlay should work and appear, including the class legend, planning-horizon selector, confidence information, address search, and supporting information available to City planning and development review staff. It does not produce a completed operational map or municipal GIS application. To achieve this aim, the research pursues five objectives:

1. To synthesize the subsurface physical, thermal, and mechanical conditions that influence permafrost thaw and thaw-related ground response relevant to development in Iqaluit.
2. To identify the climate, terrain, environmental, and local conditions that influence how thaw-related susceptibility is expressed spatially under baseline and future ground conditions.
3. To review existing permafrost hazard and susceptibility mapping approaches, engineering standards, technical guidance, and the City's planning and development review context to identify what is already addressed and where planning-scale gaps remain.
4. To develop a planning-scale framework for producing PHSI classes and presenting them through a planner-facing overlay, including indicator roles, rating and threshold methods, weighting, class construction, spatial representation, future Ground Thermal State projection, minimum evidence requirements, uncertainty, and confidence.
5. To demonstrate, through an illustrative application in Area B, how baseline and future PHSI classes could support the assessment and refinement of development proposals

during the City's planning and development review process, including discussions concerning proposed height and density, servicing, overall development intensity, further geotechnical investigation, and possible mitigation measures.

These objectives position the thesis between broad regional screening and site-specific geotechnical assessment. The contribution lies in providing a planning-scale reference during the iterative period of the City's planning and development review process, when proposal conformity and supporting technical information are assessed before a Development Permit is issued.

1.4 Research Questions

The thesis is guided by the following research questions:

1. Which subsurface, terrain, environmental, and climate-related factors are most relevant for characterizing planning-scale permafrost thaw-related land susceptibility in the populated area of Iqaluit?
2. How do existing permafrost mapping approaches, engineering standards, technical guidance, and the City's planning and development review process address permafrost-related information needs, and where do important planning-scale gaps remain?
3. How can existing scientific, engineering, spatial, and planning knowledge be translated into a framework for producing a PHSI and presenting the resulting classes through a planner-facing overlay?
4. How could the proposed framework and overlay support the City's planning and development review process when assessing development proposals and considering proposed height and density, servicing, overall development intensity, further geotechnical investigation, and possible mitigation measures?

These questions reflect the central progression of the research: identifying the factors that influence thaw-related susceptibility, examining how existing approaches address those factors, developing a transparent planning-scale framework, and demonstrating how its results could support the assessment, discussion, and refinement of proposals through the City's planning and development review process.

1.5 Scope of Study and Boundaries

The research is developed for the populated area of Iqaluit rather than the full municipal territory. This area contains the main concentration of neighbourhoods, buildings, municipal services, development activity, and planning and development review. It is therefore the part of the municipality in which questions concerning building form, height, density, site layout, servicing, drainage, and development intensity are most concentrated.

Within the broad category of municipal infrastructure, the thesis focuses primarily on building-related development. Transportation corridors, airport facilities, utilidors, coastal infrastructure, and other infrastructure systems are important in Iqaluit, but they are not the main focus of the proposed framework.

The study is limited to planning-scale land susceptibility. It examines how permafrost conditions could be organized and interpreted to support the City's planning and development review process. It does not determine the detailed engineering design of an individual development or certify whether a site is safe or suitable for development. The framework may provide information relevant to the assessment of a proposal, but it does not itself determine whether the proposal conforms to the General Plan or Zoning By-law, satisfies applicable technical requirements, or should receive a Development Permit. Those decisions remain project-specific

The research uses existing documentary and published evidence. This includes scientific literature on permafrost processes and ground response, hazard and susceptibility mapping studies, engineering standards and technical guidance, municipal plans and by-laws, publicly available maps, and descriptions of relevant terrain, climate, thermal, geotechnical, and remote-sensing information. Comparable northern studies are used to inform the design of the framework, not as direct proof of site-specific conditions in Iqaluit, and take into account applicable planning requirements, City objectives, neighbourhood initiatives, community consultation, technical submissions, city staff expertise, and other relevant considerations.

The following boundaries apply:

- The study does not include new borehole drilling, field instrumentation, laboratory testing, or original long-term ground-temperature monitoring.

- It does not compile a complete citywide Iqaluit geotechnical or permafrost database.
- It does not produce calibrated current or future MAGT and ALT surfaces for the populated area.
- It does not establish final Iqaluit-specific thresholds, weights, branch class breaks, matrix rules, minimum evidence requirements, or confidence criteria.
- It does not produce a completed, validated, operational, or City-approved overlay.
- It does not provide site-specific foundation design, structural analysis, construction verification, or engineering certification.
- It does not calculate the probability of failure or undertake a full risk assessment incorporating exposure, vulnerability, and consequences.
- It does not incorporate proposal-specific effects such as building heat, loading, clearing, grading, fill, drainage changes, snow management, foundation design, or servicing directly into the land-only PHSI.

These boundaries are intentional because the thesis addresses the planning-scale gap between broad regional screening and site-specific geotechnical assessment. Its purpose is to define a transparent framework that can be reviewed, refined, calibrated, validated, and implemented through future work.

1.6 Significance and Contribution of Research

The significance of the research lies in its effort to bridge the divide between technical knowledge and planning practice. Permafrost science and cold-regions engineering provide substantial knowledge about ground temperature, Active Layer Thickness, ground ice, thaw settlement, material behaviour, and infrastructure performance. However, this knowledge is not always organized in a form City planning and development review staff can readily use when reviewing technical submissions, and considering whether revisions, additional studies, mitigation measures, or possible conditions are required.

This gap becomes increasingly important under climate change. Decisions concerning height, density, site configuration, servicing, drainage, and long-term infrastructure performance must consider not only present ground conditions, but also how those conditions may change over the expected life of a development.

The research was motivated by practical questions arising within the City's planning and development review context. The proposed framework is intended to provide an additional planning-scale source of information during completeness review, coordinated technical and statutory review, applicant revisions, resubmissions, and re-review. It would support the existing process rather than create a separate approval pathway or replace the City's planning instruments, applicant-submitted studies, expert advice, or decision-making authority.

The thesis makes three main contributions. First, it provides an interdisciplinary synthesis of the subsurface, ground thermal, terrain, climate, and environmental conditions most relevant to permafrost thaw-related land susceptibility in Iqaluit. Second, it identifies the contributions and limitations of existing mapping approaches, engineering standards, technical guidance, and planning procedures when considered from the perspective of the City's planning and development review process. Third, it proposes a planning-scale framework for producing a PHSI and presenting the resulting classes through a planner-facing overlay. The framework distinguishes among:

- The analytical method used to organize and assess the evidence;
- The PHSI produced through that method; and
- The overlay used to display the resulting Low, Moderate, High, or Unknown / Insufficient Data class.

The framework also provides a structured approach to indicator rating, quantitative thresholds, categorical rankings, conditional rules, weighting, branch classification, matrix-based class construction, spatial representation, baseline and future ground conditions, minimum evidence requirements, calibration, validation, uncertainty, and confidence.

The illustrative application provides a further contribution by demonstrating how the framework could operate during the City's planning and development review process. It shows how baseline and future PHSI information could provide the City with an internal planning-scale reference for discussions with an applicant and the applicant's planning, engineering, and geotechnical consultants.

The contribution is methodological and applied rather than predictive. The thesis does not claim to predict exact site-level outcomes or provide a finished municipal product ready for immediate implementation. It defines what could be developed, how the analytical result should be produced and interpreted, and what further review, calibration, validation, and user testing would be required.

1.7 Thesis Structure

The thesis is organized as a problem-to-solution argument and is divided into four parts. It moves from the research problem and Iqaluit context, through the technical, methodological, engineering, and planning literature, to the development of the proposed framework and its illustrative application, and finally to a discussion of the findings, contribution, limitations, and implications.

Part I: Introduction, Study Area, and Policy Context establishes the research problem, geographic setting, and City planning and development review context. Chapter 1 introduces the research problem, aim, objectives, questions, scope, and contribution. Chapter 2 defines the study area as the populated area of Iqaluit and explains why Iqaluit is an appropriate case for developing the proposed framework. It also describes the city's strategic role, urban form, terrain, land use, zoning, and surficial context. Chapter 3 examines the policy and institutional setting, including the City's planning instruments, administrative structure, iterative development review process, and Inuit planning and land-based context.

Part II: Literature Review provides the technical, methodological, and planning basis for the framework. Chapter 4 reviews the permafrost thaw-related hazard processes and controls relevant to planning, including subsurface physical, thermal, and mechanical conditions together with climate, terrain, environmental, and local factors. Chapter 5 reviews existing approaches to mapping permafrost conditions, thaw-related hazards, and land susceptibility. It examines what each approach assesses, the indicators used, classification and weighting methods, treatment of future conditions, calibration, validation, uncertainty, and relevance to planning-scale assessment.

Chapter 6 separately reviews engineering standards, technical guidance, and the planning and development review context relevant to the framework. It clarifies where project-specific professional assessment remains necessary and where a planning-scale overlay could provide additional support.

Part III: Methodology, Framework, and Illustrative Application presents the research design, the proposed PHSI framework, the planner-facing overlay, and its illustrative application. Chapter 7 explains the research design and evidence used to develop the framework, then presents the common analytical architecture for baseline and future ground conditions. It describes the indicator roles, rating and threshold methods, weighting and class construction, spatial representation, future Ground Thermal State projection, calibration, validation, minimum evidence requirements, uncertainty, confidence, and proposed overlay. Chapter 8 demonstrates the framework through an illustrative application in Area B. It shows how an illustrative location could be understood within its planning context, how selected indicators and branch classes produce baseline and future PHSI classes, and how those results could inform discussion during the City's planning and development review process.

Part IV: Discussion and Conclusion consists of Chapter 9. The chapter returns to the research questions and discusses the main findings, contribution, implications for the City's planning and development review process, strengths, limitations, implementation considerations, and directions for future research. It concludes by restating the role and limits of the proposed framework.

Collectively, the thesis moves from identifying a planning problem in a thaw-sensitive urban setting, through the synthesis of relevant scientific, engineering, spatial, and policy knowledge, to the development and demonstration of a planning-scale framework. Its central argument is that the City's planning and development review process would benefit from a more structured and transparent way of considering permafrost thaw-related land susceptibility while proposals remain under assessment and open to revision.

1.8 Chapter Summary

This chapter introduced the research problem, aim, objectives, questions, scope, and contribution of the thesis. It identified the absence of a planning-scale permafrost hazard susceptibility mapping approach that translates existing scientific and engineering knowledge into a planner-facing spatial reference for City planning, zoning, and development review in Iqaluit. The chapter explained that the thesis responds to this translation and usability gap through the proposed framework, PHSI, and overlay.

The chapter also distinguished among the proposed framework, the PHSI produced through that framework, and the overlay used to display the resulting susceptibility classes. It established that the thesis develops an academic proposal rather than a completed operational product and defines the limits within which the framework should be interpreted.

Chapter 2 now turns to the geographic, urban, terrain, land-use, and zoning context of the populated area of Iqaluit.

Chapter 2: Study Area: Iqaluit and Populated Area

2.1 Introduction

This chapter establishes the geographic, urban, and physical context within which the proposed planning-scale permafrost hazard susceptibility framework is developed. It first situates Iqaluit within Nunavut and explains how the City's strategic role, municipal responsibilities, Inuit community context, permafrost setting, and physically constrained urban form make it an appropriate case study for this research. It then defines the populated area of Iqaluit as the practical study extent and describes the land use and surficial conditions within that area.

The chapter therefore establishes where the research is situated and why the selected study area is appropriate. The legislative framework, planning instruments, zoning and development review process through which the proposed framework could ultimately be applied are examined in Chapter 3.

2.2 Iqaluit as a Case Study

Iqaluit's suitability as a case study arises from the convergence of its strategic municipal role, community context, continuous permafrost setting, and physically constrained urban form. These characteristics are examined below before the spatial scope of the research is narrowed to the populated area.

2.2.1 Strategic role and community context within Nunavut

As shown in figure 2.1, Iqaluit is located at the head of Frobisher Bay on southeastern Baffin Island within Nunavut (Hatcher et al., 2011).

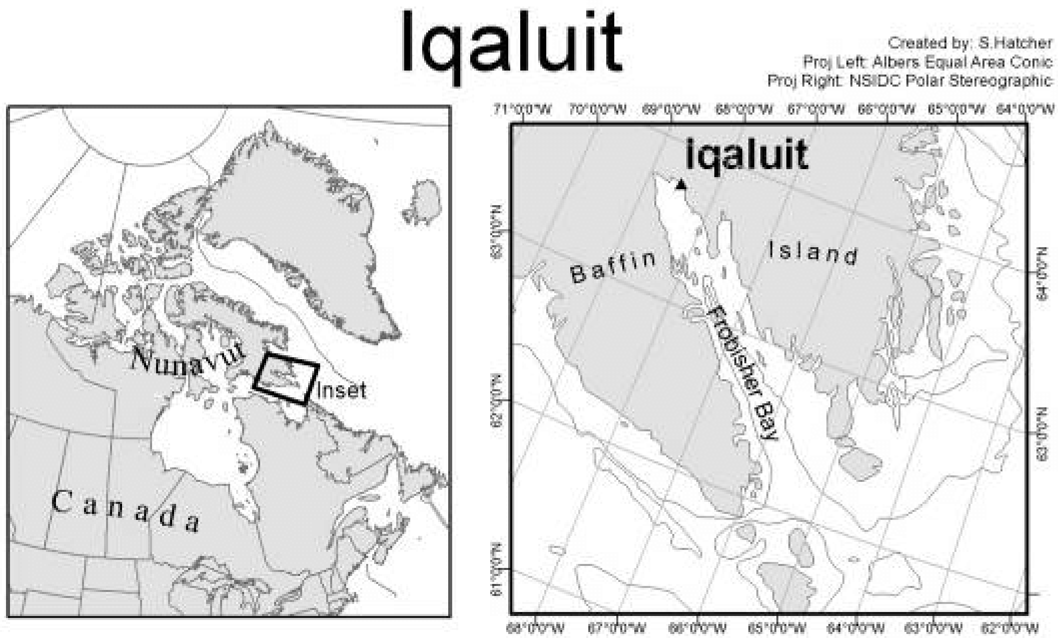

Figure 2.1. Location of Iqaluit within Nunavut and the eastern Canadian Arctic. Source: Hatcher et al (2011, Figure 1)

Iqaluit is an especially significant case for this research because it occupies an important position within the territorial and municipal landscape of northern Canada. It is the capital of Nunavut and is described by the city as "the most connected city in Canada" (City of Iqaluit, n.d. c). More specifically, the General Plan identifies Iqaluit as a major transportation Centre because of the importance of its airport, sea lift facilities, and air navigation systems (City of Iqaluit, 2020). The city is accessible from outside the community only by air and sea, with the Iqaluit International airport providing its only year-round external access (City of Iqaluit, 2020). The airport serves as a gateway to communities across the Baffin region and connects Iqaluit with southern Canada and other northern centers, while marine transportation supports the seasonal movement of goods (Canadian North, 2025; City of Iqaluit, 2020). As illustrated in Figure 2.2, Canadian North's route network connects Iqaluit directly with Ottawa in southern Canada and with numerous communities across Nunavut and Nunavik (Canadian North, 2025).

Figure 2.2. Canadian North route network showing Iqaluit's air connections with Ottawa and communities across Nunavut and Nunavik. Source: Canadian North (2025)

Beyond its transportation role, the city is responsible for a broad range of municipal services, including roads, water lines, trucked services, garbage collection, recreation, by-law enforcement, fire services, and economic development (City of Iqaluit, n.d. a). As a result, land use and development decisions in Iqaluit have implications not only for individual sites but also for the functioning of a major northern municipal government and the service systems that support it.

This institutional role matters because the thesis is concerned with planning-stage decision making. The framework is being developed for a city where formal planning instruments, public service responsibilities, and municipal decision-making are already in place (City of Iqaluit, n.d. a, n.d. b, 2021a, 2021b). For this reason, Iqaluit is analytically valuable because it is a functioning municipal government with real development pressures. The specific planning instruments, and development review process are examined in Chapter 3.

Iqaluit is also distinct because planning occurs in a city where Inuit community context is central. Statistics Canada's 2021 Census indicates that Indigenous residents account for 55.5% of Iqaluit's population, including 52.5% who identify as Inuk (Inuit) (Statistics Canada, 2022). Planning in Iqaluit therefore extends beyond the technical considerations associated with development in cold regions; it takes place within a predominantly Inuit community where social, cultural and land use considerations are integral to the municipal planning context.

2.2.2 Permafrost setting, urban form, terrain, and physical constraints

At the regional scale, Iqaluit is located within Canada's continuous permafrost zone, where permafrost is estimated to underlie 90 to 100% of the land area (CSA Group, 2019b). Figure 2.3 places Iqaluit within the broader distribution of permafrost across Canada. This regional classification establishes that permafrost is a fundamental condition underlying development in Iqaluit. However, it does not mean that ground composition, ground ice content, drainage conditions, or thaw susceptibility are uniform across the city.

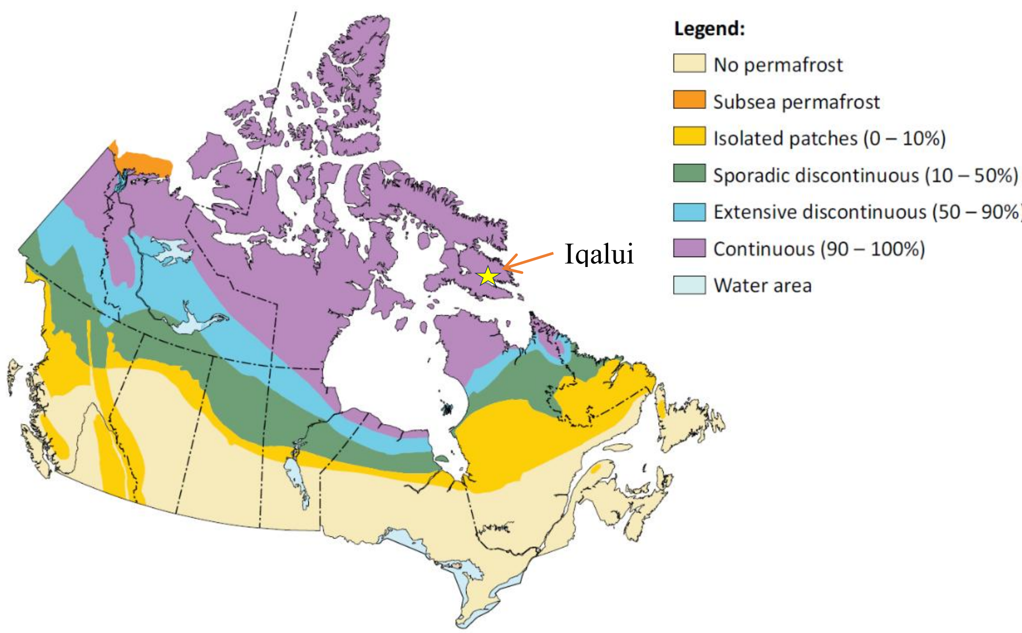

Figure 2.3. Distribution of permafrost in Canada and the continuous permafrost region encompassing Iqaluit. Source: Adapted from CSA Group (2019b), based on Heginbottom et al. (1995)

Iqaluit's urban form is shaped by a coastal setting and topographically varied terrain. The City's General Plan describes a physical environment consisting of parallel rock ridges separated by valleys of varying width, limited areas of level land, and drainage related constraints (City of

Iqaluit, 2010). The City's land use maps also show how development is constrained within a relatively constrained footprint (City of Iqaluit, 2022b). Development therefore occurs in a setting where topography, drainage, surface conditions, and servicing requirements influence how the urban area takes shape.

These physical conditions also have practical implications for infrastructure and development. The City's planning documents identify climate and permafrost related concerns associated with buildings on shallow foundations; buildings, roads, and buried pipes on steep south facing slopes or in areas of high snow accumulation, infrastructure in poorly drained areas where water may pool, and coastal infrastructure exposed to flooding and storm surges (City of Iqaluit, 2010). Servicing sloping areas with piped water and sewer infrastructure is also more difficult and expensive than servicing level land (City of Iqaluit, 2010). The physical landscape therefore matters to planning in Iqaluit in a direct and practical way. It influences not only where development can occur, but also how different sites may respond to built form, servicing demands, and land use expectations.

Put together, Iqaluit's strategic role established municipal planning system, continuous permafrost setting, and physically constrained urban form make it an appropriate case for developing a planning scale susceptibility framework.

2.3 The Populated Area as the Study Area

The proposed framework is developed for municipal use but applied specifically to the populated area of Iqaluit. This spatial focus reflects the thesis's concern with early-stage screening of building related development proposals in the part of the municipality where buildings, infrastructure, land use regulation, and development pressure are concentrated.

2.3.1 Study area boundary and land use context

The broader municipal boundary encompasses a substantial territory that includes undeveloped lands, watershed lands, and other areas beyond the ordinary focus of urban development review. The populated area, by contrast, contains the established neighbourhoods, roads, municipal services, institutional and commercial lands, and areas identified for future development. It is therefore the portion of the municipality in which development proposals are most likely to arise and where municipal planning decisions most directly shape built form and site use (City of Iqaluit, 2022a, 2022b). Figure 2.4 shows the relationship between Iqaluit's broader municipal territory and the smaller populated area used as the study area.

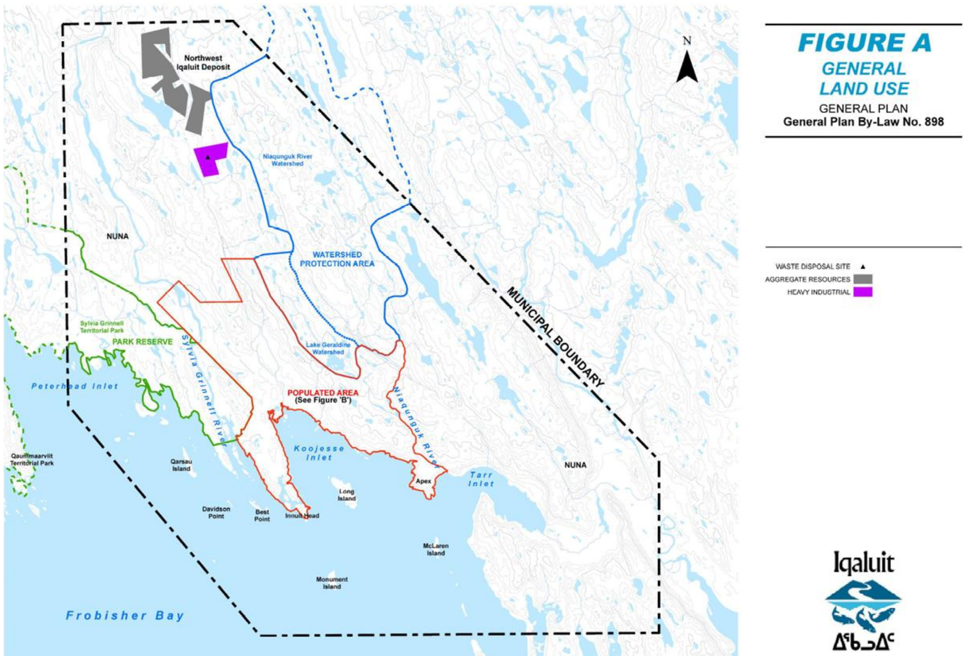

Figure 2.4. Municipal boundary and populated area of Iqaluit. Source: City of Iqaluit (2022a, 2022b)

Within this boundary, the City's Populated Area Land Use map identifies a combination of residential, mixed-use, commercial, institutional, transportation, open area, reserve, and future development lands (City of Iqaluit, 2022b). As shown in Figure 2.5, the study area is therefore not uniformly developed. It contains distinct land use functions and varying forms of existing and anticipated development, as shown in Figure 2.5.

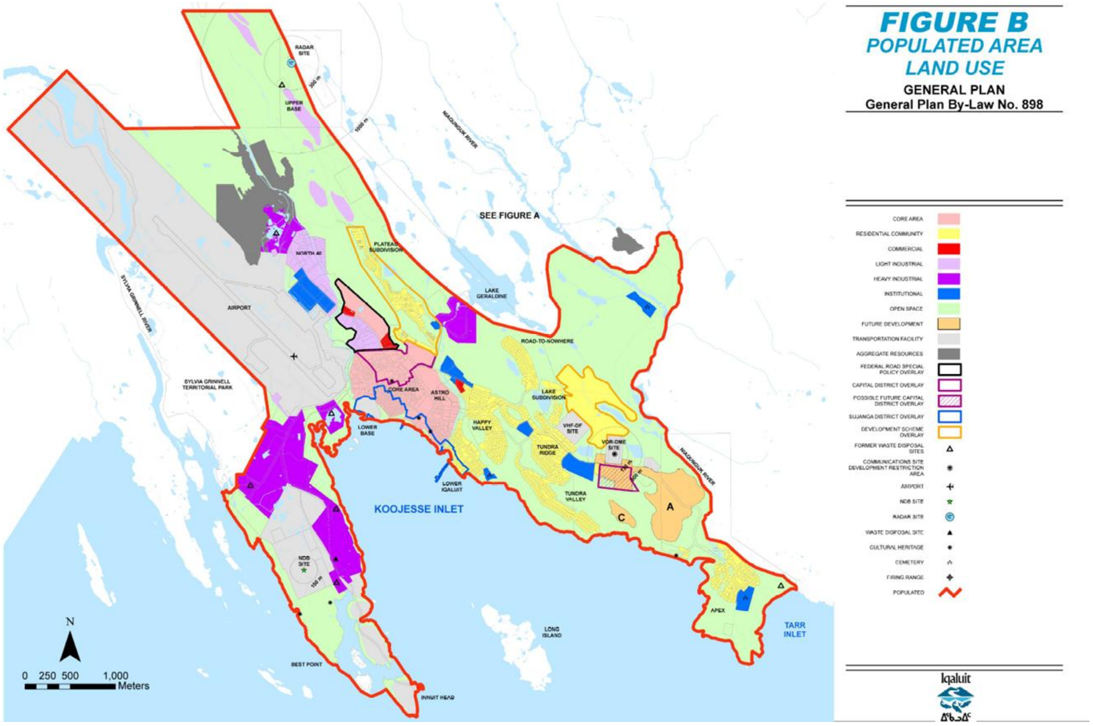

Figure 2.5. Land use designations within the populated area of Iqaluit. Source: City of Iqaluit (2022b, Figure B)

This land use structure is relevant because the proposed framework is intended to support municipal planning decisions in locations where land use permissions, development intensity, built form, and infrastructure requirements are already active considerations. The framework would add a thaw-related land susceptibility perspective to this existing planning geography. The detailed zoning structure and its relationship to development review are discussed in Chapter 3.

2.3.2 Surficial geology and spatial ground variability

Although Iqaluit is located within the continuous permafrost zone, the physical properties of the ground are not uniform across the populated area. Surficial geology mapping indicates that the city and its surroundings contain materials of different origins and engineering significance. Relatively level, sandy and gravelly glaciofluvial and glaciomarine sediments extend beneath the airport and its surroundings and within Apex, while Precambrian bedrock with partial and uneven till cover occurs beneath newer development on hilly terrain and plateaus (Allard et al., 2012). Figure 2.6 shows the distribution of these surficial materials across the populated area and surrounding terrain.

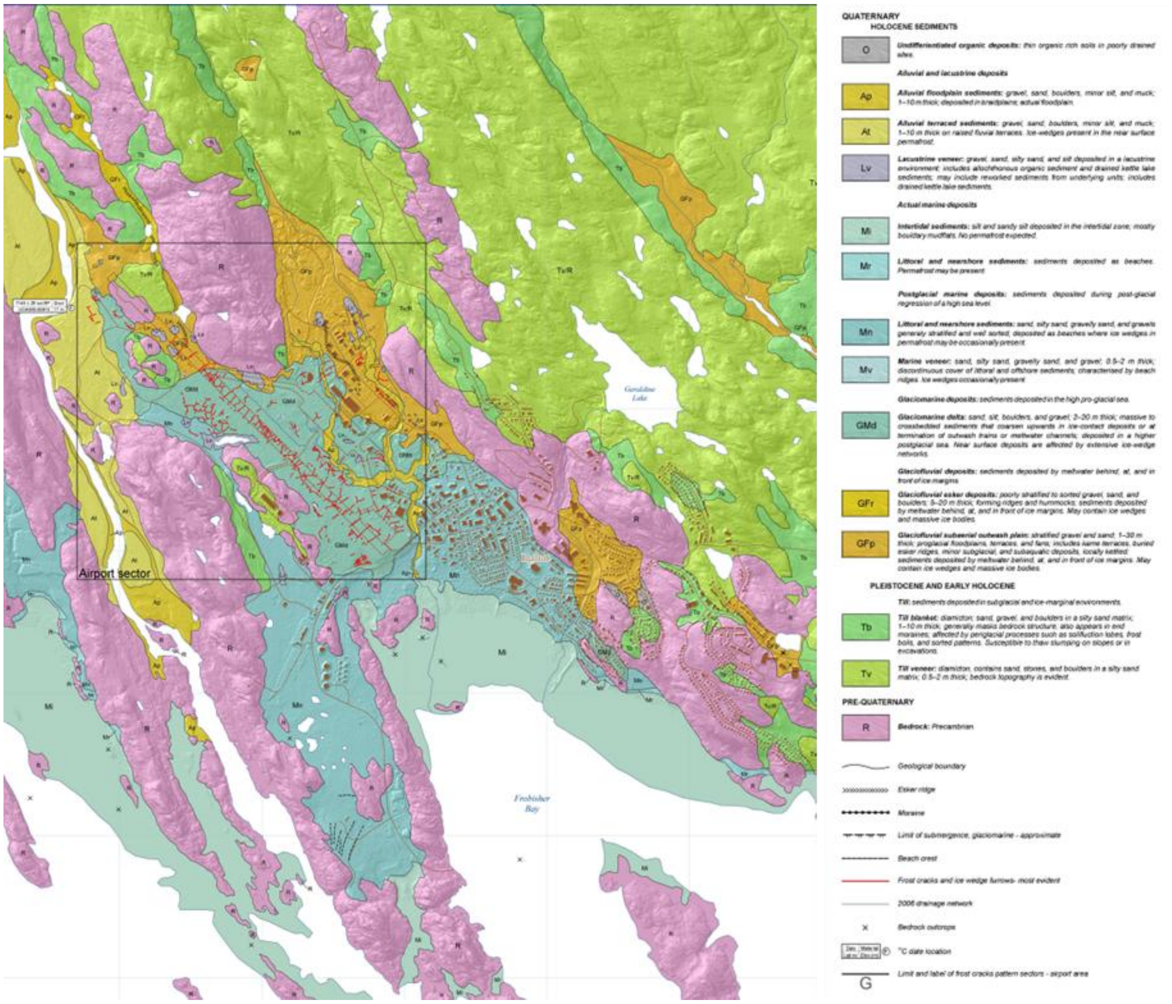

Figure 2.6. Surficial geology of the Iqaluit populated area and surrounding terrain. Source: Allard et al. (2012), Geological Survey of Canada, Canadian Geoscience Map 64

The significance of this variation is supported by local ground displacement research. LeBlanc et al. (2015) found that surficial geology and ground ice were important to interpreting seasonal surface displacement in Iqaluit. Lower displacement was generally associated with bedrock and coarse sediments, while finer sediments more likely to contain ground ice exhibited higher displacement. Surface water, drainage conditions, and annual climatic variability also contributed to the observed spatial patterns (LeBlanc et al., 2015).

Figure 2.6 does not provide a complete geotechnical interpretation, nor does it function as a direct map of thaw susceptibility. Rather, it establishes that physical ground conditions vary across the study area and that Iqaluit's regional classification as continuous permafrost does not translate into uniform local behavior. Thaw related susceptibility may also be influenced by ground ice content, drainage, topography, snow accumulation, surface disturbance, and existing development conditions. A planning-scale framework concerned with these relationships must therefore be spatially differentiated rather than applied uniformly across the populated area.

2.4 Chapter Summary

This chapter established Iqaluit as the case study and the Populated Area as the spatial focus of the research. Iqaluit's role as the capital of Nunavut, its ongoing development activity, and its predominantly Inuit community make it an appropriate setting for examining the relationship between urban growth, land use, and permafrost conditions. The Populated Area contains the main concentration of neighbourhoods, infrastructure, regulated land uses, and prospective development activity, aligning the study boundary with the municipal planning decisions the proposed framework is intended to support.

The chapter also showed that the Populated Area is not physically uniform. Its coastal terrain, varied topography, drainage and servicing constraints, surficial materials, and continuous permafrost conditions influence the location and form of development. These conditions do not determine the development and ground compatibility of an individual site, but they demonstrate the need for a spatially differentiated planning framework. With the study area established, the next chapter examines the policy, administrative, and development review context within which the proposed framework would operate.

Chapter 3: Policy Context

3.1 Introduction

Chapter 2 establishes where the thesis is situated; this chapter explains how development is governed, reviewed, and interpreted within that setting. The purpose of this chapter is to clarify the policy and institutional context within which the proposed Permafrost Hazard Susceptibility framework is intended to operate. The GIS overlay proposed in this thesis is intended to support a municipal development review process structured by long range planning policy, zoning regulation, municipal administrative review, and a separate territorial building permit and code compliance stage (City of Iqaluit, n.d.-b, 2020; 2021b).

The chapter moves from broad development pressure to specific review processes. It begins with the policy drivers that make development review increasingly important in Iqaluit, including growth, housing demand, intensification, and climate resilience. It then explains the municipal planning instruments and administrative structure through which development is guided and controlled: the General Plan, which provides long range policy direction, the Zoning By-law, which translates that direction into more specific site based rules; and Planning and Development administration, which applies those instruments through application review and related approval processes. The chapter then narrows to the development review process itself and discusses the Inuit planning context and land-based considerations that must remain central to how any technical planning tool is interpreted.

This sequence clarifies where the proposed framework fits. A planning scale GIS overlay for permafrost screening would not determine final engineering design, replace zoning, override City staff judgment, or displace the broader cultural and community context of land use decisions. Its role would be more specific: to provide an early, spatially informed indication of land susceptibility to permafrost thaw within municipal development review, so that staff can recognize potential ground related concerns before key decisions, development density, building height, servicing, drainage, foundation approach, or the scope of required technical submissions become more difficult to revise as the review process advances.

The framework is not intended to apply with equal relevance to every development application.

Its greatest value is for proposals significant enough to affect ground conditions or depend materially on ground performance, including new construction, major redevelopment, intensification projects, substantial building footprints, increased loading, grading or fill, servicing and utility installation, drainage alteration, snow storage changes, or subdivision related development. The thesis does not focus on minor works such as minor repairs, small buildings, temporary construction structures, or internal renovations with no significant exterior or use change, which the Zoning By-law distinguishes from development requiring a Development Permit (City of Iqaluit, 2021b). This scope positions the proposed GIS overlay as a planning stage support tool for proposals where the physical relationship between development and ground conditions is material to review.

Table 3.1 summarizes the strategic, institutional, physical, and regulatory characteristics that make Iqaluit an appropriate policy case for this thesis. The table frames Iqaluit not only as a study area, but also as a municipal planning context in which a planning scale GIS overlay for permafrost screening could support development review.

Table 3.1. Why Iqaluit is an appropriate policy case for the thesis

Case study characteristic	Relevance to the present research
Capital city and major territorial center	Reflects Iqaluit's role as Nunavut's administrative and service Centre, which contributes to sustained demand for land, housing, infrastructure, and municipal development review
Established municipal planning and development review framework	Provides a defined institutional setting within which a planning scale permafrost GIS overlay could inform development review
Physically constrained terrain	Reinforces that land use decisions are shaped by terrain and subsurface conditions rather than by policy alone
Active housing and intensification reforms	Makes questions of height, density, and proposal intensity particularly timely
Layered municipal territorial approval process	Highlights the need for a planning stage tool that can inform development review before a Development

	Permit is issued and the proposal advances to territorial building permit
Existing climate and permafrost attention in policy discussions	Shows that the thesis addresses recognized concerns at the intersection of municipal planning, permafrost conditions, and climate change

These characteristics show why Iqaluit is a strong policy case for the thesis. Its relevance lies in how growth pressure, formal planning instruments, northern terrain, municipal review responsibilities, and thaw sensitive ground conditions come together in an active urban development setting.

3.2 Growth, Housing Pressure, and Intensification as Policy Drivers

The policy problem addressed in this thesis is sharpened by the fact that Iqaluit is not operating in a static development environment. Recent housing and planning initiatives show that the City is pursuing measures intended to increase housing supply, enable more intensive forms of development, improve approval predictability, and strengthen climate resilience. The Housing Accelerator Fund Action Plan for Iqaluit identifies a housing supply growth target of 328 permitted units over 3 years and a 10-year municipal housing projection of 1,450 units (Canada Mortgage and Housing Corporation [CMHC], 2026). The same Action Plan identifies initiatives related to climate data and climate resiliency planning, reduced parking requirements in the core area, increased building heights and densities in targeted corridors, expanded core area permissions, clearer application requirements, delegated approval authority, e permitting workflow improvements, and private land development capacity (CMHC, 2026).

These policy shifts are directly relevant to the thesis because they show that questions of building height, density, development intensity, approval predictability, and climate resilience are already active municipal issues in Iqaluit. They also create an important planning challenge: a site may appear appropriate from a land use or zoning perspective but still require closer attention if thaw related ground conditions could affect the long-term performance of the proposed development. This is especially important where housing and intensification pressures lead to proposals involving larger building footprints, increased loading, grading, servicing, drainage alteration, or other ground affecting site changes.

In this context, the policy driver is not simply growth in a general sense. It is the combined pressure of housing demand, intensification, limited developable land, infrastructure constraints, climate change, and permafrost sensitive terrain. A planning scale permafrost screening tool is relevant because it could help staff identify early in the review process when a proposal may proceed through routine review, when it should be reviewed with greater caution, and when additional geotechnical or terrain related information may be warranted. Its value applies not only to proposals requiring rezoning or a General Plan amendment, but also to conforming major development applications where the proposed form, site disturbance, servicing, drainage, or future ground performance implications are significant enough to require closer review.

This approach aligns the proposed framework with the broader policy context of Iqaluit: supporting housing and intensification while ensuring that development review remains attentive to thaw related land conditions in a changing Arctic environment.

3.3 Planning Instruments and Administrative Structure

Municipal development review in Iqaluit is shaped by a set of connected planning instruments and administrative functions. This structure can be understood by distinguishing among three levels of decision making.

First, the General Plan establishes broad long range policy direction. It describes the kind of community the city is planning for and identifies the general direction for land use, growth, infrastructure, environmental protection, and related municipal priorities. Second, the Zoning By-law translates that broad direction into more specific, legally enforceable rules for particular lands and zones. It determines what uses are permitted or conditional, and it regulates matters such as building form, parking, and similar development standards. Third, Planning and Development administration applies these instruments through development permit review, rezoning or plan amendment processes, technical circulation, conditions, and communication with applicants.

The proposed Permafrost Hazard Susceptibility framework would sit within this third level as a planning support tool. It would help staff interpret land conditions earlier in the review process by adding a permafrost informed land screening perspective to the existing policy and regulatory structure.

Figure 3.1 summarizes this broader planning and permitting structure. It shows how the General Plan, Zoning By-law, and Planning and Development administration relate to municipal development review, and how municipal review precedes the separate territorial building permit and code review stage. Figure 3.1 presents the overall structure before the following subsections discuss each municipal component in more detail.

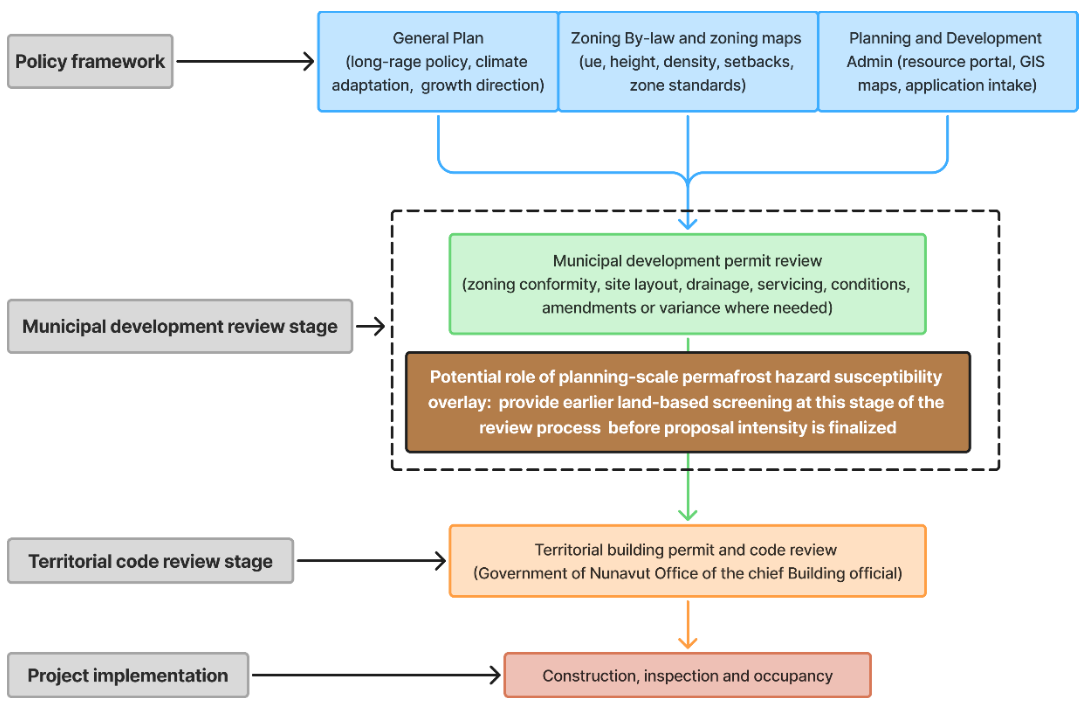

Figure 3.1. Broader planning and permitting framework for development review in Iqaluit

3.3.1 General plan

The General Plan is the City's principal long range policy instrument for guiding land use, growth, municipal investment, environmental planning, and related community objectives over a 20-year horizon (City of Iqaluit, n.d. b; City of Iqaluit, 2020). It also provides the broader policy framework through which those objectives are pursued (City of Iqaluit, 2020). In practical terms, the General Plan answers the broad "where, why, and under what policy direction" questions of municipal planning. For example, when the General Plan identifies land for future residential growth, mixed use development, open space, infrastructure, or environmental protection, it establishes the broader planning expectations for that land and the policy considerations that should guide future decisions.

This is important because it helps distinguish the General Plan from the Zoning By-law. The General Plan may indicate that an area is appropriate for future development or that certain lands should be protected, serviced, or intensified. The Zoning By-law then translates that broader direction into specific zones and rules. Development review then applies both instruments (the General Plan and the Zoning By-law) to a particular proposal. In other words, the General Plan sets the strategic direction, the Zoning By-law operationalizes that direction through enforceable land use controls, and the development review process tests whether a specific proposal conforms to both (City of Iqaluit, 2021b).

In the context of this thesis, the General Plan is important because it frames the broader policy environment within which permafrost informed review would operate. If the General Plan directs growth, intensification, or infrastructure investment toward certain areas, implementation of that direction can also be informed by early considerations of land-based constraints in those areas. The proposed Permafrost Hazard Susceptibility framework would therefore support implementation of the General Plan by adding a planning scale evidence layer. It would help staff ask whether a site that appears consistent with long range land use direction may still require more cautious review because of thaw related ground conditions. The framework would help translate permafrost hazard susceptibility, an important environmental and geotechnical consideration, into spatial information that can inform plan implementation, amendment decisions, and early-stage development review.

3.3.2 Zoning by-law and zoning schedules

Zoning By-law translates broader policy direction into more detailed and site-specific regulations. If the General Plan provides the long-range policy direction, the Zoning By-law is the principal regulatory tool used to implement that direction. It divides land into zones and establishes the rules that apply within those zones, including permitted and conditional uses, building and structure requirements, parking and loading requirements, and other development standards (City of Iqaluit, 2021).

Consider the General Plan specifies that a certain part of the city is intended for 'future residential growth', and a development proposal is submitted to the city as a 'mixed use development'. The Zoning By-law then determines what is actually permitted on a specific property at the time of application. It answers questions such as: Is the proposed use allowed? What height limits, density requirements, setbacks or other standards apply? Does the proposal require a rezoning, or General Plan amendment?

The City's planning materials direct users to the Zoning By-law and General Plan to identify applicable land use and regulatory requirements before applying for development approval (City of Iqaluit, n.d. b). The Zoning By-law itself states that it applies to all lands within the incorporated limits of the City of Iqaluit, identifies zoning schedules that divide the city into zones, and confirms that the Development Officer is responsible for administering the by-law, reviewing applications, interpreting the General Plan and Zoning By-law, and approving, approving with conditions, or refusing development permit applications subject to Council's authority (City of Iqaluit, 2021b).

The proposed Permafrost Hazard Susceptibility framework is positioned as a complementary source of planning scale information within this established regulatory and administrative structure. Its contribution would be to help staff consider whether site specific ground conditions warrant closer attention, additional technical review, or further supporting information during development review.

3.3.3 Planning and development administration

The City's Planning and Development page outlines the administrative resources and application requirements that support development review. The page provides links to the online Development Permit application system, the General Plan and Zoning By-law resources, and the GIS land use Web Map. It also states that Development Permits are required for new construction, major renovations, demolitions, changes in land use, or significant changes to a property. Projects that do not comply with current zoning or General Plan policies may require rezoning or General Plan amendments involving formal processes, community notification, and Council review (City of Iqaluit, n.d. b).

Within this administrative structure, the broad direction of the General Plan and the specific rules of the Zoning By-law is applied to individual development proposals. Planning staff, the Development Officer, technical reviewers, Council where required, and applicants each contribute to different capacities, through which policy and regulation are translated into file specific comments, revisions, conditions, and decisions. This is also where the proposed Permafrost Hazard Susceptibility framework would be most directly relevant: it could provide an additional land-based reference during completeness review, city staff review, and applicant revisions, helping staff consider whether thaw related conditions warrant additional technical information, revised submissions, or conditions while operating within existing planning authority and review processes.

3.4 Existing Development Review Pathway

Development review is the point at which the policy and regulatory instruments described above are applied to a specific proposal. In Iqaluit, publicly available City materials collectively identify a pathway involving application submission and completeness determination, staff review and comments, revised or supplementary materials where required, recommendation or decision by the applicable authority, Development Permit issuance, and the subsequent territorial building permit and code compliance stage (City of Iqaluit, n.d.-b, 2021b, 2026). The City's Planning and Development page states that Development Permits are required for new construction, major renovations, demolitions, changes in land use, and significant changes to a property. It also notes that projects that do not comply with current zoning or General Plan policies may require rezoning or plan amendments involving formal processes, community notification, and Council review (City of Iqaluit, n.d. b).

The development review pathway is presented here as a simplified synthesis of these documented components rather than a rigid procedure that applies identically to every application type. A General Plan amendment, Zoning By-law amendment, Development Permit Application, or variance may involve different procedural requirements and decision authorities. The Zoning By-law establishes application and completeness requirements, identifies delegated and Council decision making authority, and governs decisions, notices, appeals, and permit issuance (City of Iqaluit, 2021b). The April 2026 Planning and Development Committee report further illustrates the process through a sequence identifying application, compliance review, staff review and comments, revised submissions, and decision (City of Iqaluit, 2026). Taken together, these materials support the common review logic used in this chapter: an application is submitted and assessed for completeness; staff review the proposal and provide comments; revised or supplementary materials may be submitted where required; and a recommendation or decision is made by the applicable authority.

Figure 3.2 presents this simplified municipal development review sequence and identifies the stages where the proposed Permafrost Hazard Susceptibility framework could support review.

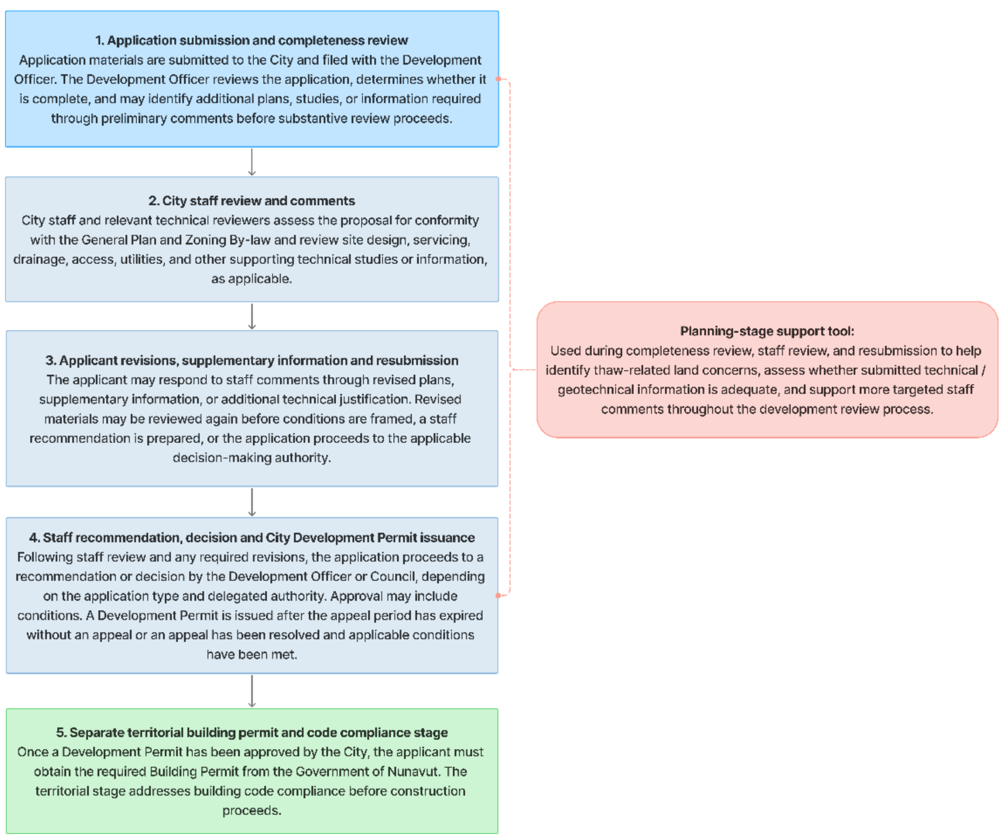

Figure 3.2. Simplified municipal development review sequence in Iqaluit and stages where the proposed Permafrost Hazard Susceptibility framework could support review

3.4.1 Application submission and completeness review

The formal review process begins when the applicant submits the required application materials to the City. The Zoning By-law states that an application for a Development Permit must be filed with the Development Officer and accompanied by the required fee and supporting plans. These generally include site, floor, and elevation plans, while additional plans, studies, or information may be required depending on the nature and scale of the proposed development (City of Iqaluit, 2021).

At this stage, the central question is whether the application package contains enough information for staff to begin meaningful review. The Zoning By-law gives the Development Officer authority to identify when an application is complete and to request additional plans, studies, or information before that determination is made. Depending on the proposal, this may include grading and drainage plans, snow and wind studies, servicing studies, traffic studies, plans of survey, environmental site assessments, or other information needed to support review. The By-law states that an application is not identified as complete until all submission requirements have been met, including any additional plans, studies, or information requested through preliminary comments (City of Iqaluit, 2021).

For this thesis, the application plans and drawings including context plans, site plans, floor plans, and elevation plans are important because they collectively describe the proposed development's location, building footprint, height, density, uses, access, parking and loading arrangements, servicing, drainage, and overall development intensity (City of Iqaluit, 2021b). The proposed Permafrost Hazard Susceptibility framework would add a complementary land-based evidence layer by indicating the site's mapped susceptibility under current and projected future climate horizons. Considered together, these sources of information would allow staff to examine how the proposed development's scale, form, and site disturbance relate to the mapped susceptibility context and to raise more spatially and temporally specific questions during review. The framework would not predict site specific ground performance or independently determine the compatibility of the proposed development with site specific ground conditions; those questions would remain subject to project specific investigation and professional judgment.

At the completeness stage, the practical question arising from this combined consideration is whether the application package is sufficiently scoped to proceed to substantive review. For example, where substantial grading, significant servicing work, or a large building footprint is proposed in an area classified as Moderate, High, or Unknown / Insufficient Data, staff may have a clearer basis for considering whether additional terrain related or geotechnical information is warranted. Completeness review therefore operates as a threshold between application submission and detailed staff review, it establishes whether the required materials are present and appropriately scoped, while the more detailed question of whether those materials adequately address planning, engineering, and permafrost related concerns is examined during staff review and comments.

3.4.2 Integrated circulation, staff review and comments

For the purposes of the simplified sequence presented in this chapter, once an application has been determined to be complete, it proceeds to staff review and comments. This stage is distinct from completeness review. Completeness review determines whether the application package contains the materials needed to begin review, staff review examines what those materials show. At this point, City staff (including technical reviewers) assess the proposal against applicable planning instruments, regulatory requirements, site conditions, and supporting technical information. The April 2026 Planning and Development Committee report illustrates consideration of General Plan and Zoning By-law conformity, site design, servicing and municipal capacity, grading and drainage, access and right-of-way improvements, utilities, snow and wind conditions, environmental considerations, and conditions involving relevant City departments and technical bodies (City of Iqaluit, 2021, 2026).

This stage is important because it is where planning and technical considerations are interpreted together in relation to a specific proposal and where questions of development ground compatibility can be examined in greater detail. A proposal may conform to the applicable land use designation and zoning requirements, but still raise questions if the proposed building form, site disturbance, servicing approach, drainage strategy, or foundation assumptions interact with permafrost sensitive ground conditions. Staff review is therefore not limited to confirming that drawings or studies exist, it considers whether the proposal and its supporting information adequately address identified site conditions and applicable planning and technical requirements.

The proposed Permafrost Hazard Susceptibility framework would support this stage by adding mapped information about current and projected future permafrost hazard susceptibility to the review of the proposal. Its role is not to replace staff judgment, technical review, or project specific geotechnical analysis. Rather, it helps staff relate the proposed development's scale, form, and intensity to the mapped susceptibility context and consider whether the submitted information addresses the thaw related questions raised by that relationship. A Low classification may support a more routine permafrost focused review posture without removing the need to address other applicable planning and technical requirements, while a Moderate, High, or Unknown / Insufficient Data classification may indicate that closer consideration, additional technical explanation, or project specific investigation is warranted.

Table 3.2 summarizes how this permafrost informed screening function can support existing staff review considerations. It pairs familiar development review topics, such as, development intensity, drainage, servicing, utilities, technical submissions, resubmissions, conditions, with the additional land based questions that the proposed overlay could help staff ask. By making those questions more spatially and temporally specific, the framework could support more targeted staff comments and inform subsequent applicant revisions, supplementary information requests, or resubmissions.

Table 3.2. Permafrost informed land screening for development review

Existing municipal review consideration	Framework enabled, permafrost informed screening question	Example concern or review implication
Site location and proposed development form	What is the site's mapped thaw related susceptibility under current and projected future climate horizons?	Relative susceptibility to thaw settlement and possible thaw sensitive or ice rich ground
Height, density, building footprint, and development intensity	Given the mapped susceptibility, does the proposed scale, intensity, or footprint warrant closer ground condition review?	Potential sensitivity to building loads and heat transfer, need for project

		specific foundation assessment
Site grading, drainage, snow storage, and layout	Could the proposed grading, drainage, snow storage, or site layout concentrate water or snow in ways that may affect ground thermal conditions?	Runoff concentration or ponding, snow accumulation, and possible active layer deepening
Servicing, utilities, access, and surface infrastructure layout	Does the mapped susceptibility warrant closer review of how differential ground movement could affect pipes, access routes, drainage, or other infrastructure?	Potential differential movement affecting pipes, access routes, and drainage infrastructure
Supporting studies, additional information, and approval conditions	What additional terrain related or geotechnical information, if any, may be warranted to support review?	Possible need for project specific investigation or professional interpretation in higher susceptibility or data deficient areas
Resulting value: an early, planned stage land screening layer that complements existing project specific review, helps staff examine development ground compatibility, and supports consideration of when closer review or additional terrain related or geotechnical information may be warranted.		

3.4.3 Applicant revisions, supplementary information, and resubmission

Not every proposal proceeds from staff review directly to recommendation or decision. Where staff review identifies unresolved planning, zoning, servicing, design, geotechnical, environmental, or other technical concerns, the applicant may be required to revise the proposal, provide additional justification, or submit supplementary information. This stage reflects the iterative nature of development review, City staff provide comments, the applicant responds through revised materials, and those materials may be reconsidered or recirculated until staff concerns are resolved, conditions can be framed, or a recommendation can be prepared (City of Iqaluit, 2020).

The purpose of this stage is to determine whether the applicant's response adequately addresses earlier staff comments. A resubmission may include revised drawings, updated studies, technical memoranda, design justifications, or written responses explaining how the proposal has changed or why the original approach remains appropriate. This stage is therefore different from the initial staff review. Staff are no longer only identifying concerns; they are assessing whether the applicant's revised materials have addressed those concerns sufficiently to allow the file to move forward.

The proposed Permafrost Hazard Susceptibility framework would remain useful throughout this revision and resubmission stage because it would provide a consistent spatial reference for evaluating applicant responses to thaw related concerns. For example, an applicant may submit a geotechnical report that describes existing subsurface conditions and assesses the proposed development in relations to the conditions investigated. However, the proposed overlay may show that the same site is classified as low susceptibility under the current horizon but shifts to moderate susceptibility at a horizon 20 years into the future. In that case, staff could use the framework to ask a more specific follow up question: does the geotechnical submission consider how projected warming, deeper seasonal thaw, or changing ground thermal conditions could affect the site over the expected life of the development? If the report does not address that future horizon, staff could consider requesting a revised or supplementary submission that discusses susceptibility and potential ground response, the assumptions used to interpret future thaw potential, and any implications identified for foundation, drainage, or servicing performance over time.

This example shows why the tool remains relevant after the first round of staff comments. It does not simply flag a site and end the review conversation. Instead, it could help staff explain why a revision is being requested, gives the applicant a clearer basis for responding, and allows staff to reassess whether the resubmission addresses the mapped susceptibility context and proposed development intensity. In this way, the framework supports the review and revision cycle by linking staff comments to a clear spatial and temporal basis, while still leaving the final adequacy of geotechnical analysis to professional judgment and project specific review.

3.4.4 Staff recommendation, decision, and development permit issuance

After staff comments have been addressed through revised submissions, supplementary information, or applicant responses, the application moves toward recommendation, decision, and, where applicable, issuance of the City Development Permit. At this stage, staff determine whether the proposal is supportable as submitted or revised, whether conditions are required, whether further information remains necessary, or whether the application should be refused or referred to the appropriate decision-making authority (City of Iqaluit, 2021b, 2026). Where a proposal involves a variance, Zoning By-law amendment, General Plan amendment, or Council consideration, the applicable decision pathway may differ, but the central function of this stage remains the same: the city formalizes its position on the application.

The proposed Permafrost Hazard Susceptibility framework remains relevant at this stage, but its role should be understood as supplementary rather than determinative. Earlier in the process, the GIS overlay helps staff identify thaw related land concerns and frame more targeted requests for technical information. At the recommendation and decision stage, it may help support the rationale for staff conclusions, proposed conditions, or continued caution, but only as one input among several. Staff recommendations and decisions are also shaped by conformity with the General Plan and Zoning By-law, submitted plans and studies, servicing and infrastructure considerations, drainage and grading, environmental constraints, comments from municipal or technical reviewers, applicant responses to earlier staff comments, and the professional judgment of planning and engineering staff. Where applicable, Council review, community input through amendment processes, and broader municipal discretion may also inform the final outcome (City of Iqaluit, 2026).

The overlay therefore does not form the basis of a decision on its own. Rather, it contributes a spatially explicit perspective on permafrost susceptibility perspective to the broader review record. For example, if the overlay indicates that a site shifts from Low present susceptibility to Moderate future susceptibility, that finding would not automatically justify approval, refusal, or a particular condition. However, if the applicant’s revised technical submission addresses projected ground change, explains the assumptions used to assess future thaw behavior, and proposes mitigation measures appropriate to the development's scale and design life, the overlay may help staff explain why approval with conditions is supportable. Conversely, if the applicant's resubmission does not respond to a mapped future susceptibility concern, the overlay may help staff explain why further information, additional revision, or a more cautious recommendation remains necessary.

The Zoning By-law also distinguishes between a decision on a Development Permit application and issuance of the Development Permit itself. After a decision is made, the Development Officer issues a Notice of Decision. A person claiming to be affected by the decision may appeal within fourteen days of the date on which the Notice of Decision was given or posted. Where the application has been approved and no appeal has been filed, the Development Permit is issued only after fourteen days have passed following the posting of the Notice of Decision and the applicable conditions of approval have been met. Where an appeal is filed, the Permit may be issued only after the Development Appeal Board has heard the matter and in accordance with its decision and any modifications it determines (City of Iqaluit, 2021b).

This distinction is important because it shows why screening earlier in the process matters. By the time a recommendation, decision, or Notice of Decision is reached, the review outcomes have become more formal. The proposed framework is therefore most valuable when it has already informed staff review, applicant revisions, and the framing of possible conditions before the application reaches formal decision and development permit issuance.

3.4.5 Separate territorial building permit and code compliance stage

City Development Permit approval does not complete the full construction approval process. The City's Planning and Development page states that a Building Permit from the Government of Nunavut is required once a Development Permit has been approved by the City (City of Iqaluit, n.d. b). The Government of Nunavut similarly states that, where a Development Permit is required, it must be obtained before the Building Permit application is submitted to the Office of the Chief Building Official (Government of Nunavut, n.d.). This establishes an important distinction between municipal development review and the later territorial building permit stage. The municipal stage focuses on whether the proposed development is acceptable within the City's planning and regulatory framework, including conformity with the General Plan and Zoning By-law, site planning requirements, servicing considerations, and conditions attached through municipal review. The territorial building permit stage addresses building and plumbing code compliance, detailed building plans, foundation and structural information, professional design requirements, inspections, and related technical obligations (Government of Nunavut, 2025).

The Zoning By-law reinforces this separation. It states that issuing a Development Permit does not exempt the permit holder from being constructed in accordance with the National Building Code, National Fire Code, Arctic Airports Zoning Regulations, or other applicable standards and regulations. It also clarifies that approval by the Development Officer or Council should not be interpreted as confirmation that those separate standards have been met (City of Iqaluit, 2021b). Therefore, a City Development Permit confirms municipal planning approval, it does not certify that the project satisfies all building code, fire code, aviation, engineering, or construction related requirements.

This distinction clarifies the intended location and limits of the proposed Permafrost Hazard Susceptibility framework. The framework is a municipal planning stage support tool. It can help City staff identify thaw related land concerns earlier in development review, assess whether submitted technical or geotechnical information is adequate for the site's mapped susceptibility context, and support more targeted staff comments, revisions, or conditions before a City Development Permit is finalized. It does not determine whether the Government of Nunavut should issue a Building Permit, nor does it replace detailed foundation design, code compliance review, inspection, or professional engineering responsibility.

The separation between municipal and territorial review strengthens the case for using the framework upstream. By the time a proposal reaches the territorial building permit stage, the project is typically more advanced in design and municipal review expectations may already be formalized. If thaw related concerns are identified only at that later stage, there may be less opportunity to reconsider site layout, development intensity, servicing assumptions, drainage strategy, or the scope of geotechnical information requested through municipal review. The value of the framework is therefore indirect but important, it supports the municipal review record by helping staff identify, communicate, and document permafrost related concerns before the application advances to territorial code compliance review.

3.5 Inuit Planning Context and Land based Considerations

The policy context for development review in Iqaluit cannot be understood solely in procedural, regulatory, or technical terms. Planning occurs in a predominantly Inuit community where decisions about land are connected not only to zoning, servicing, and development capacity, but also to Inuit cultural values and knowledge, access to land, cultural heritage, and land-based activities. The City's General Plan states that the city will strive to emphasize and reflect Inuit cultural values and knowledge in the land use planning process. It also provides that buildings and locations of cultural significance, including beach and camping areas, archaeological sites, and burial sites, will receive special consideration when development proposals are reviewed (City of Iqaluit, 2025).

This broader context is also reflected in the General Plan's use of Nuna. *Nuna* an Inuktitut term referring to the land. Within the General Plan, "Nuna" is also used as a planning designation for the undeveloped hinterland beyond the Populated Area where traditional and recreational activities occur. The Plan emphasizes the importance of access to Nuna for fishing, hunting, snowmobiling, berry picking, and camping. It further notes that access to Nuna is important for residents and visitors and that cultural heritage resources within Nuna require protection (City of Iqaluit, 2025). Although this thesis focuses on the Populated Area and municipal development review rather than the entire municipal hinterland, this policy context remains important because it shows that land in Iqaluit is not treated only as a physical surface for development. It is also understood through cultural, social, recreational relationships and through continued access to land.

The Area B Development Scheme reinforces this point at the neighborhood planning scale. Area B is relevant to the thesis because it is a future development area considered later in the illustrative application. The Development Scheme describes itself as a Neighbourhood Plan and states that its design aspires to support the community's traditional, cultural, and recreational requirements alongside its development needs (City of Iqaluit, 2015). The Scheme addresses housing, roads, servicing, and land-use layout, but does so within a broader community context. This demonstrates planning for future growth is not solely a technical or servicing exercise. It must also be understood in relation to community priorities and the ways people continue to move through, use, and value the surrounding landscape.

This context is important for positioning the proposed Permafrost Hazard Susceptibility framework. The overlay is intended to identify thaw related land concerns at the planning review stage; it is not intended to provide a complete determination of development and ground compatibility on its own to assign broader planning value to land. A low susceptibility classification would not establish that a proposed development is compatible with site conditions or that approval is warranted. Similarly, a high susceptibility classification would not override cultural, community, heritage, or land access considerations or determine that a proposal should be refused. Instead, the susceptibility reading should be interpreted alongside the General Plan, Zoning By-law, applicable development schemes, servicing constraints, cultural heritage resources, community priorities, access to land, staff judgment, and place-based knowledge.

The framework therefore contributes one spatial layer showing permafrost hazard susceptibility layer to a broader planning process. It can help staff ask more informed questions about thaw related ground conditions, and determine whether additional technical information, or geotechnical review may be warranted. However, it should not narrow land use decision making to a technical classification alone. In Iqaluit, planning informed by permafrost conditions must remain connected to the broader meaning of land, including Inuit cultural values and knowledge, cultural heritage, access to Nuna, and community priorities.

3.6 Chapter Summary

This chapter established the policy and development review context in which the proposed Permafrost Hazard Susceptibility framework would operate. It demonstrated that Iqaluit already has an established municipal planning system shaped by growth and housing pressures, intensification objectives, climate resilience concerns, the General Plan, the Zoning By-law, the City's Planning and Development function, and a separate territorial building permit and code compliance stage. Within this setting, the proposed framework is positioned as a supplementary planning stage support tool rather than a replacement for existing planning instruments, staff judgment, studies submitted by applicants, or geotechnical review specific to individual projects.

The chapter also clarified where the framework would be most useful in the development review pathway. Its value lies in helping staff identify thaw related land concerns earlier, assess whether submitted technical or geotechnical information is adequate in relation to the site and proposal, and maintain a clearer spatial basis for staff comments, applicant revisions, and possible conditions. At later recommendation and decision stages, the GIS overlay may support the review record, but it remains one input among broader planning, technical, and discretionary considerations.

Finally, the chapter emphasized that development review in Iqaluit must be understood within an Inuit planning context. City policy recognizes Inuit cultural values and knowledge, culturally significant places, access to land, and traditional, cultural, and recreational land uses. A permafrost susceptibility classification should therefore not be treated as a complete measure of development and ground compatibility or used to determine broader planning value. It must be interpreted alongside the broader planning, cultural, community, and land-based considerations already embedded in the City's policy context.

Having established the policy setting and the intended municipal role of the framework, the thesis now turns to its technical foundation by reviewing the permafrost hazard processes and controls most relevant to planning scale assessment.

PART II: Literature Review

Chapter 4: Permafrost Hazard Processes and Controls Relevant to Planning

4.1 Introduction

This chapter reviews the thaw related hazard processes and controlling factors most relevant to the planning scale assessment of ground conditions in permafrost terrain. Its purpose is to establish the technical basis through which thaw related instability can be interpreted in a municipal planning context. The chapter distinguishes between two related questions: which processes generate thaw related hazards, and which controls determine how those hazards are expressed across the landscape. This distinction is important because in Iqaluit, the planning question is not primarily whether permafrost is present, but where differences in ground conditions may increase susceptibility to thaw settlement and associated instability, thereby warranting closer consideration during development review.

Permafrost behavior is governed by the interaction of frozen ground properties, climate forcing, surface and environmental conditions, and local disturbance. These controls do not operate independently. Soil type, ice content, cryostructure, and ground temperature establish the intrinsic susceptibility of the ground (Andersland and Ladanyi, 2004; French, 2017; Smith and Burgess, 2004), while snow cover, vegetation, slope, drainage, surficial geology, and changing climate influence how that susceptibility is expressed spatially and temporally (Smith and Burgess, 2004). Additional factors such as salinity, anthropogenic disturbance, and coastal processes may further intensify or redistribute thaw related instability in particular settings (Hivon and Sego, 1993; Smith and Burgess, 2004; Wang et al., 2023).

Figure 4.1 summarizes the process logic used in this chapter. Permafrost hazards relevant to planning emerge through a chain of interactions linking subsurface properties, climate and environmental modifiers, and local disturbance to specific ground response mechanisms. This process oriented perspective is important because it shifts attention away from permafrost as a simple binary condition and toward the pathways through which apparently similar sites may respond differently to development and climate change.

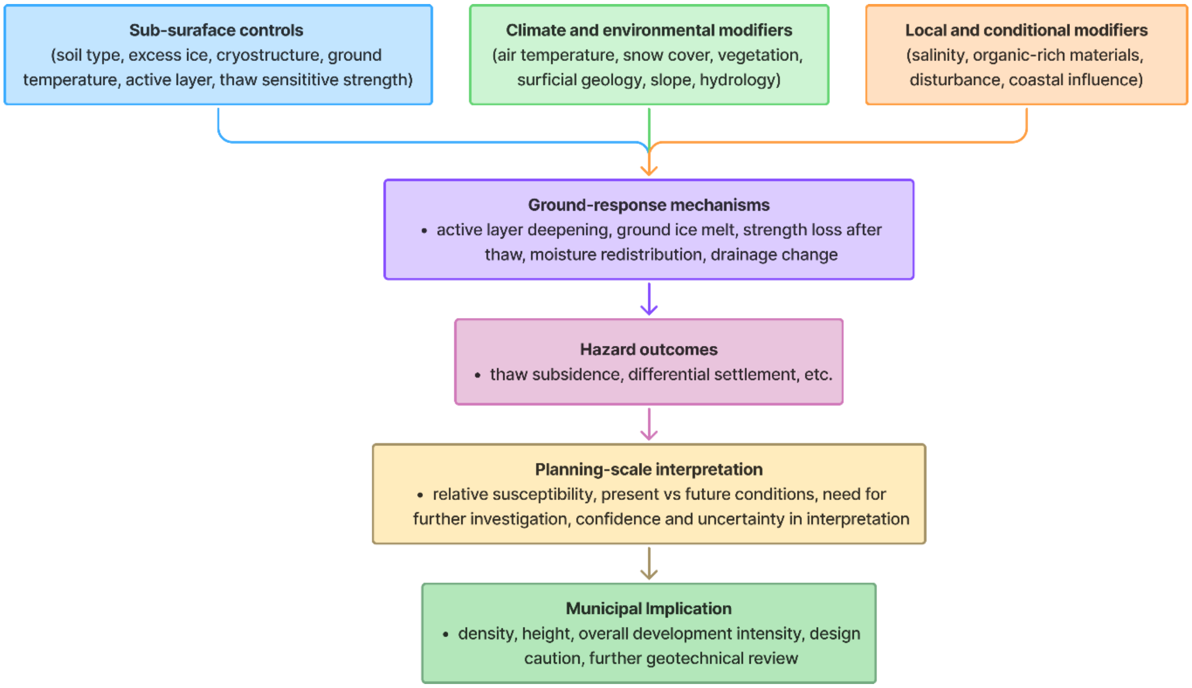

Figure 4.1. Hazard pathways linking permafrost controls to ground response mechanisms

4.2 Thaw-related Hazard Processes Relevant to Municipal Planning

In a planning context, the most important consideration is not merely that permafrost is present, but that frozen ground may change state or behavior over time. The transition from frozen to thawed conditions affects the volume, strength, stiffness, and drainage characteristics of the ground (Andersland and Ladanyi, 2004; Smith and Burgess, 2004). Where permafrost contains excess ground ice, this transition can produce deformation or instability large enough to affect buildings, linear infrastructure, and municipal service systems (Andersland and Ladanyi, 2004; Doré and Zubeck, 2009). Therefore, this section treats thaw settlement, including differential settlement as the principal ground deformation response, thaw induced reduction in soil strength and bearing capacity as an associated mechanical response and engineering consequence, and thermokarst as a terrain expression of thaw and irregular settlement (Harris et al., 1988; Smith and Burgess, 2004).

4.2.1 Thaw and differential settlement

Thaw settlement occurs when frozen ground containing excess ice thaws and loses volume as ice melts and water drains from the thawed ground (Smith and Burgess, 2004). The magnitude and rate of settlement depend on the amount and geometry of ground ice, the compressibility of the thawed soil skeleton, drainage conditions, and the rate and depth of thaw (Andersland and Ladanyi, 2004; French, 2017). In engineering terms, thaw settlement is especially important where ice rich fine-grained soils, organic deposits, or segregated ice lenses are present (Andersland and Ladanyi, 2004; Smith and Burgess, 2004). Even where total settlement is moderate, differential settlement across a building footprint may create serviceability problems, structural distortion, or utility damage (Smith and Burgess, 2004).

At the planning scale, thaw settlement matters because it is not uniformly distributed across a municipality. Terrain underlain by similar permafrost temperatures may behave differently depending on soil composition, excess ice, and surface conditions (Smith and Burgess, 2004). A municipal screening framework therefore needs enough information to distinguish areas where thaw is likely to produce minor deformation from areas where thaw may create substantial or uneven thaw settlement.

4.2.2 Thaw weakening and bearing capacity loss

Frozen soils often possess high apparent strength because ice bonds soil particles together and increases stiffness and shear resistance. When thaw occurs, those ice bonds weaken or disappear, and the ground may no longer support the same loading safely (Andersland and Ladanyi, 2004; Smith and Burgess, 2004). Where water released during thaw cannot drain rapidly, excess pore pressure may develop, reducing effective stress and shear strength. This response is referred to as thaw weakening (Harris et al., 1988). Thaw weakening may reduce the bearing capacity available to support building loads, embankments, or other imposed stresses; instability can occur if those loads exceed the reduced capacity of the ground (Andersland and Ladanyi, 2004; Harris et al., 1988). The problem may be especially acute in saturated silts, clays, and organic soils that become weak and compressible after thaw (Andersland and Ladanyi, 2004; Smith and Burgess, 2004).

For municipal planning, bearing capacity loss is important because it links the properties of the land to the characteristics of the proposed development. A site that may be acceptable for low intensity development may become problematic under a more heavily loaded or thermally disruptive proposal (Andersland and Ladanyi, 2004). This supports the thesis's later distinction between ground susceptibility to thaw settlement and proposal intensity.

4.2.3 Thermokarst

Thermokarst refers to the processes and characteristic landforms that result from the thaw of ice rich permafrost and subsequent settlement or collapse of the ground surface (Harris et al., 1988; Kokelj and Jorgenson, 2013). Recognized expressions include depressions, pits, mounds, ponding, thaw lakes, and hillslope features such as retrogressive thaw slumps (Harris et al., 1988; French, 2017; Kokelj and Jorgenson, 2013). Thermokarst is associated with ground containing abundant excess ice and may be initiated or accelerated by climatic warming, changes in drainage, or disturbances to the ground thermal regime (Harris et al., 1988; French, 2017).

From a municipal perspective, thermokarst is significant because it creates strong spatial variability and can transform local site conditions over time (French, 2017; Kokelj and Jorgenson, 2013). Thermokarst therefore represents an irregular and potentially evolving expression of thaw settlement that may affect site access, drainage, erosion, and long-term infrastructure reliability. Thermokarst features may be active or inactive, so their presence does not by itself establish continuing thaw or current subsurface conditions (Harris et al., 1988). They may nevertheless identify areas where assumptions of uniform ground support are inappropriate and closer investigation is warranted.

4.3 Subsurface Conditions Influence Thaw Related Ground Behavior

The hazard processes outlined above are governed first by the intrinsic properties of the ground. For the purposes of this thesis, these intrinsic properties are treated as subsurface controls on ground susceptibility to thaw settlement. They do not fully determine how a site will behave under all conditions, but they establish the underlying potential for thaw related deformation, strength loss, and instability.

Figure 4.2 summarizes the hierarchy of controls used in this chapter, distinguishing between subsurface controls, broader climate and environmental modifiers, and localized conditional modifiers. These control groups are discussed in Sections 4.3, 4.4, and 4.5, respectively.

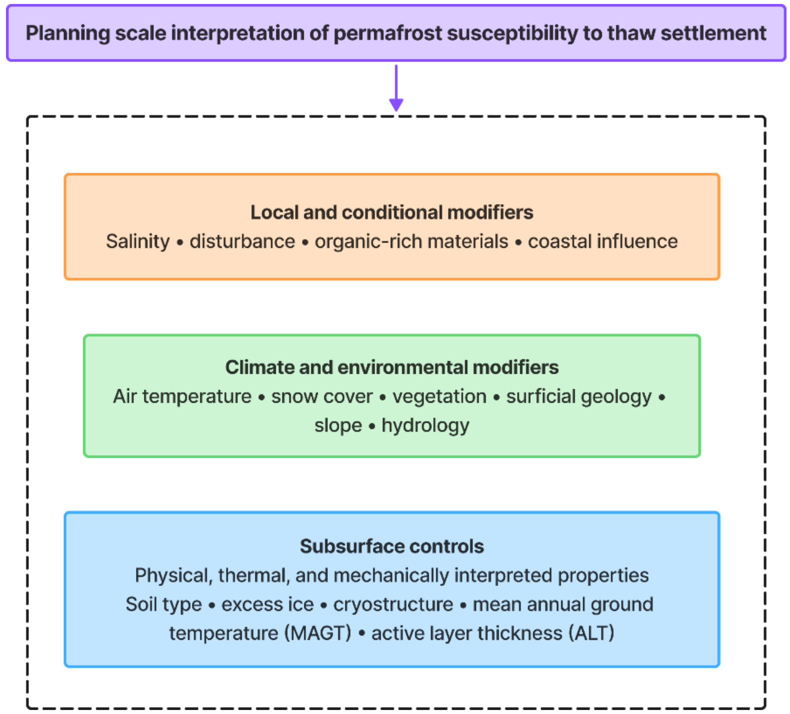

Figure 4.2. Conceptual hierarchy of subsurface controls, climate and environmental modifiers, and localized conditional modifiers used to interpret ground susceptibility to thaw settlement at the planning scale

4.3.1 Physical properties

Physical properties describe the material composition and internal structure of frozen ground. They include soil type, grain size distribution, plasticity, porosity and void ratio, water and ice content, cryostructure, depth to bedrock, and the thickness and arrangement of stratigraphic units. These properties influence permeability, the formation and distribution of ground ice, thaw compressibility, and the potential magnitude of thaw settlement (Andersland and Ladanyi, 2004; French, 2017).

Grain size is especially important because it affects ground ice formation and the response of the ground after thawing. Silts and very fine sands can sustain capillary water migration to a freezing front contributing to formation of segregated ice, while fine grained soils may also exhibit substantial settlement and strength loss after thaw depending on their structure, excess ice content and drainage conditions. Plasticity further affects thaw behavior by influencing water retention, compressibility, and the rate at which thawed soil consolidates under loading (Andersland and Ladanyi, 2004).

Excess ice content and cryostructure are among the most important physical controls on thaw settlement. The distinction between pore ice and excess ice, along with cryostructure and distribution of ice lenses and massive ice bodies is central to estimating the potential volume loss when a frozen layer thaws (Smith and Burgess 2004; French, 2017). In planning terms, this means that areas with similar surficial appearance may have very different settlement potential if their internal ice conditions differ. Where direct measurements of excess ice are unavailable, surficial geology and terrain history often serve as practical spatial proxies, supplemented by site-specific supporting evidence from available geotechnical records (Smith and Burgess, 2004; Oldenborger et al., 2022).

Depth to bedrock and the stratigraphic arrangement of frozen and unfrozen materials also matter. Shallow bedrock may reduce the thickness of deformable thaw sensitive sediments, while thick unconsolidated deposits can increase the zone over which thaw induced settlement may occur (Andersland and Ladanyi, 2004; French, 2017). At the planning scale, these variables are valuable because they help distinguish areas where thaw settlement is likely to be shallow and limited from areas where the ground profile contains a greater thickness of potentially deformable material.

These physical properties are typically characterized by borehole drilling, logging, sampling, and laboratory testing (Andersland and Ladanyi, 2004). At the municipal scale, however, direct subsurface data may not be available throughout the municipality. A planning scale framework must therefore use both direct geotechnical evidence and indirect spatial indicators to represent the physical component of ground susceptibility to thaw settlement. The objective is not to reproduce full site design information at the city scale, but to identify the physical factors most relevant to interpreting relative differences in that susceptibility.

4.3.2 Thermal properties

Thermal conditions and properties govern how heat enters, moves through, and is stored within frozen ground. Relevant thermal-state indicators include mean annual ground temperature and active-layer thickness, whereas material and phase-change properties include thermal conductivity, heat capacity, latent-heat effects, and unfrozen-water content near the freezing point.

Together, these variables influence the timing and depth of seasonal thaw and permafrost degradation over time, including whether thaw reaches ice-rich materials that are susceptible to settlement (Andersland and Ladanyi, 2004; Romanovsky et al., 2010).

Ground temperature is a particularly important integrative indicator because it reflects both regional climate and local site conditions (Smith and Burgess 2004; Romanovsky et al., 2010). Permafrost that is already warm and close to its freezing point generally has less thermal buffer against thaw than colder permafrost. As a result, environmental or anthropogenic changes can more readily induce warming or thaw in warm permafrost terrain. Active layer thickness is similarly significant. Because the active layer marks the zone of annual thaw, increases in its thickness indicate deeper seasonal penetration of thaw may increase the likelihood that underlying ice-rich layers will be affected (AMAP, 2017).

Thermal conductivity and heat capacity influence the rate at which ground responds to atmospheric forcing, vegetation change, snow accumulation, and development related heat inputs. Because thermal conductivity and heat capacity vary with mineralogy, density, and water and ice content, different materials transmit and store heat differently. The latent heat required to melt ground ice means that heat can be absorbed during phase change without a corresponding rise in temperature, complicating any simple relationship between temperature and thaw depth (Andersland and Ladanyi, 2004. These factors help explain why air temperature alone is not a sufficient for assessing permafrost thaw related hazard (Smith and Burgess, 2004). In practice, the thermal response of the ground is mediated by both intrinsic properties and surface conditions.

For municipal planning, thermal properties are important because they connect present conditions with future change. A planning framework concerned only with current ground conditions would miss the fact that permafrost temperature and thaw depth can change under continued warming or altered surface cover, potentially exposing ice-rich material to thaw (AMAP, 2017). Thermal information therefore supports a dynamic interpretation of ground susceptibility to thaw settlement.

4.3.3 Mechanical properties

Mechanical properties describe the strength, stiffness, deformation characteristics, and time dependent response of frozen and thawing ground. In frozen soils, ice acts as a cementing agent that can substantially increase compressive strength, shear resistance, and stiffness. These properties are highly temperature-dependent: as temperature decreases, frozen soils are generally stronger and brittle, while near the freezing point, they become weaker, more deformable, and more sensitive to loading duration and strain rate (Andersland and Ladanyi, 2004).

One of the most significant features of frozen soil mechanics is creep. Under sustained loading, frozen soils may deform progressively over time even without full thaw. This time dependent behaviour becomes especially important in warm permafrost, under heavy structures, or where thermal changes gradually reduce stiffness and strength (Andersland and Ladanyi, 2004). Once thaw occurs, the mechanical contrast between the frozen and thawed states can be substantial, with marked losses in bearing capacity and increased compressibility and potential for settlement (Andersland and Ladanyi, 2004). Mechanical behaviour therefore provides the bridge between geotechnical description and infrastructure performance.

In a municipal scale framework, mechanical properties are often more difficult to map directly than physical or thermal variables because their characterization generally requires laboratory or field testing, while their engineering significance depends on site-specific loading conditions (Andersland and Ladanyi, 2004). For that reason, they are best understood as interpretive controls rather than as complete standalone spatial layers. Their role in the present thesis is to inform how physical and thermal conditions are translated into planning relevant hazard pathways. In other words, mechanical properties help explain why certain combinations of soil type, ice content, temperature, and moisture are likely to matter more than others when considering how ground conditions may respond to different forms and intensities of development.

4.4 Climate and Environmental Modifiers

The subsurface controls described above establish the underlying potential for thaw-related ground deformation, strength loss, and instability, but they do not fully explain why thaw related behavior varies across the landscape. That variability is shaped by climate and environmental modifiers, which influence the surface energy balance, moisture regime, snow distribution, and terrain response (Smith and Burgess, 2004; AMAP, 2017). For municipal planning, these modifiers are valuable because many can be represented spatially through climate products, digital elevation models, surficial mapping, aerial imagery, and remote sensing.

4.4.1 Air temperature and climate forcing

Air temperature is the primary climatic driver of the ground thermal regime. Long term warming trends influence mean annual ground temperature, thawing and freezing degree days, active layer thickness, and the persistence of ground ice. Across the Arctic, permafrost warming and active layer deepening have been widely documented, although the local response varies depending on soil properties and surface conditions (Romanovsky et al., 2010; AMAP, 2017; IPCC, 2021). For planning purposes, the key implication is that the potential for permafrost thaw and associated ground impacts may change over time. The same site may present different levels of concern under present and projected climate conditions.

Air temperature, however, is not a sufficient standalone indicator. Ground response depends on how atmospheric forcing is filtered through snow, vegetation, surface moisture, and soil thermal properties (Smith and Burgess 2004; AMAP, 2017). Nevertheless, climate forcing remains essential because it provides the broader trajectory within which local modifiers operate. In a municipal framework, temperature related information is therefore most useful when treated as a scenario-based modifier rather than as a single static input.

4.4.2 Snow cover

Snow cover is one of the most influential surface controls on the permafrost thermal regime because it acts as an insulating layer between the atmosphere and the ground. Thick or persistent snow cover can reduce winter heat loss from the ground and result in warmer subsurface conditions than would be expected from air temperature alone (Smith and Burgess, 2004; AMAP, 2017). Conversely, thin or wind scoured snow cover may allow stronger winter cooling and colder ground temperatures.

The planning relevance of snow cover extends beyond regional climate. In built areas, snow distribution is shaped by buildings, fences, roads, grading, snow clearing practices, and drifting (Andersland and Ladanyi, 2004; Doré and Zubeck, 2009). As a result, development itself can create localized thermal contrasts by concentrating snow in some areas and removing it from others. This means that snow cover functions not only as a climate variable but also as a development sensitive modifier. A planning scale framework should therefore treat snow as a critical control on local ground temperatures and the potential for permafrost thaw in developed and developing areas.

4.4.3 Precipitation and moisture regime

Precipitation influences permafrost through its effects on snow accumulation, surface wetness, infiltration, and runoff. Rainfall and snowmelt can enhance heat transfer to the ground, increase pore water availability, and alter drainage pathways, while saturated conditions may intensify settlement, erosion, and strength loss after thaw. In some cases, changing precipitation regimes also interact with thermokarst and ponding to create feedback that further accelerates degradation (French, 2017; Wang et al., 2023).

In municipal planning, moisture regime is especially relevant because it is closely tied to site grading, drainage design, and stormwater management. Locations prone to ponding, concentrated flow, or poor drainage may experience more pronounced thaw-related ground deformation or instability than nearby better drained terrain. The importance of precipitation therefore lies not only in its total amount, but also in its timing, intensity, and form as rain or snow, which influence seasonal ground-moisture conditions.

4.4.4 Vegetation and surface organic cover

Vegetation and organic surface materials influence permafrost through shading, evapotranspiration, wind sheltering, snow trapping, and thermal insulation. Organic layers and peat can reduce heat transfer to underlying mineral soil, while vegetation cover can moderate summer warming and affect snow retention in winter (Smith and Burgess, 2004; French, 2017). When vegetation or organic cover is disturbed or removed, ground temperatures often increase, and the active layer may deepen.

This is highly relevant to urban growth because development commonly involves clearing, grading, and replacement of natural cover with gravel, pads, roads, or buildings. In planning terms, vegetation should therefore be understood both as an indicator of existing conditions and as a variable that may change with development. Remote sensing products can provide useful spatial information on vegetation cover, but their interpretation should remain linked to underlying thermal and hydrological processes rather than being treated as a simple land cover category.

4.4.5 Surficial geology

Surficial geology is an important bridge between direct geotechnical observations and planning scale spatial interpretation. It provides information on the origin, texture, and likely ground ice conditions of near-surface materials and is therefore widely used as a proxy input in permafrost mapping and studies of thaw-related ground response (Smith and Burgess, 2004; Oldenborger et al., 2022). Marine sediments, glaciomarine deposits, alluvium, colluvium, till, and bedrock each imply different moisture, grain size, and cryogenic histories that affect thaw behaviour.

At the municipal scale, surficial geology is often one of the most practical ways of extending sparse borehole information across a broader area. It does not replace direct site investigation, but it can help identify neighbourhoods or landforms where similar subsurface conditions are more likely to recur. For this reason, surficial geology is a key input in planning scale interpretation of thaw-related ground deformation and instability.

4.4.6 Topography, slope, aspect, and microrelief

Topography influences permafrost conditions and thaw-related ground behaviour by affecting solar exposure, snow redistribution, drainage, runoff concentration, and slope stability. Slope angle can affect how quickly water drains or remains on a site, while aspect refers to the compass direction a slope faces. Aspect can influence radiation balance because slopes facing different directions may receive different amounts of solar energy, which can affect snow persistence, surface moisture, and ground temperature. Microrelief refers to small scale variations in the ground surface, such as shallow depressions, hummocks, ridges, or uneven terrain, that can influence ponding, snow retention, and localized thaw or frost processes (French, 2017; Oldenborger et al., 2022).

From a planning perspective, topographic information is especially useful because it is widely available from digital elevation models and can be mapped continuously across a municipality. However, its significance depends on the local context. In some areas, slope may matter primarily as a drainage and erosion modifier; in others, it may also indicate terrain that is more prone to thaw slumping or uneven settlement. The key point is that topography modifies how underlying ground conditions influence thaw-related deformation and instability; it does not replace subsurface evidence.

4.4.7 Hydrology and surface water

Hydrology strongly influences permafrost through surface water storage, groundwater movement, drainage connectivity, and the thermal effects of open water. Wet ground and high active-layer water content can prolong freeze-back and maintain warmer ground, while drainage conditions influence where water accumulates or is removed from a site (LeBlanc and Oldenborger, 2021). More broadly, ponding and drainage change can modify local thaw conditions and interact with thermokarst and erosion in ice-rich terrain (French, 2017; Wang et al., 2023).

For municipal planning, hydrology matters because it connects natural terrain processes with infrastructure design decisions. Culverts, ditches, road embankments, filled areas, and altered runoff paths can all change local moisture and thaw behaviour (Doré and Zubeck, 2009). A planning scale framework should therefore treat hydrology as a central modifier of the potential for permafrost thaw and associated ground impacts, especially where development may alter drainage patterns or where current terrain already shows evidence of ponding and wetness.

4.5 Additional Local and Conditional Modifiers

Not all relevant controls operate as universal municipal scale layers. Some are highly important where present but spatially limited, episodic, or strongly dependent on the local context. In this chapter, these are treated as additional local and conditional modifiers. Their significance lies in the fact that they may intensify thaw-related ground impacts or alter the interpretation of areas that otherwise appear similar based on subsurface controls and broader climate and environmental modifiers.

4.5.1 Salinity and pore water chemistry

In coastal and glaciomarine environments, saline pore water can depress the soil freezing point and allow substantial unfrozen water to persist below 0 °C (Hivon and Sego, 1993; Lyu et al., 2025). Salinity therefore alters ice formation, thermal behaviour, and thaw response. In the simulations reported by Lyu et al. (2025), non-saline permafrost temperatures increased more rapidly, whereas saline permafrost exhibited a more pronounced thawing rate because of its lower freezing point and associated latent-heat consumption.

For planning scale work, salinity is rarely available as a continuous municipal dataset, but it may be inferred from geological setting, coastal history, or site investigation records. It is therefore best treated as a targeted modifier or investigation trigger.

4.5.2 Organic rich materials and post thaw decomposition

Organic rich soils and peat influence are relevant not only through their thermal properties but also through their post thaw behaviour. This differs from the surface organic cover discussion in Section 4.4.4: here the focus is on organic rich deposits as thaw sensitive materials, not only on their role as surface insulation. Once thawed, these materials may undergo substantial consolidation and over longer periods, decomposition and structural loss. Settlement may therefore continue after the initial thaw as water drains from the soil and the thawed organic material compresses and decomposes (Andersland and Ladanyi, 2004; French, 2017). In planning terms, organic rich deposits may therefore present both a combination of immediate and delayed settlement concerns.

Where mapped peatlands or organic deposits are present, they should receive explicit attention in an assessment of ground susceptibility to thaw settlement. Where such units are absent or only locally significant, they may be treated as contextual modifiers rather than study area wide controls.

4.5.3 Disturbance and land cover modification

Disturbance is especially important because many permafrost-thaw related hazards are intensified by the act of development itself. Clearing vegetation, removing organic cover, altering drainage, adding fill, changing snow distribution, or introducing building heat can modify the ground thermal regime and moisture balance. Smith and Riseborough (2010) showed that right-of-way disturbance can alter permafrost conditions beyond the infrastructure footprint, while Li et al. (2021) reviewed evidence of long-lasting permafrost degradation following forest fires.

This has direct relevance to municipal planning. Disturbance is not simply a background variable to be mapped after the fact; it is part of the mechanism through which planning decisions affect future ground response. Existing disturbed land can be mapped from aerial imagery and land use information (Wang et al., 2023), but future disturbance also depends on the form and intensity of a proposed development. For that reason, disturbance is an important bridge between the ground-condition assessment developed in this chapter and the proposal-screening logic developed later in the thesis.

4.5.4 Coastal and marine influence

In Arctic coastal communities, shoreline processes introduce an additional set of hazards that can interact with permafrost degradation. Coastal erosion, thermal abrasion (erosion caused by wave action against frozen coastal sediments), flooding, storm surge, tidal exposure, and seawater contact may accelerate thaw, remove support from ice rich sediments, or create compound hazards along waterfront zones (French, 2017; Hatcher and Forbes, 2015). Hatcher and Forbes (2015) show that coastal hazards are directly relevant to Iqaluit, where coastal processes, sediment conditions, and tidal setting matter for urban adaptation planning.

Because coastal influence is spatially concentrated, it should generally be represented through targeted overlay zones or area specific modifiers rather than merged indiscriminately into a study area wide base assessment. Its relevance to the present research lies in demonstrating that some planning areas may require a compound interpretation that combines thaw-related ground deformation or instability with shoreline erosion and flooding.

4.6 Chapter Summary

The literature reviewed in this chapter suggests that the potential for thaw-related ground deformation and instability at the planning scale is best understood as the product of three nested levels of control. The first level is the subsurface condition of the ground, defined by physical, thermal, and mechanical properties such as soil type, excess ice, cryostructure, ground temperature, active layer thickness, and changes in strength and stiffness following thaw. The second level consists of climate and environmental modifiers, including air temperature, snow, moisture regime, vegetation, surficial geology, topography, and hydrology, which influence where, when, and how this underlying potential is expressed across the landscape. The third level consists of local and conditional modifiers such as salinity, organic rich deposits, disturbance, and coastal influence, which may intensify ground impacts or require separate interpretation in particular settings.

Figure 4.2 introduced this conceptual hierarchy earlier in the chapter. Table 4.1 now translates the same hierarchy into a planning scale evidence framework by identifying the principal hazard relevance of each control family and the forms of evidence most likely to support assessment.

Table 4.1. Control groups, hazard relevance, and evidence

Control family	Illustrative indicators	Main hazard relevance	Typical evidence or spatial proxy
Subsurface controls	Soil type, grain size, excess ice, cryostructure, ground temperature, active layer, thaw sensitive strength	Defines intrinsic susceptibility to thaw settlement, bearing capacity loss, frost heave, and thermokarst	Boreholes, logs, samples, laboratory tests, temperature monitoring
Climate and environmental modifiers	Air temperature, snow cover, vegetation, surficial geology, slope, hydrology, moisture regime	Modifies the spatial and temporal expression of intrinsic susceptibility under current and future conditions	Climate grids, remote sensing, aerial imagery, DEMs, surficial maps
Local and conditional modifiers	Salinity, organic rich materials, disturbance, coastal and marine influence	Intensifies or complicates local thaw response and	Targeted studies, site history, special

	may create compound or area specific hazards	overlays, coastal hazard zones

In practical terms, this chapter supports three conclusions that are central to the chapters that follow. First, a defensible planning scale assessment must begin with subsurface evidence; environmental and climate information cannot substitute for direct or interpreted information about ground conditions. Second, a purely subsurface view is insufficient because surface and climatic controls modify where, when, and how thaw-related ground impacts may develop under present and future conditions. Third, some locally significant processes require conditional treatment rather than blanket inclusion in a single generalized score.

These conclusions provide the technical foundation for the next stage of the thesis. Having established the principal hazard processes and controls relevant to municipal development, the following chapter examines how existing hazard mapping approaches, standards, guidance documents, and planning tools currently organize this knowledge, and where important gaps remain at the municipal planning scale.

Chapter 5: Existing Approaches to Permafrost Hazard and Susceptibility Mapping

5.1 Introduction

Building on the hazard processes and controlling factors reviewed in Chapter 4, this chapter examines existing approaches used to map permafrost conditions and ground hazards associated with permafrost thaw. Chapter 4 explained how climate forcing interacts with ground ice, surficial materials, terrain, drainage, snow conditions, and surface disturbance to influence the likelihood and physical consequences of thaw. This chapter shifts from that physical understanding to how these conditions and relationships have been represented spatially, combined into classifications, and used in mapped assessments. The purpose is to identify the elements of existing approaches that can inform a planning-scale framework for assessing the susceptibility of land in the populated area of Iqaluit to thaw-related permafrost hazards.

The approaches reviewed in this chapter can be grouped into several broad and sometimes overlapping categories. These include climate sensitivity and early hazard zonation, indicator- and index-based hazard and susceptibility mapping, mapping observed ground deformation and predicting thaw sensitivity, process models linking climate warming to ground and infrastructure response, and integrated mapping for communities and infrastructure. Studies that extend hazard and susceptibility mapping to exposure, vulnerability, or risk are considered only where they help distinguish between these different assessment endpoints. These broader dimensions are not included in the thesis, which focuses on the susceptibility of land. The approaches differ in the endpoint assessed, spatial scale and resolution, intended users, input data, analytical and classification methods, validation procedures, treatment of climate change and uncertainty, and type of output. Despite these differences, they provide a useful methodological basis for this research.

No single approach was developed for the exact purpose of this thesis, that is, to support planners by assessing the relative susceptibility of land in populated Iqaluit to ground hazards associated with permafrost thaw, translating the results into an interpretable municipal GIS overlay, and linking the resulting classes to the early stages of development review. The review therefore examines what each approach contributes and how it defines the assessment endpoint, selects and combines indicators, establishes classes and thresholds, represents current and future conditions, validates results, and communicates uncertainty. Comparing the approaches in this way helps identify which elements can be adapted for the framework developed later in the thesis and where important limitations remain.

Figure 5.1 shows how these methodological approaches relate to one another. It also shows how lessons from the reviewed approaches inform the present framework, while making clear that no single approach provides all the elements needed to assess land conditions, classify susceptibility transparently, communicate uncertainty, and support the early screening of development proposals in Iqaluit.

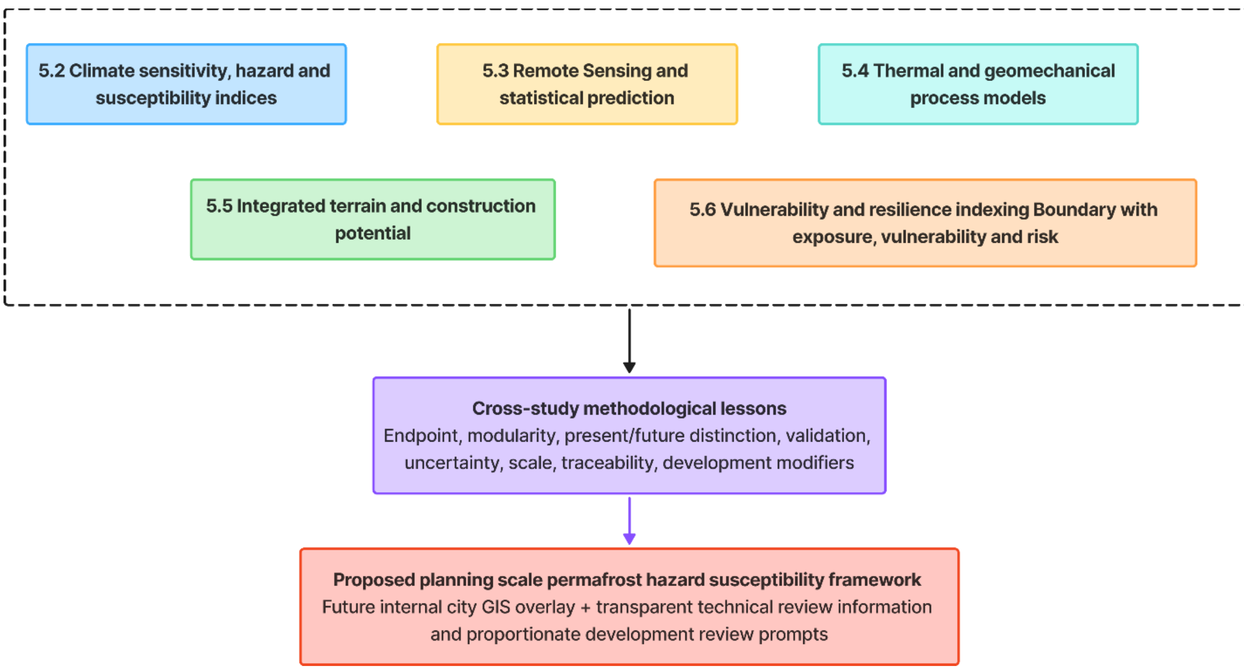

Figure 5.1. Existing permafrost mapping and assessment approaches reviewed in Chapter 5 and the methodological lessons informing the proposed planning-scale framework

5.2 Climate Sensitivity, Hazard Zonation and Susceptibility Indices

Early permafrost mapping approaches sought to identify where climate warming could produce the greatest changes in permafrost conditions and where those changes could lead to damaging ground responses. Across this literature, terms such as *sensitivity*, *hazard*, *susceptibility*, and *risk* are used to describe different assessment endpoints. Some approaches focus on the thermal response of permafrost to warming, some estimate the potential for thaw settlement, and others combine climate, terrain, and ground-ice indicators into composite indices. This section examines how each approach defines the condition being mapped, selects and combines indicators, and translates the results into spatial classifications.

5.2.1 National climate sensitivity mapping

Smith and Burgess (2004) developed one of the earliest national assessments of permafrost sensitivity to climate warming in Canada. The study examined the relative sensitivity of existing permafrost during the transition towards a warmer climate. Sensitivity was conceptualized as having two related but distinct components, the thermal response of permafrost and the physical response of the ground.

The thermal component considered the existing thermal state of permafrost and the degree to which surface conditions could buffer the ground against changes in atmospheric temperature. Snow cover, vegetation, the surface organic layer, and the thermal properties of mineral soil were treated as controls on the rate and magnitude of ground temperature change. Warm permafrost was generally considered more thermally sensitive because relatively little additional warming would be required to bring it to the thawing point. The study also recognized that surface conditions could strengthen or weaken the relationship between air temperature and ground temperature.

The physical response component represented the relative potential for thaw settlement once ground ice melted. Because a consistent national dataset describing excess ground ice was unavailable, surficial geology and peatland occurrence were used as proxies. Bedrock, colluvium, and coarse-textured sediments were generally assigned a low potential physical response. Till and alluvial sediments were assigned a moderate response, while fine-textured and organic sediments were assigned a higher response. Smith and Burgess also noted that locally occurring massive ice could produce severe settlement within terrain assigned a lower regional class.

The thermal and physical components were combined at a spatial resolution of approximately 10 km. Physical response was given greater importance than thermal response in the final low, moderate, and high sensitivity classification.

The study is particularly useful to the present research because it separates permafrost warming from the physical consequences of thaw. A location may contain thermally sensitive permafrost but experience limited settlement where bedrock or coarse, well-drained materials predominate. Conversely, ice-rich sediments may have substantial ground response potential even where the existing permafrost is relatively cold. This distinction is relevant to Iqaluit, where bedrock, thin sediment cover, and thicker deposits containing ground ice can occur within a comparatively small area. The separation of thermal response from physical ground response therefore provides an important conceptual basis for the framework developed later in the thesis.

5.2.2 Circumpolar thaw settlement hazard zonation

Nelson et al. (2002) developed a circumpolar approach to represent the potential effects of permafrost degradation on infrastructure and human activities. The study formulated a settlement index as:

$$I_s = \Delta z_{ALT} \; X \, V_{ICE}$$

where Δz_{ICE} represents the relative increase in active layer thickness and V_{ICE} represents the volumetric proportion of near-surface ground ice. The formulation assumes that meltwater can drain and that settlement is approximately proportional to the volume of ice lost from the thawed layer.

Changes in active layer thickness were estimated using the Kudryavtsev analytical solution and climate projections from general circulation models. The calculations were implemented on a 0.5º x 0.5º circumpolar grid. The resulting settlement index values were logarithmically transformed and classified using nested means into stable, low, moderate, and high hazard classes. Infrastructure and human activities were then overlaid on the physical hazard surface to identify areas of potential concern.

The approach connects a change in active layer thickness to the amount of ground ice contained within the affected material. It therefore represents settlement as the interaction between a thaw forcing variable and a ground response variable. This is an important methodological contribution because active layer deepening is more likely to produce substantial settlement where the newly thawed material contains sufficient ground ice.

The infrastructure overlays also show how a physical hazard surface can be considered separately from the location of infrastructure and human activity. This distinction is relevant to the present thesis because the proposed framework focuses first on the susceptibility of land. Exposure, vulnerability, and risk can then be considered separately where information about buildings, infrastructure, and their consequences is available.

5.2.3 Multi-criteria permafrost settlement hazard indices

Hong et al. (2014) developed a Permafrost Settlement Hazard Index for Alaska using six indicators: ground ice volume, air temperature, soil texture, snow depth, vegetation, and soil organic content. Each indicator was standardized on an ordinal scale from one to five and weighted using the analytic hierarchy process (AHP). Ground ice received the largest weight of 0.44, reflecting its dominant influence on settlement after thaw. The weighted indicators were combined to produce current and projected hazard maps for 2050.

The study found comparatively high settlement hazard in parts of discontinuous permafrost Alaska and projected increases across portions of northern and northwestern Alaska. Some areas received lower future index values where near-surface permafrost was projected to disappear. Within the structure of the index, these lower values reflect the way continuing permafrost settlement hazard was represented after the modelled near-surface permafrost had thawed.

The analytic hierarchy process provides a structured method for translating variables measured in different units into a common ordinal scale. It also makes the relative importance assigned to each indicator explicit through the weighting process. The resulting classified map provides a single spatial output that can be interpreted more readily than the individual environmental datasets.

For the present thesis, Hong et al. provide a useful example of how climate, ground ice, soil properties, snow, vegetation, and organic content can be combined within one index. The approach also demonstrates the importance of retaining the individual indicators and documenting how expert judgement enters the weighting process. These elements are important where a final susceptibility class must remain traceable to the conditions that produced it.

5.2.4 Circumpolar permafrost and multi-index geohazard mapping

Karjalainen et al. (2019) developed a detailed circumpolar dataset containing seven permafrost maps and 24 geohazard maps. The study assembled 797 mean annual ground temperature observations and 303 active layer thickness observations for land areas north of 30ºN. Baseline conditions represented the period from 2000 to 2014 and were mapped at a resolution of 30 arcseconds, or approximately 1-kilometre scale, although the east-to-west cell width decreases with latitude.

Mean annual ground temperature (MAGT) was predicted using an ensemble of generalized linear, generalized additive, generalized boosted, and random forest models. Active layer thickness (ALT) was predicted using a generalized linear model. Predictors included freezing and thawing degree days (FDD, TDD), precipitation occurring above and below 0°C, potential incoming solar radiation, and soil organic carbon. Water body coverage was also included in the ground temperature models. Future conditions were projected for 2041-2060 and 2061-2080 under three representative concentration pathways RCP2.6, RCP4.5, and RCP8.5.

Four geohazard indices were derived:

- The settlement index, (Is), reproduced the Nelson et al. formulation by multiplying relative active layer increase by volumetric ground ice content.
- The risk zonation index, (Ir), adapted the procedure developed by Daanen et al. It differentiated bedrock from sediment, distinguished fine and coarse materials, and incorporated a thermal criterion related to modelled near-surface permafrost thaw.
- The analytic hierarchy process index, (Ia), combined ground temperature, ground ice content, relative active layer increase, fine sediment occurrence, and slope. The reported weights were 0.525, 0.248, 0.122, 0.071, and 0.035, respectively.
- The consensus index, (Ic), assigned the majority class from the three preceding indices. Where all three indices disagreed, the cell was assigned moderate hazard.

The statistical models were evaluated using spatially blocked cross-validation and hindcasting against earlier observations. Model performance was strong for mean annual ground temperature, with reported baseline explanatory performance of approximately (R^2 = 0.95). Performance was lower for active layer thickness, with approximately ($R^2 = 0.37$) for the baseline model. This difference reflects the difficulty of representing the fine-scale snow, vegetation, soil moisture, and microtopographic conditions that influence active layer thickness across a circumpolar dataset.

Karjalainen et al. (2019) make two particularly important methodological contributions. First, the study compares several index formulations derived from the same general set of permafrost and environmental data. Second, it maps the areas in which the different formulations agree or disagree. This makes it possible to examine how the selected conceptual model influences the resulting hazard pattern.

For the present thesis, the study demonstrates how explicit climate scenarios, spatial validation procedures, multiple index formulations, and mapped model disagreement can be incorporated into a geohazard assessment. Model disagreement is particularly relevant because it can identify locations where the assigned class is sensitive to the way indicators are selected and combined.

5.2.5 Multi-index integration along the Qinghai-Tibet railway

Ni et al. (2021) evaluated thaw settlement hazard across the permafrost regions of the Qinghai–Tibet Plateau, with particular relevance to the Qinghai-Tibet Railway. The study calculated three indicators representing settlement potential, risk zonation, and allowable bearing capacity, and then produced an integrated consensus classification.

The three indices generated substantially different spatial patterns. Their integration was intended to reduce reliance on any one formulation and identify areas that were repeatedly classified as susceptible. Under RCP4.5 for 2061-2080, 45.38% of the assessed area was classified as low hazard, while more than 40% was classified as moderate or high hazard. Areas near the existing permafrost boundary were particularly prominent because the thermal state of permafrost in these areas was more responsive to future warming. Ground ice remained a critical control on the spatial distribution of settlement potential.

The study shows how several indicators can be calculated separately before being brought together in a consensus classification. Comparing the individual outputs makes it possible to identify areas where the different methods produce similar classifications and areas where the results depend more strongly on the selected indicator.

This approach is relevant to the framework developed in this thesis because it supports the comparison of alternative formulations during model development. It also demonstrates how disagreement among indicators can be retained as information about uncertainty rather than removed during the production of a single final map.

5.2.6 Mapping inherent thaw settlement susceptibility

Mohammadi and Hayley (2023) developed a qualitative Thaw Settlement Potential Index for Canadian permafrost terrain. Their approach focused on the inherent susceptibility of frozen ground to settlement if thaw occurs. The index used three factors: excess ground ice, surficial deposit type, and bedrock type. Analytic hierarchy process weights of 0.78, 0.15, and 0.07 were assigned to the three factors, respectively.

This formulation gives dominant importance to excess ground ice, consistent with its direct influence on thaw strain. Surficial deposits provide information about material texture and expected consolidation behaviour, while bedrock is assigned relatively low settlement potential. The output is a relative qualitative classification of ground response potential under thaw conditions.

The approach is useful because it provides a clear assessment endpoint. It represents the relative susceptibility of the ground based on the materials and ground ice conditions present. Thermal forcing can then be represented through a separate component when the index is used within a broader hazard assessment.

This modular structure is especially relevant to Iqaluit. A baseline ground susceptibility layer can be developed from excess ground ice, surficial materials, and bedrock conditions, while changes associated with future climate conditions can be represented in a separate layer. The two components can then be considered together without implying that existing ground susceptibility and projected thaw forcing represent the same physical process.

5.2.7 Critical assessment

The studies reviewed in this section represent several related but distinct assessment endpoints. Smith and Burgess (2004) separated the thermal response of permafrost from the physical response of the ground. Nelson et al. (2002) represented settlement potential through the interaction between relative active layer increase and ground ice. Hong et al. (2014) combined climate, ground, and surface indicators within a weighted index. Karjalainen et al. (2019) and Ni et al. (2021) compared several index formulations, while Mohammadi and Hayley (2023) focused on the inherent susceptibility of frozen ground to settlement if thaw occurs. These approaches demonstrate that the condition being assessed must be defined clearly before indicators are selected and combined.

One recurring methodological choice is whether thermal forcing and physical ground response should be included within one index or represented separately. Combining the two can produce a single classified output, but the final class may reflect several different processes. A high class may result from warm permafrost, substantial ground ice, fine-textured materials, increased active layer thickness, or a combination of these conditions. A modular approach provides a clearer interpretation because the existing susceptibility of the ground and the potential for future thaw can be examined separately before being brought together.

Scale and data resolution are also important. The reviewed national and circumpolar approaches were developed using grid sizes ranging from approximately one (1) kilometre to ten (10) kilometres, while some of the input data were mapped at even coarser resolutions. These scales are useful for identifying broad regional patterns, but they cannot consistently represent the local variation in bedrock, sediment thickness, ground ice, drainage, snow accumulation, and surface disturbance at a municipal scale.

Ground ice information remains a particular challenge. Several approaches use surficial geology, peatland occurrence, or broad volumetric ground ice categories as proxies for settlement potential. These indicators provide useful regional information, but they may not identify localized segregated ice, ice wedges, or buried glacial ice. They may also combine pore ice and excess ice even though the two have different implications for thaw settlement. For a planning-scale framework, the source, resolution, and interpretation of ground ice information must therefore be communicated clearly.

Composite indices introduce additional decisions concerning standardization, weighting, classification thresholds, and the way indicators interact. The analytic hierarchy process makes expert judgement more explicit, but different weights can produce different spatial patterns. Ordinal scoring can also allow a low value in one indicator to be offset by higher values in others, even where the physical relationship is conditional. For example, substantial settlement requires both thaw and the presence of material capable of losing volume after thaw.

The treatment of active layer change also affects the resulting classification. Relative active layer increase can produce high index values where the initial active layer is thin, even when the absolute increase is limited. Future index values may also decrease in areas where near-surface permafrost is projected to disappear. These results describe the endpoint used by the index and must be interpreted in relation to the earlier period of thaw and ground adjustment.

5.3 Remote Sensing and Statistical Prediction

Remote sensing and statistical prediction approaches differ from the indicator and index-based mapping approaches reviewed in Section 5.2 because they use observed surface behaviour or empirically derived relationships to characterize thaw sensitivity. These approaches can provide direct evidence of ground movement, extend observed relationships into unmapped areas, and support projections under future climate conditions. Observed deformation, predicted thaw sensitivity, and future thaw threat nevertheless represent different assessment endpoints. This section examines how each approach defines the condition being assessed, uses observations and predictor variables, and produces spatial information that may inform the proposed framework.

5.3.1 DinSAR measurement at Iqaluit airport

Short et al. (2014) applied RADARSAT-2 differential interferometric synthetic aperture radar, or DInSAR, to measure seasonal ground displacement at Iqaluit Airport. The study compared remotely sensed displacement with surficial geology, known permafrost features, and field measurements. Spatial patterns in the interferograms corresponded with differences among terrain materials and revealed localized features associated with ice wedges and frost cracking. At dry comparison sites, the DInSAR results showed subcentimetre consistency with ground-based measurements.

The study demonstrates that satellite observations can detect spatially variable ground movement within Iqaluit. It also provides empirical evidence that terrain units and subsurface ice conditions can produce different deformation responses over relatively short distances. The DInSAR measurements represent relative displacement along the satellite line of sight during the observation period, providing an observational record of where movement was occurring and how it varied across the airport area.

For the present research, this study provides a direct Iqaluit example of how observed deformation can support a susceptibility framework. DInSAR can be used to compare mapped terrain classes with observed behaviour, identify areas that may require field investigation, and support future updates as longer displacement records become available.

5.3.2 Neural network prediction of thaw sensitivity

Oldenborger et al. (2022) developed a supervised neural network approach for predicting permafrost thaw sensitivity near Rankin Inlet, Nunavut. A reference classification was created through a process-informed interpretation of DInSAR seasonal subsidence, ground temperature, active layer, and ground ice conditions. A multilayer perceptron then predicted the reference classes using surficial geology, high-resolution topography, and multispectral imagery.

The resulting model classified terrain into low, medium, high, and very high thaw sensitivity. Using a spatially dispersed training dataset, the model achieved a generalized accuracy of 70.8%. When the classification was simplified to a binary distinction between stable and unstable terrain, accuracy increased to 81.8%. High and very high sensitivity classes were comparatively uncommon and were underpredicted, showing the effect of class imbalance. Models trained using spatially distributed examples also transferred more effectively across the study area than models trained within limited parcels.

The study demonstrates how relationships between observed ground behaviour and terrain conditions can be extended into areas where direct deformation measurements are unavailable. It also shows the importance of reporting performance by class rather than relying only on overall accuracy. A model may classify common low-sensitivity terrain successfully while missing less common high-sensitivity areas that are important for decision-making.

For the present thesis, the study provides a useful precedent for using observed deformation and field information to develop a reference classification and then using terrain and remote sensing variables to extend that classification spatially. This structure could support the calibration or testing of a susceptibility model based on terrain conditions.

5.3.3 Machine learning prediction of future thaw threat

Fatolahzadeh Gheysari and Maghoul (2024) developed a framework for predicting permafrost thaw threat along three northern Canadian transportation corridors, the Hudson Bay Railway, the proposed Mackenzie Northern Railway corridor, and the Inuvik–Tuktoyaktuk Highway and Dempster Highway corridor. Long short-term memory models predicted ground surface temperature using air temperature, solar radiation, wind speed, and snow depth. ERA5-Land reanalysis data supported estimates of present conditions, while regional climate model projections were used to examine RCP4.5 and RCP8.5 conditions through 2100.

The predicted mean annual ground surface temperature was combined with mapped ground ice categories to construct a thaw threat index. Segregated ice, ice wedges, and relict ice were represented in the demonstration, with equal weights assigned to the three ice categories. The resulting index therefore represents the interaction between predicted thermal conditions and the spatial distribution of potentially thaw-sensitive ground ice.

The reported machine learning performance was strong when evaluated against held-out ERA5-Land data. Mean root mean square errors were below approximately 0.3°C and maximum absolute errors were below 2°C. The framework was then used to represent how projected warming could alter thaw threat along the selected transportation corridors.

The study provides a clear example of how a future thermal forcing module can be connected to a separate ground ice layer. For Iqaluit, a similar structure could help distinguish the existing susceptibility of the ground from the likelihood that warming may activate that susceptibility during a planning period/horizon.

5.3.4 Critical assessment

The studies reviewed in this section represent three different uses of remote sensing and statistical prediction. Short et al. (2014) mapped observed seasonal ground displacement. Oldenborger et al. (2022) used observed deformation and field-informed reference classes to predict thaw sensitivity in unmapped terrain. Fatolahzadeh Gheysari and Maghoul (2024) predicted future ground surface temperature and combined it with mapped ground ice to produce a thaw threat index. These endpoints are related, but evidence of present movement, a predicted sensitivity class, and a future thaw threat do not represent the same condition.

Remote sensing is particularly useful as direct evidence of surface behaviour, but its interpretation depends on the observation period and measurement conditions. DInSAR records relative displacement along the satellite line of sight, and both seasonal frost heave and thaw settlement may contribute to the signal. Atmospheric effects, temporal decorrelation, surface water, soil moisture, acquisition geometry, and the choice of reference point can also affect the results. Terrain that appears stable during the observation period may remain susceptible where thaw has not yet reached ice-rich material or where surface disturbance has not occurred.

Statistical prediction can extend observed relationships into areas without direct measurements, but model performance depends on the quality and representativeness of the reference classification and training data. In the Oldenborger et al. study, the reference classes were themselves derived from DInSAR and process interpretation. Uncertainty in these sources is therefore carried into the neural network model. The underprediction of high and very high-sensitivity classes also shows the importance of class imbalance. Transfer between communities would require locally representative information because relationships among surface cover, geology, moisture, and deformation may vary between locations.

Future predictions introduce additional sources of uncertainty. The performance reported by Fatolahzadeh Gheysari and Maghoul represents agreement with held-out ERA5-Land data rather than independent validation against a dense network of observed ground surface temperatures. The projections also inherit uncertainty from the regional climate models and mapped ground ice inputs. Present ground ice distributions were held constant, while site-specific stratigraphy, drainage, talik development, and infrastructure loading were not fully represented. The resulting thaw threat index should therefore be understood as an indicator of combined thermal and ground ice conditions rather than a direct prediction of settlement magnitude or infrastructure failure.

For the proposed framework, remote sensing is most useful as an observational and validation layer. Statistical and machine learning models may also help extend observations spatially or represent future conditions. However, the framework should clearly identify whether each layer represents observed deformation, predicted susceptibility, or future thaw threat. It should also communicate the uncertainty associated with observations, reference classifications, training data, climate projections, and ground ice information.

These findings support a modular approach in which susceptibility based on terrain and ground conditions, observed surface behaviour, and projected thermal forcing remain distinguishable. Observed stability during a limited period should not automatically be interpreted as low susceptibility, but observed deformation can provide important evidence for testing and updating the framework over time.

5.4 Thermal and Geomechanical Process Models

Thermal and geomechanical process models represent the physical relationships among climate, surface conditions, ground temperature, thaw, settlement, and soil strength. Unlike ordinal indices, these approaches can produce outputs in physical units, including changes in active layer thickness, thaw settlement, and bearing capacity. This section examines how process models connect climate warming and surface disturbance to ground and infrastructure response, and what they contribute to the proposed planning-scale framework.

5.4.1 Bridging regional climate and engineering assessment

Daanen et al. (2011) developed a proof-of-concept framework for connecting regional climate and permafrost simulation with engineering recommendations in Greenland. The Geophysical Institute Permafrost Laboratory model was driven by HIRHAM regional climate projections through 2080. The authors introduced Permafrost Thaw Potential, defined as the potential increase in active layer thickness resulting from climate warming and changes to surface conditions.

Permafrost Thaw Potential was combined with terrain information, including sediment or bedrock conditions and expected ground ice, in a qualitative risk zoning procedure. Applications to Sisimiut and Ilulissat classified both communities as having high thaw potential. The underlying regional climate information had a spatial resolution of approximately 25 km, and the resulting zones were used to translate modelled permafrost change into broad engineering screening categories.

The study provides an early example of how projected climate change can be connected to terrain conditions and engineering considerations. It also recognizes that changes to surface conditions associated with development can affect the ground thermal regime. These principles are relevant to the present thesis because they support the inclusion of future thermal conditions and development related surface disturbance within a planning-scale assessment.

5.4.2 Infrastructure as a modifier of permafrost hazard

Schneider von Deimling et al. (2021) examined the consequences of permafrost degradation for a gravel road along the Dalton Highway in Alaska using laterally coupled one-dimensional CryoGrid simulations. The model represented the road embankment, adjacent tundra, snow redistribution, surface water, and lateral heat exchange under historical conditions and an RCP8.5 scenario.

The simulations showed that the road altered the local surface energy balance and increased net heat transfer into the ground. Snow accumulation and water ponding beside the road promoted lateral talik development, which could become a more important failure mechanism than vertical thaw directly beneath the road centre. The modelled response developed in two phases, an initially slow period followed by more rapid degradation after a critical thermal condition was reached.

This transition could occur within an infrastructure service life of approximately 30 years.

The study demonstrates that infrastructure can modify the permafrost conditions it is exposed to. Roads, fills, drainage changes, vegetation disturbance, and snow accumulation can alter heat and moisture transfer and intensify thaw. Susceptibility is therefore influenced not only by the conditions present before development, but also by how a proposed development changes the surface and surrounding drainage.

For the proposed framework, this finding supports a distinction between existing terrain susceptibility and development related modification. A municipal overlay can represent baseline land conditions, while proposed roads, fills, drainage alterations, and snow storage practices can be considered as additional factors during development review.

5.4.3 High resolution thermal and geomechanical projection

Wang et al. (2026) integrated a process-based ground thermal model with geomechanical models of thaw settlement and bearing capacity across the Arctic Coastal Plain and four northern Alaskan communities, Utqiaġvik, Wainwright, Point Lay, and Kaktovik. The framework produced outputs at a spatial resolution of 30 m under RCP4.5 and RCP8.5.

Thaw settlement calculations incorporated both the drainage of meltwater from excess ground ice and consolidation under an assumed infrastructure load. Bearing capacity was calculated using temperature-dependent long-term strength and creep failure relationships. The resulting outputs were expressed as physical settlement and engineering bearing capacity, connecting modelled ground warming to quantities that can be interpreted in an engineering context.

Hindcast thaw subsidence was compared with in situ measurements near Point Barrow and InSAR observations near Prudhoe Bay. Modelled no-load subsidence rates were broadly consistent with the available observations. The future simulations showed nonlinear change, with comparatively limited impacts during earlier decades followed by more rapid settlement and bearing capacity loss as warming and talik development progressed.

The study provides an advanced example of how thermal, and geomechanical models can be integrated at relatively high spatial resolution. It also demonstrates how future ground temperature, excess ground ice, drainage, loading, settlement, and bearing capacity can be represented within one modelling framework. For the present thesis, it provides a useful benchmark for understanding the types of analysis that may follow where planning-stage screening identifies higher susceptibility or rapid future change.

5.4.4 Critical assessment

The studies reviewed in this section represent different applications of thermal and geomechanical modelling. Daanen et al. (2011) connected regional climate projections to active layer change and qualitative engineering zones. Schneider von Deimling et al. (2021) examined how infrastructure and associated changes to snow and drainage can alter local permafrost conditions. Wang et al. (2026) connected ground thermal change to physical estimates of settlement and bearing capacity.

Process models provide a direct physical connection among climate warming, ground temperature, thaw, settlement, and soil strength. They can also represent nonlinear behavior. This is important because the response of permafrost terrain may remain limited for a period before accelerating after a thermal threshold is reached or a talik develops. The timing and severity of ground response may therefore not increase gradually or uniformly.

The reviewed studies also show that infrastructure is not simply exposed to an existing hazard. Development can modify the hazard through changes in surface cover, albedo, drainage, snow accumulation, vegetation, and loading. A site classified according to its existing terrain conditions may respond differently after development. This supports the inclusion of development related modifiers within municipal screening, particularly where a proposal involves substantial fill, altered drainage, road construction, water ponding, or snow storage.

The terminology and output of each model must be interpreted carefully. The qualitative risk zones used by Daanen et al. are more closely related to thaw potential and engineering constraints than to a complete risk assessment based on likelihood, exposure, vulnerability, and consequence. The regional climate inputs also limit the extent to which the resulting zones can represent conditions at the parcel scale.

Process models also require detailed information about ground temperature, soil properties, excess ground ice, drainage, surface conditions, and infrastructure loading. The Schneider von Deimling et al. results depend on the geometry and environmental conditions surrounding the modelled road. Applying the same approach elsewhere would require locally appropriate information about snow redistribution, surface water, embankment conditions, and lateral heat transfer.

Similarly, the 30 m resolution outputs produced by Wang et al. do not mean that every input variable is known at the same resolution or level of confidence. Soil and ground ice information may be derived partly from coarser datasets, while the geomechanical calculations depend on assumptions about compressibility, excess ice, foundation geometry, loading, drainage, and long-term soil strength. Validation was also limited geographically relative to the full modelled area. The nominal output resolution should therefore not be interpreted as equivalent certainty in all model inputs or predictions.

A planning-scale framework does not need to reproduce a fully coupled thermal and geomechanical model to benefit from these studies. It should recognize that thaw response may be nonlinear, represent future thermal conditions explicitly, and identify development characteristics that may intensify thaw. It should also distinguish baseline land susceptibility from changes introduced by a proposed development.

Where the framework identifies higher susceptibility, rapid projected change, or development conditions that could alter drainage and the ground thermal regime, the planning response should be to require more detailed site-specific thermal and geotechnical investigation. In this way, the municipal overlay supports early screening without attempting to replace engineering analysis or final design.

5.5 Integrated Terrain and Construction Potential

Integrated community mapping approaches bring together permafrost information, terrain evaluation, construction constraints, and outputs intended for local use. Compared with broad regional indices, these approaches generally rely more heavily on local field information and produce classes that can be interpreted in relation to community planning and infrastructure. This section examines how these approaches distinguish among ground conditions, construction potential, observed impacts, and broader risk, and what this separation contributes to the proposed framework.

5.5.1 Integrated mapping in Nunavik communities

Allard et al. (2023) documented an integrated methodology applied across 13 Nunavik communities. The work combined surficial geology mapping, boreholes, backhoe excavations, ground penetrating radar, thermistor monitoring, laboratory analysis, aerial imagery, and elevation data at high resolution. Four distinct products were prepared for each community: surficial geology maps, permafrost condition maps, construction potential maps, and geohazard or risk maps.

The separation among these products is methodologically important. Permafrost condition maps described ground ice, sediment, bedrock depth, and thermal conditions. Construction potential maps translated terrain sensitivity and slope constraints into three relative classes. The geohazard or risk assessment was conducted separately and considered several hazard types together with probability, potential consequences, and exposure. Construction potential was therefore treated as a separate product from both permafrost conditions and broader risk.

Local thermistor records were used to calibrate numerical ground temperature models, and future conditions were examined to 2100 under RCP4.5 and RCP8.5. The mapping process also included community consultation and consideration of Inuit aspirations, local priorities, cultural practices, and leadership. The work therefore addressed both the technical development of the maps and the community context in which they would be used.

This approach is a great precedent for the proposed Iqaluit framework. It brings together terrain information, ground ice, slope, climate change, and outputs intended to support community decisions, while maintaining clear distinctions among permafrost conditions, construction potential, and risk. It also demonstrates how field information and community knowledge can contribute to the development and interpretation of mapped classes.

5.5.2 Road focused thaw settlement susceptibility in Ilulissat

Scheer et al. (2024) developed a thaw settlement susceptibility assessment for roads in Ilulissat, Greenland. The study integrated 1,127 borehole records, terrain and sediment information, road condition inventories, and remotely observed displacement. Fine frost susceptible sediments, areas of water ponding, and locations affected by snow accumulation from road maintenance were associated with higher susceptibility.

The study distinguished among hazardous terrain, infrastructure vulnerability, and observed impact. Approximately 39% of roads were located on highly hazardous terrain, 9% were classified as vulnerable, and 3% were assessed as severely impacted. Approximately 12% of paved roads were located on sediments classified as highly susceptible to thaw settlement.

The distinction among these categories shows that a road may cross susceptible terrain without yet displaying severe damage. The condition of the infrastructure also depends on factors such as design, drainage, maintenance, loading, and age. The study further reinforces the finding from the process models reviewed in Section 5.4 that snow management and water ponding can modify local thaw conditions.

For the present thesis, the study demonstrates how a land susceptibility layer can remain separate from information about infrastructure condition and performance. Road condition, maintenance practices, drainage, and observed damage could later be added to the assessment without embedding these asset characteristics within the original land susceptibility classification.

5.5.3 Nunavut land development suitability mapping

The Incorporating Climate Change into Land Development (ICCiLD) - Terrain Analysis project provides an important Nunavut precedent. As documented by Flynn et al. (2019), ICCiLD used interferometric synthetic aperture radar to monitor ground disturbance and categorize land development suitability in seven Nunavut communities. The published evaluation focused on Arviat.

The project demonstrates that satellite deformation information can be translated into land development suitability classes for northern community planning. Its geographical and institutional setting makes it particularly relevant to Iqaluit. It provides a Nunavut example of how technical information about permafrost related ground movement can be converted into a form intended to support municipal land decisions.

For the present thesis, ICCiLD is important both as a mapping precedent and as an example of the practical use of permafrost information within community planning.

5.5.4 Critical assessment

Integrated community mapping studies provide some of the closest methodological precedents for the proposed framework because they combine local terrain and permafrost information with classes intended for practical interpretation. They also demonstrate the importance of keeping the purpose of each mapped product clear. A permafrost conditions map identifies characteristics such as ground ice, sediment type, bedrock depth, and thermal conditions. A susceptibility map represents the relative likelihood of a damaging ground response. A construction potential map may add slope, drainage, accessibility, and other development constraints. A risk map introduces exposed assets, potential consequences, and the likelihood of damage.

A restrictive construction class may result from thaw-sensitive ground, steep terrain, poor drainage, limited access, or several conditions acting together. Keeping the permafrost contribution identifiable allows planners to understand why a location has been assigned a particular class and what additional information may be needed.

The Nunavik work also shows the value of local calibration. Boreholes, excavations, geophysical surveys, thermistor records, laboratory analysis, and community knowledge provide a stronger basis for interpreting local terrain than regional datasets alone. However, this level of investigation requires considerable time, funding, technical expertise, and community engagement. The resulting classifications are also locally developed and would need to be adapted before being applied in Iqaluit.

The road focused assessment in Ilulissat adds a distinction between the susceptibility of the terrain and the condition of an asset located on that terrain. Existing damage reflects not only ground conditions, but also design, age, loading, drainage, snow management, and maintenance. These characteristics are useful for evaluating existing infrastructure, but they should remain separate from a baseline classification of undeveloped land.

The ICCiLD project demonstrates that remote sensing observations can be translated into land development suitability classes within a Nunavut planning context. However, a classification based on observed deformation remains influenced by the observation period, surface coherence, and the conditions present when the measurements were collected. Terrain that appears stable during the observation period may still contain susceptible materials that respond to future warming or surface disturbance.

For the proposed framework, the principal lesson is that mapped outputs should remain modular. The municipal GIS overlay should identify the relative susceptibility of land to thaw related permafrost hazards. Slope, drainage, access, development characteristics, infrastructure condition, and broader consequences can then be considered as separate planning information. This structure keeps the influence of permafrost visible while allowing other factors to be added as the assessment moves from land susceptibility towards construction potential, infrastructure evaluation, or risk.

5.6 Boundary of Hazard Mapping versus Exposure, Vulnerability and Risk

The reviewed literature uses the terms susceptibility, hazard, exposure, vulnerability, and risk in different ways. Some studies use risk to describe physical terrain and permafrost conditions, while others use vulnerability to describe combinations of environmental, infrastructure, and social information. To maintain consistency, the following definitions are used throughout this thesis.

Physical susceptibility refers to the relative propensity of a land unit to experience a damaging thaw-related ground response if the relevant thaw process occurs. Hazard refers to the potentially damaging physical process and is more fully characterized when its magnitude, frequency, probability, or time horizon is specified. Exposure describes the presence of people, buildings, roads, utilities, or other valued elements within an affected area. Vulnerability describes the propensity of those exposed elements to suffer harm, including their physical sensitivity and capacity to cope or adapt. Risk concerns the potential consequences produced through the interaction of hazard, exposure, and vulnerability.

5.6.1 Infrastructure exposure in circumpolar hazard zones

Hjort et al. (2018) combined circumpolar permafrost geohazard projections with mapped infrastructure and population to examine exposure to future permafrost change. The physical hazard information was derived from the underlying permafrost and geohazard modelling later documented in detail by Karjalainen et al (2019). A mean if 69% of existing infrastructure within the present circumpolar permafrost domain was located in areas where near-surface permafrost was projected to thaw by 2050. A mean of 33% of existing pan-Arctic infrastructure was located in high-hazard environments where thaw-related ground instability could severely damage infrastructure.

Karjalainen et al. (2019) documents how the underlying permafrost and geohazard layers were produced and how the predictive performance of the MAGT and ALT models was evaluated, while Hjort et al. (2018) use those layers to examine where infrastructure and population are located in relation to projected hazard zones. Together, these studies therefore demonstrate how exposure can be added after a physical hazard surface has been developed.

This structure is relevant to the proposed framework because it allows the physical classification of land to remain separate from the amount or value of infrastructure located on it. Building density, population, and asset value can be added later without being incorporated into the original susceptibility score.

5.6.2 Infrastructure and community vulnerability indices

Alessa et al. (2023) developed a Permafrost Vulnerability Index for critical infrastructure, community resilience, and national security in Alaska. The approach considered existing infrastructure, permafrost conditions, spatial proximity, and potential interactions among community and infrastructure systems. Results were generated for 186 communities and 30 military facilities and were compared with existing permafrost threat rankings.

The index supports strategic prioritization by examining where permafrost change may disrupt interconnected community and infrastructure systems. Its focus extends beyond physical ground conditions by including the presence and relationships of infrastructure and community systems.

Ramage et al. (2025) developed the Arctic Permafrost Vulnerability Index for 260 circumpolar subregions. The index combines physical and social indicators to represent exposure to permafrost thaw and adaptive capacity. The authors found that 97% of the assessed subregions were classified as moderately vulnerable, while exposure and adaptive capacity varied more substantially among regions.

The index supports broad adaptation planning and comparison among regions by showing how physical exposure and the capacity to respond vary across the Arctic. Together, the Alessa et al. and Ramage et al. studies demonstrate how permafrost information can be combined with infrastructure, community, social, and institutional conditions to support strategic prioritization.

5.6.3 Scope boundary for the proposed framework

The framework developed in this thesis focuses on variables that describe the land and the physical processes acting on it. These include excess ground ice, surficial material, bedrock, slope, drainage, present thermal conditions, and future thaw forcing. Buildings, population, infrastructure criticality, asset condition, replacement cost, social capacity, and institutional resources are kept outside the physical susceptibility calculation.

The reviewed studies help clarify this boundary. Hjort et al. shows how infrastructure and population exposure can be added to a regional hazard surface. Alessa et al. and Ramage et al. show how infrastructure relationships, social conditions, and adaptive capacity can be incorporated into broader vulnerability assessments. These approaches build on physical permafrost information, but they address different planning questions from the baseline land susceptibility framework proposed in this thesis.

Keeping these dimensions separate allows the susceptibility classification to retain a clear physical interpretation. A densely developed area should not receive a higher physical susceptibility class simply because it contains more buildings or infrastructure. The same land classification can also support different future applications depending on which exposure and vulnerability information is added.

A future municipal risk assessment could overlay the susceptibility map with buildings, roads, utilities, planned development, infrastructure condition, and information about the consequences of damage. This would allow physical susceptibility, exposure, vulnerability, and risk to be considered as connected stages of assessment without combining them within one baseline index.

Development-related changes to snow, drainage, vegetation, and loading occupy a particular position within this structure because they can alter the physical process itself. They are therefore treated as development scenarios or modifiers rather than as exposure variables or inherent properties of undisturbed land. This separation keeps baseline terrain conditions, changes introduced by development, exposure, vulnerability, and risk identifiable within the broader assessment process.

5.7 Comparative Synthesis and Lessons for the Proposed Framework

The approaches reviewed in Sections 5.2 to 5.6 range from broad circumpolar screening to locally calibrated community and infrastructure assessments. Their differences extend beyond spatial resolution. They represent different physical conditions, rely on different forms of evidence, incorporate climate change in different ways, and use different methods of validation. This section compares the approaches, identifies the lessons that recur across the literature, and explains how they inform the structure of the proposed framework.

5.7.1 Comparative assessment

The reviewed approaches are compared according to the condition being assessed, scale and treatment of climate change, analytical method, form of validation or supporting evidence, and main lesson for the proposed framework as summarized in Table 5.1.

Table 5.1. Comparative assessment of reviewed permafrost mapping and assessment approaches

Study	Actual analytical endpoint	Scale and climate treatment	Principal method and output	Validation or evidence	Main limitations and transferable contribution
Smith and Burgess (2004)	Relative thermal and physical sensitivity	Canada; approximately 10 km; no prescribed future scenario	GIS combination of thermal state, buffering factors, surficial material, and peatlands	Comparison with established permafrost and terrain knowledge	Too coarse for municipal use; establishes the distinction between thermal response and ground response
Nelson et al. (2002)	Relative thaw settlement hazard	Circumpolar; (0.5^\circ); mid-century climate scenarios	Relative active layer increase multiplied by ground ice content	Mechanistically based regional comparison	Coarse inputs and drainage assumptions; explicitly links thaw forcing with ground ice
Hong et al. (2014)	Composite settlement hazard	Alaska; current and 2050	Six ordinal indicators weighted through analytic hierarchy process	Comparison of mapped patterns with expected regional conditions	Subjective weights and mixed endpoints; demonstrates an accessible composite index
Karjalainen et al. (2019)	Permafrost conditions and four alternative geohazard indices	Circumpolar; 30 arc-seconds; three RCPs and two future periods	Statistical MAGT and ALT models plus settlement, risk	Spatially blocked validation, hindcasting, and model comparison	Coarse ground ice and disagreement among indices; demonstrates

			zonation, AHP, and consensus indices		scenario mapping and structural uncertainty
Ni et al. (2021)	Integrated thaw settlement hazard	Qinghai–Tibet Plateau and railway corridor; RCP4.5	Three physical indicators and a consensus classification	Cross-comparison among indices	Consensus is not independent validation; shows the value of retaining model disagreement
Mohammadi and Hayley (2023)	Inherent ground response susceptibility	Canada; national baseline; climate excluded	Excess ground ice, surficial material, and bedrock weighted through AHP	Consistency with established thaw settlement controls	Does not identify when thaw occurs; provides a clear baseline susceptibility module
Short et al. (2014)	Observed seasonal ground displacement	Iqaluit Airport; observation period only	RADARSAT-2 DInSAR	Ground measurements and terrain comparison	Observation is temporally conditional; provides direct local evidence and validation
Oldenborger et al. (2022)	Predicted thaw sensitivity class	Rankin Inlet; community scale	Neural network trained from process-informed DInSAR classes	70.8% four-class and 81.8% binary accuracy	Underpredicts uncommon high classes; demonstrates empirical spatial prediction

Fatolahzadeh Gheysari and Maghoul (2024)	Future thaw threat	Three Canadian transportation corridors; RCP4.5 and RCP8.5	LSTM ground surface temperature prediction combined with ground ice	Held out comparison with ERA5-Land	Reanalysis validation and static ground ice; demonstrates a separate future forcing module
Daanen et al. (2011)	Permafrost Thaw Potential and engineering constraint zones	Greenland; approximately 25 km regional forcing; projections to 2080	Process-based thermal model and qualitative engineering assessment	Application in Sisimiut and Ilulissat	Too coarse for parcels; bridges climate modelling and engineering screening
Schneider von Deimling et al. (2021)	Road induced thermal degradation processes	Dalton Highway transect; historical and RCP8.5	Laterally coupled CryoGrid modelling	Process comparison with observed road environments	Site specific rather than a map; demonstrates that development modifies hazard
Wang et al. (2026)	Quantitative thaw settlement and bearing capacity	Northern Alaska; 30 m outputs; RCP4.5 and RCP8.5	Coupled ground thermal and geomechanical modelling	Hindcasts compared with in situ and InSAR observations	Parameter and input scale uncertainty; provides physically meaningful engineering outputs
Allard et al. (2023)	Permafrost conditions, construction	Thirteen Nunavik communities;	Integrated field, geophysical, thermal, terrain, and	Extensive field characterization and monitoring	Resource intensive; closest precedent for

	potential, and separate risk products	locally calibrated future scenarios	community information		locally grounded municipal mapping
Scheer et al. (2024)	Road terrain susceptibility, vulnerability, and observed impact	Ilulissat roads; present conditions	Boreholes, terrain, road condition, and deformation observations	Comparison with existing road condition	Asset specific and not future oriented; clearly separates terrain hazard from infrastructure condition
Flynn et al. (2019)	Effectiveness of municipal hazard and suitability mapping	Seven Nunavut communities; Arviat evaluation	InSAR based suitability mapping plus user evaluation	Interviews with 19 creators and users	Operational and communication barriers; establishes usability as part of effectiveness

5.7.2 Cross-study lessons

First, the conditions being assessed must be defined clearly. Mean annual ground temperature, active layer change, thaw potential, thaw settlement susceptibility, observed deformation, bearing capacity, exposure, vulnerability, and risk describe different conditions. The title and classes of a map should reflect what the approach actually represents.

Second, thermal forcing and physical ground response should remain distinguishable. Ground temperature and active layer change indicate how thaw conditions may develop, while excess ground ice, surficial materials, bedrock, and drainage influence how the ground responds when thaw occurs. These components may be brought together within an overall classification, but their individual influence should remain visible.

Third, present susceptibility and future change answer different planning questions. Present susceptibility identifies where thaw-sensitive ground conditions exist. Future change indicates where projected warming may activate or intensify that susceptibility during a planning period. Present and future conditions may therefore be communicated through paired maps, separate modules, or a classification that clearly retains both components.

Fourth, statistical and machine learning models provide a way to extend observed ground thermal conditions across space and into future planning horizons. Karjalainen et al. (2019) demonstrate how observed mean annual ground temperature and active layer thickness can be paired with geospatial predictors to calibrate statistical and machine learning models. Spatially blocked cross-validation and hindcasting can then be used to evaluate model performance at locations and time periods that were not used during calibration. Future climate predictors can also be applied to estimate mean annual ground temperature and active layer thickness under defined climate scenarios. For municipal application, these methods would require representative local observations, spatially appropriate evaluation, and separate reporting of model performance for each predicted variable.

Fifth, ground ice is consistently identified as one of the strongest controls on thaw settlement, but it is also one of the least consistently mapped variables. Regional ground ice datasets cannot resolve all localized ice bodies, and total volumetric ice is not equivalent to excess ice capable of producing settlement. Generalized or incomplete ground ice information should therefore affect the confidence assigned to the final classification.

Sixth, weighting and classification decisions can materially change the mapped pattern. Expert weights, normalization procedures, class thresholds, additive scoring, and consensus rules should be documented and tested. A moderate consensus class may indicate moderate physical susceptibility, but it may also result from disagreement among several models. The evidence and reasoning used to establish each rating, threshold, and weight should therefore be recorded, and sensitivity testing should be used to examine how these choices affect the final classes.

Seventh, observed deformation provides a different and complementary form of evidence. DInSAR can be used to compare mapped terrain or susceptibility classes with observed ground behaviour, support the development of reference classifications, identify local anomalies, and guide future updates. However, the absence of measured movement does not confirm low future susceptibility. DInSAR observations depend on the monitoring period, surface conditions, current development, measurement geometry, and whether thaw has reached ice-rich material. Where statistical models are trained using reference classes derived partly from DInSAR, evaluation should also use independent observations, separate locations, or later monitoring periods where possible. Class-specific performance should be reported because overall accuracy may conceal the underprediction of less common High susceptibility classes.

Eighth, development can modify the physical hazard. Snow accumulation, drainage alteration, water ponding, vegetation removal, fill placement, changes in albedo, and structural loading can affect heat and moisture transfer. These changes should be considered as explicit development scenarios or modifiers rather than assumed to be represented by existing terrain conditions.

Ninth, higher nominal spatial resolution does not necessarily mean higher confidence. A model may produce outputs at 30 m while relying on climate, soil, or ground ice information mapped at much coarser scales. Output resolution, input resolution, data support, and the appropriate scale of decision making should therefore be reported separately.

Tenth, uncertainty arises from several sources across the reviewed approaches. Data and proxy uncertainty result from incomplete observations, generalized ground ice information, and the use of indirect indicators such as surficial geology. Spatial uncertainty results from uneven coverage, scale differences, and the interpolation of conditions between observations. Predictive uncertainty concerns the performance of statistical, machine learning, and process models. Structural uncertainty arises where alternative models or index formulations produce different mapped patterns from similar inputs. Additional uncertainty is introduced through thresholds, weights, class rules, future climate scenarios, assumptions about variables held constant over time, and the transfer of relationships from one region or community to another. These sources should remain distinguishable because they cannot all be addressed in the same way.

The reviewed studies also show several ways of evaluating and communicating uncertainty. These include spatial cross-validation, hindcasting, held-out testing, comparison with field and remote sensing observations, sensitivity testing, comparison among alternative models and indices, and the mapping of model disagreement. No single method addresses every source of uncertainty. A planning-scale framework should therefore combine several forms of evaluation and make remaining uncertainty visible in the mapped output and supporting documentation.

Eleventh, traceability concerns whether the final mapped class can be reconstructed from the evidence and analytical decisions that produced it. Traceability is strongest where the source, date, resolution, and limitations of each input are recorded, together with the reclassification rule, threshold, rating, weight, analytical branch, intermediate index, final class boundary, and validation result. For the proposed framework, this requires a clear sequence from the original input to its branch-specific rating, to the intermediate index, to the final PHSI and planner-facing overlay class. The controlling indicators and evidence basis should also remain available for each mapped unit. Confidence can summarize the strength of this evidence, but it should not replace the underlying analytical record.

Twelfth, usability is part of the effectiveness of a mapped assessment. Classes should be understandable, accessible, connected to defined planning actions, and accompanied by an explanation of their limitations and controlling indicators. The output should help municipal staff determine what information is available, what conditions require closer attention, and what level of additional review may be appropriate. A planner-facing class should therefore be supported by an accessible explanation of why the class was assigned, how strongly it is supported, and what information or analytical steps sit behind it.

Table 5.2 summarizes the main approaches identified in the literature for addressing uncertainty and supporting traceability, together with the lesson each provides for the proposed framework.

Table 5.2. Literature-derived approaches for addressing uncertainty and traceability

Issue	Literature precedent	Method used	Lesson for the proposed framework
Data and proxy uncertainty	Smith and Burgess (2004), Karjalainen et al. (2019), Allard et al (2023).	Identification of proxy variables, reporting of input scale, and comparison of generalized mapping with local field evidence	Record the source, date, resolution, proxy status, and known limitations of each input. Use local evidence to test and refine generalized interpretations.
Predictive uncertainty	Karjalainen et al.(2019), Oldenborger et al.(2022), Fatolahzadeh Gheysari and Maghoul (2024)	Spatial cross-validation, hindcasting, held-out testing, class-specific accuracy, and prediction ranges	Report model performance for each predicted variable and class. Avoid treating all modelled outputs as equally reliable.
Model and structural uncertainty	Karjalainen et al. (2019), Ni et al.(2021)	Comparison among alternative statistical models and geohazard indices, together with mapped agreement and disagreement	Test alternative formulations and retain information showing where the final class depends strongly on model selection.
Threshold and weighting uncertainty	Smith and Burgess (2004), Hong et al. (2014), Karjalainen et al.(2019), Daanen et	Explicit ordinal ratings, analytic hierarchy process weighting, consistency	Document the evidence and purpose of each threshold and weight. Use sensitivity testing to

	al.(2011), Ni et al.(2021)	testing, nested means, and rule-based thresholds	examine how analytical choices affect the final map.

5.8 Chapter Summary

This chapter reviewed existing approaches used to map permafrost conditions, thaw-related ground hazards, land susceptibility, observed deformation, construction potential, infrastructure exposure, vulnerability, and risk. The review moved from climate sensitivity and hazard zonation to remote sensing and statistical prediction, thermal and geomechanical process models, integrated community mapping, and broader infrastructure and community assessments. These approaches differ in their scale, data requirements, analytical methods, treatment of climate change, validation procedures, intended users, and type of output.

Several lessons emerge from the reviewed literature. The condition being assessed must be defined clearly, and thermal forcing should remain distinguishable from the physical response of the ground. Present land susceptibility and future thermal change also answer different planning questions. Ground ice is consistently identified as an important control on thaw settlement, although its spatial distribution is often uncertain or represented using generalized information. The review further showed that indicator selection, ratings, weights, classification thresholds, model structure, and spatial resolution can influence the mapped result. Exposure, vulnerability, and risk should also remain separate from the baseline physical susceptibility of the land.

Statistical and machine learning approaches provide a way to extend observed ground thermal conditions across space and into future planning horizons. Karjalainen et al. (2019) demonstrate how observed mean annual ground temperature and active layer thickness can be paired with geospatial predictors to calibrate statistical regression and tree-based machine learning models. Their use of spatial cross-validation, hindcasting, and uncertainty analysis provides a way to evaluate model performance and transferability. Future climate predictors can then be used to project mean annual ground temperature and active layer thickness under defined Representative Concentration Pathways. Their comparison of several geohazard indices also shows that different model formulations can produce different mapped patterns and that this disagreement provides useful information about model uncertainty. These methods are particularly relevant to the future thermal state component of the proposed framework.

Remote sensing provides a different and complementary form of evidence. DInSAR can identify where measurable surface displacement has occurred, support comparison between mapped terrain classes and observed ground behaviour and help identify local conditions that may not be represented by broader terrain information. It can also support future updates as longer observation records become available. However, the absence of observed deformation during a particular monitoring period does not confirm low future susceptibility. Remote sensing is therefore most useful for observation, validation, and monitoring, while calibrated statistical models provide a stronger pathway for extending ground thermal information spatially and projecting future conditions.

The strongest approach for a future municipal application would combine these methods. Statistical and machine learning models could use observed ground temperature and active layer information together with geospatial predictors to estimate current and future thermal conditions. Boreholes, ground ice information, surficial geology, laboratory testing, and field observations could support the physical ground response component. DInSAR and other monitoring information could then be used to test mapped patterns, identify disagreement, and support later updates. The confidence assigned to a mapped class would depend on the quality, scale, coverage, and agreement of these different forms of evidence.

Thermal and geomechanical process models add an important understanding of how thaw-related ground response may develop. They show that change may be nonlinear and that infrastructure can modify the conditions it experiences through altered drainage, snow accumulation, vegetation removal, fill placement, surface cover, and loading. These development-related effects should be considered explicitly rather than assumed to be represented by existing terrain conditions.

Integrated community mapping approaches provide some of the closest precedents for municipal application. They demonstrate the value of local terrain mapping, boreholes, geophysics, thermistor monitoring, field investigation, community knowledge, and outputs that can be interpreted in relation to planning and construction decisions. They also show the importance of maintaining distinctions among permafrost conditions, land susceptibility, construction potential, infrastructure condition, exposure, vulnerability, and risk.

Taken together, the reviewed approaches provide the methodological basis for a planning-scale permafrost hazard susceptibility framework for the populated area of Iqaluit. Literature supports a modular structure in which current ground susceptibility, present and future thermal conditions, development-related modifiers, observational evidence, and uncertainty remain identifiable. It also supports locally calibrated thresholds and weights, comparison among alternative model formulations, explicit documentation of data limitations, and a planner-facing output that remains traceable to the evidence and analytical steps behind it.

Chapter 6: Existing Engineering Standards and Technical Guidance

6.1 Introduction

Following the review of mapping approaches in Chapter 5, a second body of relevant work lies in engineering standards, codes, manuals, and administrative guidance. This landscape shows that permafrost informed practice already has a substantial technical foundation. Existing materials address frozen soil description and testing, permafrost foundation investigation and design, northern drainage and infrastructure systems, permitting, and professional review. The key issue for this thesis is not the absence of technical knowledge, but the way that knowledge is distributed across scales, sectors, and stages of the project life cycle.

The standards and guidance landscape is especially important for the present thesis because it reveals a persistent mismatch of scale. Much of the existing material is either too detailed and project specific, or too broad and strategic, to function directly as a municipal development screening tool. The most relevant documents therefore need to be read not only for what they prescribe, but also for the level of decision they are intended to support.

6.2 Standards and Guidance Across Jurisdictional Scale

6.2.1 International guidance

At the international level, the materials produced by ASTM International's Subcommittee D18.19 on Frozen Soils and Rock maintains standardized language and testing procedures for frozen ground. The ASTM D18.19 portfolio includes standards relevant to frozen soil description, creep behavior, frozen soil strength, and pile testing in permafrost (ASTM International, n.d.). This family of standards is foundational because it improves the consistency and reliability of technical inputs used later in design and assessment. ISO 19906 provides a different example of mature Arctic specific engineering standardization, although in the offshore petroleum sector rather than municipal land use planning (International Organization for Standardization, 2019). Together, these materials demonstrate that Arctic engineering standardization is well developed where the question concerns testing, terminology, and specialized structural design.

Useful extra national practice guidance is also available from Alaska. Connor et al. (2020), prepared for the Alaska Department of Transportation and Public Facilities, synthesize practice for roads and airfields constructed on permafrost. The report links geotechnical investigation, climate effects, slope stability, adaptation strategies, and design, construction, and maintenance phases. Its practical lesson is that permafrost performance depends on the interaction of climate, soil, ice, hydrology, and disturbance, and that alignment, drainage, and thermal preservation strategies must be considered together. However, this guidance remains strongly tied to transportation infrastructure. It helps clarify engineering principles, but it does not provide a municipal framework for classifying land or screening development proposals.

6.2.2 National guidance in the Canadian context

At the national level, the National Building Code of Canada 2025 is the current national model code and provides the overarching model code baseline for building safety and performance, with jurisdictional adoption occurring through provincial and territorial legislation (Canadian Board for Harmonized Construction Codes, 2025). For the purposes of this thesis, the Code is important less because it is a permafrost specific document than because it defines the broader regulatory setting into which permafrost related standards and local requirements must fit. On its own, however, the Code does not tell municipalities how to identify thaw sensitive land or how to screen development proposals according to susceptibility.

Canada's most directly relevant permafrost and northern infrastructure standards are found within the Northern Infrastructure Standardization Initiative and related guidance. CSA S500:21 addresses thermosyphon foundations for buildings in permafrost regions, while CSA S501:21 addresses the moderation of permafrost degradation effects on existing building foundations. CSA S503:20 focuses on community drainage system planning, design, and maintenance in northern communities. CSA S502:21, CSA S505:20, and CSA TS 506:25 extend the toolkit to changing snow load risks, high winds and snow drifting, and climate risks informed asset management in northern regions. CSA PLUS 4011:19 and CSA PLUS 4011.1:19 further provide technical guidance on infrastructure and foundations in permafrost regions (CSA Group, 2019a, 2019b, 2020a, 2020b, 2021a, 2021b, 2021c, 2025). These materials collectively show that Canada already has substantial guidance for site investigation, foundation adaptation, drainage, climate related infrastructure management, and asset management questions in a changing northern climate.

The BNQ standards are especially relevant because they move part of the conversation toward risk-based investigation and planning. CAN/BNQ 2501 500/2025 provides a methodology for geotechnical site investigations for foundations of buildings or structures in permafrost zones, while CAN/BNQ 9701 500/2023 addresses a risk-based approach to community planning in northern regions (Bureau de normalisation du Québec, 2023, 2025). The latter is particularly important because it comes closest to the planning scale addressed in this thesis. Even so, the BNQ planning standard does not resolve the specific municipal need identified here. It does not, by itself, supply a place specific workflow for constructing a planner facing permafrost hazard susceptibility overlay, assigning transparent classes, expressing uncertainty spatially, and linking those classes to development review actions. Related national climate risk tools, including the PIEVC Protocol administered by PIEVC Program Alliance and broader Engineers Canada guidance, are also useful in showing how infrastructure vulnerability can be assessed systematically, but they operate at a more general risk screening level than the land diagnosis focus of the present research (PIEVC Program Alliance, 2024; Engineers Canada, n.d.).

6.2.3 Regional and northern practice manuals

Regional and northern practice manuals further strengthen the technical base. The Transportation Association of Canada's Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions provide best practice guidance for the planning, design, construction management, maintenance, and rehabilitation of transportation infrastructure in northern permafrost terrain (McGregor et al., 2010). Northern building and utility manuals, such as the Government of the Northwest Territories' Good Building Practice for Northern Facilities and Good Engineering Practice for Northern Water and Sewer Systems, provide practical direction on design, maintenance, drainage, utilities, grading, and operations in cold region environments (Government of the Northwest Territories, 2017, 2021). Their value lies in translating cold regions engineering principles into recurring infrastructure decisions. Their limitation, however, is that they remain sector specific and project oriented. They help practitioners respond to known ground and climate conditions, but they do not organize those conditions into a municipal land screening tool for development review.

6.2.4 Territorial guidance and permitting in Nunavut

At the territorial level, Nunavut's Building Code Act (2012), Building Code Regulations (2018), and Building Code Regulations, amendment (2024), together with the Office of the Chief Building Official and related building permit resources establish the formal pathway for building permit review, inspection, and code administration. The Building Code Regulations (2018), as amended in 2024, adopt the National Building Code of Canada 2015 for Nunavut; publication of newer national model codes does not by itself change the applicable territorial requirements. The Government of Nunavut's Good Building Practices Guideline is especially important because it consolidates northern construction experience into practical advice on foundations, building envelopes, site preparation, utilities, and environmental conditions (Government of Nunavut, 2020). The guideline is advisory and is intended to supplement rather than replace mandatory codes and regulations (Government of Nunavut, 2020). Territorial requirements for architects and engineers also clarify the role of professional responsibility in design and field review. Together, these requirements and guidance shape what must be demonstrated at the building-permit stage for projects in Iqaluit.

The territorial regime nevertheless operates primarily as a project compliance and professional review system. Its main concern is whether a particular building proposal satisfies building code, design, and inspection requirements, not whether a municipality has a planner facing way to classify land before proposals become highly advanced. In that sense, Nunavut's territorial guidance is essential but downstream relative to the problem addressed in this thesis. It reinforces the importance of geotechnical competence and code compliance, but it does not replace the need for earlier municipal screening.

6.2.5 Municipal guidance and planning instruments in Iqaluit

At the municipal level, the City of Iqaluit's planning resources make available the General Plan By-law No. 898, Zoning By-law No. 899, and GIS Web Map, and they structure how applicants and staff navigate land use review (City of Iqaluit, n.d.-b; 2021b, 2025). These instruments are indispensable for development control because they determine land use permissions, zoning processes, and the administrative pathway through which proposals move. Municipal design guidelines and related infrastructure guidance provide further direction on servicing, roads, drainage, and civil works (City of Iqaluit, 2005). They therefore represent the institutional location where a planning scale permafrost overlay would ultimately need to operate.

However, the municipal planning instruments reviewed do not themselves constitute a formal permafrost hazard susceptibility overlay for routine development review. They establish the planning and design context into which such a tool could be inserted, but they do not yet provide a harmonized method for translating geotechnical, terrain, climate, and environmental information into classes usable by planning and technical review staff and proposal screening responses. This is why the municipal scale matters in the thesis: it is the point at which land use and zoning decisions are made, yet it is also where the technical guidance for selecting and organizing relevant ground, terrain, hydrological, and climate information; translating that information into susceptibility classes; communicating uncertainty; and linking the resulting classes to development-review responses has historically been least consolidated.

6.2.6 Lessons from existing standards and guidance

The standards and guidance review reveals three main points. First, there is already substantial direction on how frozen soils should be characterized, tested, and investigated. Second, there is a strong body of permafrost relevant engineering guidance for foundation systems, drainage, transportation infrastructure, operations, maintenance, and climate adaptation. Third, existing institutional frameworks in Nunavut and Iqaluit already provide permitting and planning pathways into which better land diagnosis tools could be inserted. The technical and administrative base needed to support permafrost aware decision making therefore exists, but it remains partly distributed across documents, sectors, and stages of review.

Table 6.1 summarizes the most relevant scales of standards and guidance and shows their implications for this thesis. The consistent pattern is that existing materials are strongest at the site investigation, design, construction, and permit review stages, but comparatively limited at the municipal planning stage where questions of land suitability, development intensity, and early screening first arise.

Table 6.1. Permafrost-informed development review standards and guidance

Scale	Representative sources	What is already addressed	What remains limited for this thesis
International / extra national	ASTM D18 frozen soils standards; ISO 19906; Alaska DOT permafrost guidance	Terminology, test methods, sector specific Arctic design and practice	No municipal land classification or proposal screening workflow
National	NBCC; CSA Group northern standards; BNQ standards; PIEVC related guidance	Model code baseline, permafrost foundations, drainage, site investigation, climate risk and asset management tools	Technical content remains distributed across documents and life cycle stages
Regional	TAC guidance; northern facilities and utility manuals	Practical design and maintenance guidance for roads, buildings, and services	Mostly sector specific and project oriented
Territorial	Nunavut building permits, OCBO, Good Building Practices	Permit review, inspection, professional responsibility, northern building practice	Focuses on compliance after projects are sufficiently defined
Municipal	Iqaluit planning resources, General Plan, Zoning By-law, GIS and design guidance	Land use controls, application pathways, local infrastructure context	No harmonized permafrost hazard susceptibility overlay or decision matrix

6.3 Implications and Contribution of the Present Research

When the mapping literature and the standards and guidance landscape are read together, several observations relevant to this thesis emerge. The first is a synthesis challenge. Knowledge relevant to thaw related planning exists, but it is dispersed across geotechnical studies, climate and remote sensing research, codes, standards, manuals, and municipal documents. A planner or municipal reviewer is unlikely to encounter these materials as one coherent decision support system. One contribution of the present research is therefore to organize selected parts of this existing knowledge into a clearer planning-oriented framework.

The second observation concerns scale and decision context. Existing approaches tend to cluster at either the strategic scale of national and regional screening or the detailed scale of site investigation and engineering design. The municipal planning scale sits between these levels. It is the scale at which questions of land suitability, density, height, and development intensity are negotiated, yet it is also the scale at which diverse technical inputs must be translated into forms that are usable in development review. This does not mean that only municipal scale work remains to be done; rather, it identifies the particular scale at which the present thesis is positioned to contribute.

The third observation is a translation and usability challenge between land diagnosis and development review. Existing literature often stops at the production of hazard, sensitivity, or vulnerability maps, while standards and permits focus on the requirements of a specific project. For the purposes of this thesis, a key need is a transparent way to move from mapped land conditions to municipal planning responses. This includes the construction of a planner facing permafrost hazard susceptibility overlay, the backend analytical procedure needed to generate it, the meaning of the classes it displays, the treatment of uncertainty, and the connection between those classes and development review prompts.

The fourth observation concerns change over time. Permafrost susceptibility is dynamic because it is shaped by evolving thermal and environmental conditions, including snow, vegetation, drainage, and climate warming. Many existing documents acknowledge these factors, but fewer show how present conditions, future scenarios, and planning use can be brought together in one structured workflow. This is particularly important in Iqaluit, where the planning question is not only what the ground is like now, but how land conditions may influence future development choices under continued warming.

Altogether, these observations show the specific contribution of the present thesis within a broader and still evolving field. The thesis does not claim that international, national, regional, territorial, or engineering scale work is complete. Rather, it focuses on a narrower gap: the need to synthesize existing technical and planning knowledge into a planning scale framework for a future internal, city staff facing GIS overlay, including backend classification logic that could complement the City of Iqaluit's existing review processes, and its evolving Climate Hazard Mapping initiative (City of Iqaluit, 2026). The framework is intended to support one part of municipal development decision-making. It does not replace continued community consultation, site-specific geotechnical investigation, detailed engineering design, or consideration of other planning, policy, servicing, environmental, and land related factors.

6.4 Chapter Summary

This chapter has shown that substantial knowledge already exists across multiple scales. The literature on hazard and susceptibility mapping provides useful methodological lessons about indicator selection, climate scenarios, scale, and the distinction between susceptibility, vulnerability, and risk. The standards and guidance landscape provides strong support for testing, site investigation, project level engineering design, climate adaptation, and permit review. Read together, these bodies of work provide much of the technical and procedural foundation on which the present research builds. The remaining gap is the translation of that foundation into a planning scale framework and tool specification that can support municipal development review in Iqaluit and inform or be evaluated alongside the City's evolving hazard mapping work. The following chapter explains how the study develops that framework.

PART III: Methodology, Framework and Illustrative Application

Chapter 7: Representative Standards and Guidance Relevant to Permafrost-informed Planning

7.1 Introduction

Chapters 4, 5, and 6 established the basis for the proposed framework. Chapter 4 identified the physical, thermal, mechanical, climatic, terrain, and environmental factors that influence thaw-related ground behavior. Chapter 5 examined how existing mapping approaches select, rate, combine, project, and validate these factors at different scales. Chapter 6 reviewed the standards, guidance, and planning context that define where municipal screening could support development review and where site-specific professional assessment remains necessary.

This chapter explains how these bodies of evidence were translated into a proposed framework for developing a Permafrost Hazard Susceptibility Index (PHSI). The resulting susceptibility classes would inform the creation of a future GIS overlay for the populated area of Iqaluit.

The thesis develops a framework rather than an operational municipal model. The framework defines how the PHSI could be constructed from available evidence and how the resulting classes could later be represented through a municipal GIS overlay. It does not produce a completed citywide overlay, a functioning web portal, final Iqaluit thresholds or weights, or parcel-specific engineering conclusions. Local data compilation, field investigation, calibration, validation, municipal user testing, and GIS deployment remain future implementation tasks. The framework is an academic proposal and is not presented as a City-approved product. The PHSI brings together two linked questions:

- How strongly do the available conditions indicate potential for thaw-related change? and
- What physical ground response could occur if thaw reaches susceptible material?

The result is expressed as relative land susceptibility: Low, Moderate, High, or Unknown / Insufficient Data. These are susceptibility classes, not probability of failure, risk levels, statements of site safety, or development decisions. A risk assessment would also require information about exposure, vulnerability, and the potential consequences of the hazard.

Section 7.2 describes the research design, case study, and intended users. Section 7.3 identifies the evidence supporting the framework and the required traceability. Section 7.4 presents the common PHSI architecture and its application to baseline and future conditions. Section 7.5 specifies the analytical and spatial procedures. Section 7.6 explains how the resulting GIS overlay could support municipal review. Section 7.7 outlines the implementation requirements and methodological limitations.

7.2 Research Design, Case Study and Intended Users

The research uses an applied, qualitative case study design centered on framework development, with Iqaluit as the single case. Iqaluit provides the physical setting and municipal development review context in which the framework is considered. A case study design is appropriate because the research addresses a contemporary planning problem that is closely connected to its local technical and institutional context (Yin, 2018).

Document analysis was used to review and evaluate the evidence used to develop the framework (Bowen, 2009). The materials examined included peer-reviewed scientific publications, mapping studies, engineering standards, technical guidance, municipal plans and by-laws, maps, and descriptions of relevant datasets. The analysis involved three tasks:

- Identify the physical factors and forms of evidence needed to characterize thaw-related land susceptibility.
- Identify defensible methods for representing, rating, combining, calibrating, validating, and communicating those factors.
- Translate the analytical results into a framework that can inform a future GIS overlay for early municipal development review without replacing site-specific investigation or municipal judgement.

The intended area of application is the populated area of Iqaluit defined in Chapter 2. The framework is developed for planning-scale screening within this area rather than the full municipal territory.

The intended users of the future GIS overlay are members of an internal municipal technical review team. Depending on the proposal, this may include City and community planners, transportation planners, engineers with expertise in geotechnical engineering, municipal infrastructure, utilities, and water systems, and other City staff with relevant expertise. The visible output should be understandable to staff without specialized permafrost expertise, while the supporting technical record should allow qualified reviewers to trace the evidence, assumptions, processing rules, and limitations behind the mapped class.

Discussions with City of Iqaluit planning staff helped clarify the development review context and the types of questions that may arise when a site is examined. These discussions were contextual and were not conducted as formal interviews or municipal user testing. They do not constitute municipal endorsement of the proposed framework.

7.3 Evidence Base and Traceability

The framework draws on literature and evidence that support specific design decisions. Table 7.1 identifies each design element, its contribution to the proposed framework, the decision it informs, and its status in this thesis. Standards and municipal documents inform the use and implementation of the overlay and are addressed in Sections 7.6 and 7.

Table 7.1. Literature and evidence informing the design of the proposed framework

Framework design element	Contribution to the proposed framework	Decision informed	Status in this thesis	Supporting sources
Conceptual architecture	Separates the potential for thaw from the physical ground response if thaw occurs, and treats thaw potential as a function of thermal response and ground thermal state	Common architecture used for baseline and future conditions	Adapted conceptually	Smith and Burgess (2004)
Future ground thermal state projection	Pairs observed mean annual ground temperature and active layer thickness with geospatial predictors. Applies projected climate inputs to estimate future thermal conditions	Method for producing future GTS, not the overall PHSI architecture	Methodological precedent	Karjalainen et al. (2019), Daanen et al. (2011), Ni et al. (2021), and Allard et al. (2023)
Indicator selection and analytical roles	Identifies variables that represent thermal response (TR), ground thermal state (GTS), and thaw impact (TI)	Assignment of evidence to TRI, GTS, and TII	Indicator groups proposed from literature.	Smith and Burgess (2004); Nelson et al. (2002); Hong et al. (2014); Karjalainen et al. (2019); Mohammadi and Hayley (2023)
Ratings, thresholds, weights, and	Provides methods for reclassifying variables expressed in different forms, applying weights within each branch,	Indicator ratings, weighting, TPI and PHSI	Procedures specified	Smith and Burgess (2004); Hong et al. (2014); Karjalainen et

class construction	defining class breaks, and combining branch results	matrices, and final classes		al. (2019); Ni et al. (2021); Saaty (2008)
Spatial representation and local scale	Shows how mapped layers and point observations can be combined without assuming equal coverage or resolution	Analytical unit, effective resolution, local prediction surfaces, and parcel queries	Local pilot and reliable data required before operational mapping	Hengl (2006); Short et al. (2014); Oldenborger et al. (2022); Allard et al. (2023)
Calibration, validation, uncertainty, and traceability	Provides methods for comparing mapped results with local observations, testing transferability and sensitivity, and documenting uncertainty	Calibration, spatial validation, confidence, evidence requirement, and Unknown / Insufficient Data	Procedure specified	Short et al. (2014); Karjalainen et al. (2019); Oldenborger et al. (2022); Ni et al. (2021); Allard et al. (2023)

7.4 Proposed Framework Structure

7.4.1 Overall conceptual architecture

The proposed framework contains five analytical components. Table 7.2 defines the function, principal information, and output of each component.

Table 7.2. Analytical components of the proposed framework

Component	Function	Principal information	Output
Thermal Response Index (TRI)	Represents how surface, terrain, and near-surface conditions modify heat transfer between the atmosphere and the ground	Snow, vegetation and organic cover, surface moisture and drainage, terrain, and the thermal role of surface material	Low, Moderate, or High thermal-response class
Ground Thermal State (GTS)	Represents the observed or projected thermal condition of the ground	Mean annual ground temperature (MAGT), active layer thickness (ALT) or end of season thaw depth, and thermal trend	Low, Moderate, or High ground thermal-state class
Thaw Potential Index (TPI)	Represents the potential for thaw-related change at the selected condition and horizon	Explicit combination of TRI and GTS	Low, Moderate, or High thaw-potential class
Thaw Impact Index (TII)	Represents the potential physical ground response if thaw reaches the relevant material	Surficial setting or material type, soil texture or grain size, and ground ice content	Low, Moderate, or High thaw-impact class

Permafrost Hazard Susceptibility Index (PHSI)	Represents the combined relative susceptibility of the land to thaw-related ground effects	Explicit combination of TPI and TII	Low, Moderate, High, or Unknown / Insufficient Data, with confidence reported separately

The common relationships are:

$$TPI = f(TRI, GTS)$$
$$PHSI = f(TPI, TII)$$

Smith and Burgess (2004) provide the main conceptual precedent for separating the thermal response of permafrost from the physical response of the ground. This thesis adapts that distinction by using TRI and GTS to characterize thaw potential and TII to characterize the physical response if thaw reaches susceptible material. The indicator roles, weighting procedure, spatial treatment, future GTS method, minimum evidence requirement, confidence criteria, and municipal interface draw on the wider evidence summarized in Table 7.1.

Figure 7.1 presents the common architecture. The minimum evidence requirement is applied before a PHSI class is assigned. If essential evidence for TRI, GTS, or TII is missing, the result is Unknown / Insufficient Data. Confidence is reported beside the class and does not change the susceptibility rating.

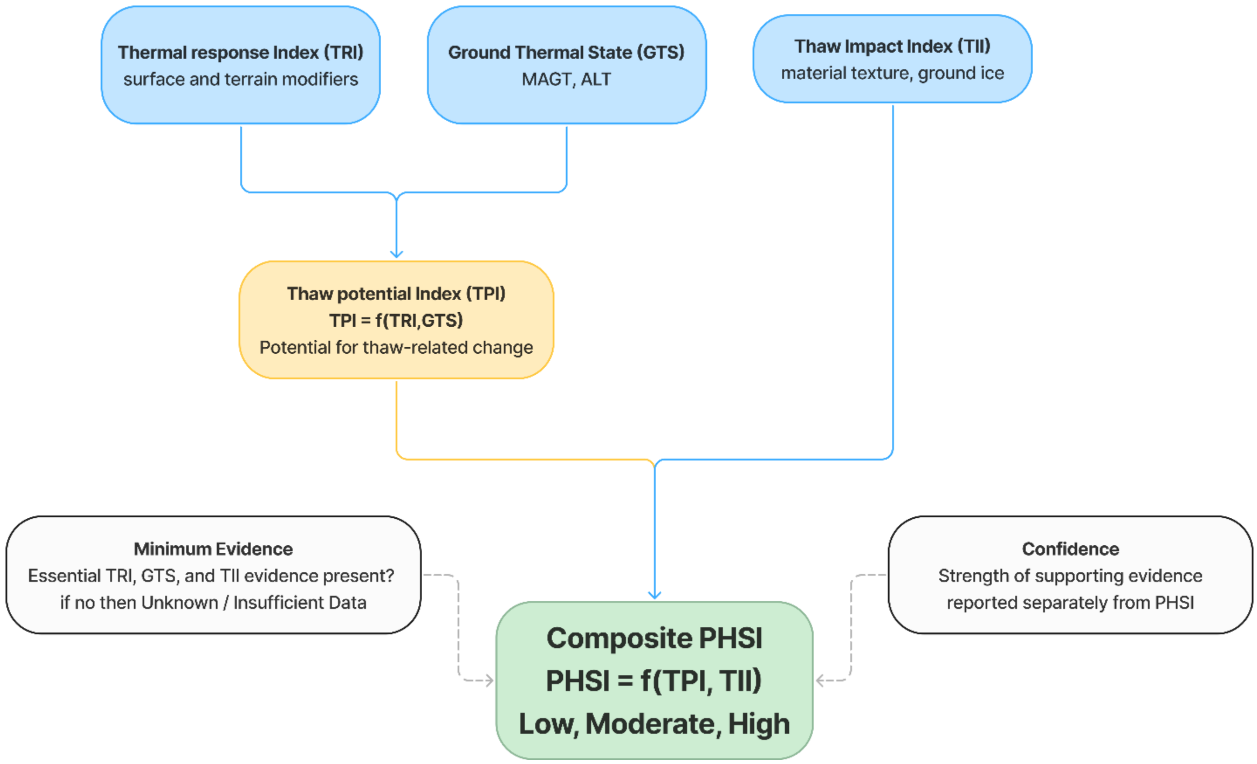

Figure 7.1. Overall conceptual architecture of the proposed Permafrost Hazard Susceptibility Index framework

7.4.2 Current/baseline condition

The baseline condition applies the common architecture to a defined reference period. Current TRI represents available surface and near-surface thermal modifiers. Current GTS represents observed or locally modelled MAGT, active layer thickness, and relevant thermal trends. Current TII represents the baseline physical ground setting, principally material type, soil texture, and ground ice content, which control the response if thaw occurs. The baseline relationships are:

$$TPI_0 = f(TRI_0, GTS_0)$$
$$PHSI_0 = f(TPI_0, TII_0)$$

where the subscript 0 denotes the defined baseline or reference period. Rated indicators are combined within TRI, GTS, and TII. TRI_0 and GTS_0 form TPI_0, and TPI_0 and TII_0 form $PHSI_0$. The minimum evidence requirement determines whether the required branches are sufficiently supported, while confidence is reported separately.

Current observations of MAGT and ALT are likely to be point-based and unevenly distributed. Where they are too sparse for direct continuous mapping, they may be paired with geospatial predictors to produce locally calibrated GTS surfaces. The resulting surface must be evaluated at the scale at which it will be used. A modelled or interpolated value is not treated as a direct measurement at every cell. The baseline application assumes:

1. A defined reference period;
2. Evidence that is sufficiently current and spatially suitable for that period;
3. Undeveloped land with no known prior anthropogenic disturbance, unless disturbance is represented explicitly; and
4. Assessment of land conditions independently of a particular building, servicing plan, or engineering design.

Previously disturbed land requires current fill, grading, drainage, snow redistribution, thermal disturbance, and observed performance to be represented where relevant. Effects associated with a particular proposal remain outside the land-only PHSI and are considered during development review.

7.4.3 Future condition

The same architecture is applied to a selected future planning horizon and climate scenario. Future GTS is the component that changes directly through climate projection and ground thermal modelling. It is derived from projected MAGT and ALT or thaw depth using the method described in Section 7.5.4.

The framework retains TRI_0 unless suitable projected information is available for snow, vegetation, organic cover, moisture, drainage, or other surface modifiers at the required spatial scale. Retaining TRI_0 does not imply that these conditions will remain unchanged. It indicates that their future spatial change cannot be represented defensibly with the available evidence. Where a suitable projected Surface modifier becomes available, it may replace the corresponding baseline indicator.

TII_0 is also retained as the reference physical ground setting. The framework does not simulate progressive depletion of ground ice, post-thaw consolidation, or changes in material composition. Where depth-resolved borehole, geophysical, or material information shows that projected thaw would reach a different unit, TII_0 should be interpreted using the baseline properties of that deeper unit. This keeps the physical ground setting fixed while allowing the relevant depth of assessment to follow projected thaw penetration. The future relationships are:

$$TPI^f = f(TRI_0, GTS^f)$$
$$PHSI^f = f(TPI^f, TII_0)$$

where the subscript f denotes the selected future horizon and scenario. Future PHSI therefore changes mainly through GTS^f unless defensible information on future surface conditions is introduced. The horizon, scenario, model version, calibration period, retained baseline variables, and depth interpretation of TII must be recorded for each future layer. Daanen et al. (2011), Karjalainen et al. (2019), and Allard et al. (2023) provide precedents for scenario-based projection of ground thermal conditions.

The future class remains a land susceptibility projection informed by the selected climate scenario. It does not predict the effects of a future development. Building heat, clearing, grading, fill, drainage changes, snow management, servicing, loading, and foundation design are considered separately for a defined proposal during review.

7.5 Analytical and Spatial Specification

7.5.1 Indicator roles and required evidence

An indicator should be included only where a defined physical relationship connects it to the Thermal Response Index (TRI), Ground Thermal State (GTS), or Thaw Impact Index (TII). Table 7.3 identifies the proposed role of each indicator group, the evidence required, and its spatial treatment. Mapped layers, observation points, boreholes, transects, laboratory results, and monitoring records do not provide the same level of spatial coverage

Table 7.3. Proposed indicator roles and required evidence

Indicator or evidence group	Analytical role and reason	Required or preferred evidence	Spatial treatment	Supporting sources
Snow depth, duration, density, timing, and redistribution	TRI. Snow affects seasonal heat exchange between the atmosphere and the ground	Local observations or modelled seasonal surfaces, together with terrain, wind, vegetation, and snow management information	Seasonal or climatological mapped surface, supported by local observations	Smith and Burgess (2004); Zhang (2005); AMAP (2017)
Vegetation and organic cover	TRI. Surface cover affects insulation, radiation, moisture, and near-surface heat transfer	High-resolution imagery, land-cover mapping, field checks, and organic-layer observations	Surface classes or terrain units refined using field evidence	Smith and Burgess (2004); Karjalainen et al. (2019)
Surface moisture, drainage, hydrology, slope, aspect, and microrelief	TRI. These conditions affect heat transfer, ponding, snow redistribution, and local terrain response	High-resolution elevation data, terrain derivatives, surface-water and drainage mapping, imagery, and field observations	Raster layers, drainage units, or terrain units at a locally supportable scale	Karjalainen et al. (2019); Wang et al. (2023)
Surficial setting and surface material	TRI. Surface material affects heat transfer and moisture behaviour	Surficial geology and terrain mapping supported by exposures, boreholes, geophysics, and field checks	Material or terrain units with a TRI-specific rating	Smith and Burgess (2004); Oldenborger et al. (2022)

Mean annual ground temperature (MAGT) and thermal trend	GTS. MAGT directly represents how warm or cold the ground is and whether it is changing	Quality-controlled thermistor records with depth, observation period, and site information, together with locally calibrated model outputs	Monitoring points and locally calibrated prediction surfaces	Daanen et al. (2011); Karjalainen et al. (2019); Allard et al. (2023)
Active layer thickness (ALT)	GTS. ALT represents the depth of seasonal thaw and how it changes relative to a defined local condition	Repeated georeferenced measurements near the seasonal maximum, with the date, substrate, moisture, and surface setting recorded	Monitoring points and locally calibrated prediction surfaces	Brown et al. (2000); Hinkel and Nelson (2003); Karjalainen et al. (2019)
Surficial or subsurface material type and soil texture or grain size	TII. Material type and texture affect the potential physical response if thaw occurs	Boreholes, cores, test pits, laboratory classification, exposures, and geotechnical records	Material or terrain units characterized using point and transect evidence	Smith and Burgess (2004); Nelson et al. (2002); Mohammadi and Hayley (2023)
Ground ice content and distribution	TII. Excess ground ice controls the amount and form of potential thaw settlement. Cryostructure supports interpretation of the ground ice	Boreholes and cores, calibrated geophysics, exposures, laboratory information, and geotechnical records	Depth-specific point or transect evidence used to characterize or subdivide material units	Smith and Burgess (2004); Nelson et al. (2002); Hong et al. (2014)

Moisture content, thaw strain, and strength response	Supporting calibration and validation evidence used to test the proposed response of TII units	Laboratory testing and project geotechnical records with suitable sampling information	Point evidence linked to the sampled material and depth, not a default continuous index layer	Nelson et al. (2002); Mohammadi and Hayley (2023)
DInSAR, surveyed deformation, terrain observations, and documented ground performance	Calibration and validation. These observations allow mapped conditions to be compared with observed surface response	Quality-controlled, multi-date displacement or performance records interpreted with the limits of the method	Observation surfaces, points, transects, or asset records. Independent records should be retained for validation	Short et al. (2014); Oldenborger et al. (2022)
Climate projections and derived climate variables	Future GTS. These data provide the climate information used to predict future MAGT and ALT	A documented climate scenario, planning horizon, downscaled variables, and ground thermal model inputs	A separate set of inputs for each supported scenario and horizon	Daanen et al. (2011); Karjalainen et al. (2019); Allard et al. (2023)

The same source variable may have different roles within the framework. Surficial geology, for example, may contribute to TRI through the thermal behavior of the surface material and to TII through the expected physical response if thaw occurs. The rating must therefore be specific to the branch in which the variable is used. The same evidence should not be counted more than once within one branch.

Snow requires a process-specific rating. Greater snow depth cannot be assigned a universal Low or High value because its thermal effect depends on timing, duration, density, redistribution, melt, terrain, and vegetation. Winter snow commonly insulates the ground, but local accumulation, removal, and redistribution can change the strength of this effect (Zhang, 2005; AMAP, 2017).

ALT also cannot be treated as a stand-alone measure of susceptibility. Its significance depends on the measurement date, interannual variability, soil and ground ice conditions, and whether thaw reaches susceptible material. The same ALT over bedrock or ice-poor coarse sediment may have a different implication from that ALT in ice-rich fine-grained soil (Nelson et al., 2002).

Mechanical probing can provide repeatable local estimates of ALT where refusal can reasonably be attributed to frozen ground. Measurements should be taken near the seasonal maximum at fixed, georeferenced locations. The date, vegetation, moisture, and substrate should also be recorded. Probing is unreliable where clasts, fill, bedrock, or water cause refusal. Thermistors, thaw tubes, boreholes, or geophysical methods may then be required (Brown et al., 2000; Hinkel and Nelson, 2003).

7.5.2 Ratings, thresholds, weighting, and class construction

The proposed analytical process moves through three levels. Individual indicators are first rated within the Thermal Response Index (TRI), Ground Thermal State (GTS), or Thaw Impact Index (TII). The rated indicators are then combined within their assigned branch and converted into a Low, Moderate, or High branch class. The branch classes are then combined to form the Thaw Potential Index (TPI) and the final Permafrost Hazard Susceptibility Index (PHSI).

Figures 7.4 and 7.5 illustrate the proposed analytical process at two levels of detail. Figure 7.4

presents the complete workflow, beginning with indicator evidence and proceeding through indicator rating, within-branch combination, branch classification, construction of the Thaw Potential Index (TPI), and assignment of the final Permafrost Hazard Susceptibility Index (PHSI) class. Figure 7.5 expands the matrix-based steps shown in that workflow by presenting the proposed rules for combining the Thermal Response Index (TRI) and Ground Thermal State (GTS) classes into TPI, and the TPI and Thaw Impact Index (TII) classes into PHSI.

The examples below explain how quantitative thresholds, categorical rankings, conditional rules, weighting, and rule-based combination could be applied. They illustrate the process and do not establish final Iqaluit thresholds, weights, class breaks, or matrix rules.

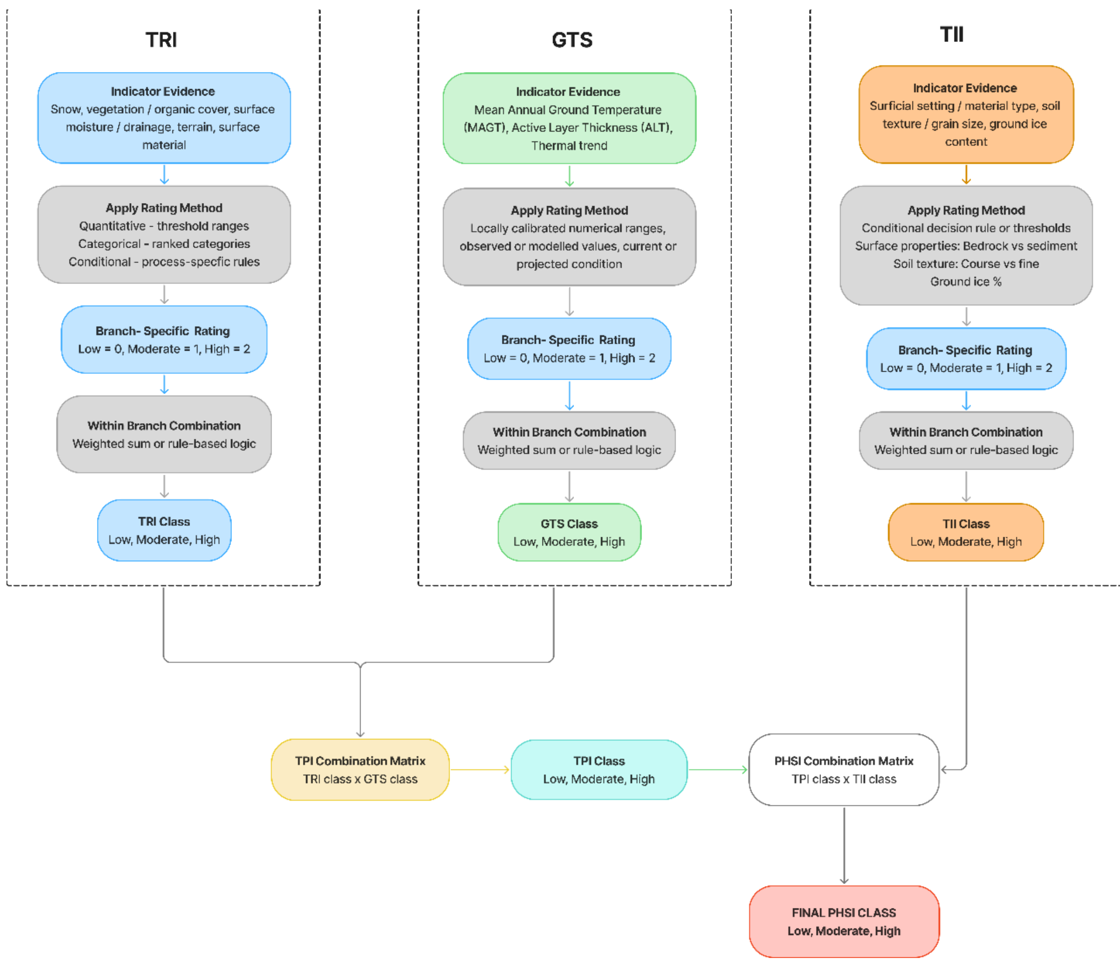

Figure 7.2. Proposed analytical workflow for indicator rating, within-branch combination, branch classification, and final PHSI construction

Note: the figure presents the complete sequence from indicator evidence to the final PHSI class. Indicators are first rated within TRI, GTS, or TII, then combined and classified within their respective branches. TRI and GTS are combined to form TPI, which is then combined with TII to form PHSI. The figure does not establish final Iqaluit thresholds, weights, class breaks, or matrix rules. These require local calibration, sensitivity testing, and validation.

TPI = TRI class x GTS class

TRI class

GTS class

GTS / TRI	Low	Moderate	High
Low	Low	Moderate	Moderate
Moderate	Moderate	Moderate	High
High	High	High	High

PHSI = TPI class x TII class

TPI class

TII class

GTS / TRI	Low	Moderate	High
Low	Low	Moderate	Moderate
Moderate	Moderate	Moderate	High
High	High	High	High

Rule summary: Low+High = Moderate, Moderate +High =High, Moderate+Moderate = Moderate

The matrices preserve both branches and do not replace local calibration or engineering judgement

Figure 7.3. Proposed TPI and PHSI class-combination matrices

Note: the figure expands the matrix-based combination steps shown in Figure 7.4. The first matrix combines TRI and GTS classes to form TPI. The second combines TPI and TII classes to form PHSI. The distinction between thaw potential and physical ground response is informed by Smith and Burgess (2004). The exact matrix cells are proposed in this thesis and require local calibration, sensitivity testing, and validation.

Indicator rating methods: Ratings translate indicators measured in different units or described using different categories into a common ordinal scale within TRI, GTS, or TII. Three rating methods are proposed:

1. Quantitative thresholds
2. Categorical rankings
3. Conditional or process-specific rules

These methods are not assigned exclusively to one branch. They are selected according to the form of the indicator and the physical relationship being represented. Whether an indicator value is observed or modelled, and whether it represents a baseline or future condition, does not constitute a separate rating method. These terms describe the source and time horizon of the evidence. Once the indicator value has been established, it is rated using a quantitative threshold, categorical ranking, or conditional rule.

Table 7.4. Proposed rating methods for different forms of indicator evidence

Rating Method	When it is used	Example	Result
Quantitative thresholds	The indicator is represented by a measured or modelled numerical value	MAGT, ALT, slope, or snow depth divided into locally supported ranges	Branch-specific rating of 0, 1, or 2
Categorical rankings	The indicator is represented by named classes	Drainage ranked as well drained, intermediate, or poorly drained; material grouped as bedrock, coarse sediment, or fine sediment	Branch-specific rating of 0, 1, or 2
Conditional or process-specific rules	The effect of one indicator depends on another condition or cannot be represented by a simple increasing scale	Snow interpreted using depth, timing, duration, and redistribution; TII determined from material type, grain size, and ground ice	Branch-specific rating or direct branch class
Missing essential evidence	The available information does not support a rating	Ground ice information is absent for a material unit	Unknown / insuficient data

Quantitative thresholds: quantitative threshold is a numerical boundary used to separate Low, Moderate, and High conditions. Mean Annual Ground Temperature (MAGT), for example, could be divided using two locally established thresholds, T_1 and T_2:

- MAGT $< T_1$
- $T_1 \leq$ MAGT $\leq T_2$

- $MAGT \geq T_2$

These ranges could then be assigned Low, Moderate, and High GTS ratings, with warmer ground closer to 0°C generally receiving the higher rating. The final values of T_1 and T_2 would be based on Iqaluit observations, the relationship between ground temperature and observed ground response, and sensitivity testing.

Active Layer Thickness (ALT) could be represented in a similar range structure using thresholds A_1 and A_2. Its rating, however, cannot be based on depth alone. A deeper active layer over bedrock or ice-poor coarse sediment may have a different implication from the same ALT where thaw approaches ice-rich fine-grained soil. ALT ranges would therefore need to be interpreted with the material and ground ice profile before Low, Moderate, or High GTS ratings are assigned.

Snow depth is also measured quantitatively and could initially be divided using thresholds S_1 and S_2. However, the direction of the rating cannot be determined from depth alone. The thermal effect of snow also depends on its timing, duration, density, redistribution, melt, terrain setting, and vegetation. A deeper snow cover may provide stronger insulation in one setting, while wind redistribution or snow removal may produce a different thermal response in another. Snow therefore demonstrates that a quantitative measurement may still require a conditional rating rule (Zhang, 2005; AMAP, 2017).

Categorical rankings: Categorical indicators are represented by named classes rather than continuous numerical values. The categories are ranked according to their expected behavior within the relevant branch. Drainage, for example, could be described as well drained, intermediate, or poorly drained. These categories could then be assigned Low, Moderate, or High TRI ratings where local evidence shows how drainage and ponding affect heat transfer and ground conditions. Material type provides another example. Bedrock, coarse-grained sediment, and fine-grained sediment may receive different TII ratings because they have different expected physical responses if thaw occurs. Bedrock and coarse-grained sediment would generally be associated with lower thaw-settlement response than fine-grained, ice-rich sediment.

The same categorical variable may receive different ratings in different branches. Coarse surficial material, for example, may permit relatively strong heat transfer and receive a higher TRI rating, while the same material may have comparatively limited thaw-settlement potential and receive a lower TII rating. The rating must therefore reflect the physical question addressed by the branch.

Conditional or process-specific rules: A conditional rule is used where the interpretation of one indicator depends on another condition. It is also appropriate where the physical relationship cannot be represented by a simple progression from smaller to larger values. Snow is one example. A deep and persistent snow cover may provide strong winter insulation, but its effect depends on timing, duration, density, wind redistribution, terrain, and vegetation. A snow rating may therefore begin with a depth range and then be adjusted using an explicit rule that accounts for these additional conditions.

TII provides a clearer example of a conditional decision structure. The assessment could first distinguish bedrock from sediment. Bedrock could be assigned a Low TII class because limited settlement is expected from thaw of intact rock. Where sediment is present, the assessment would proceed to soil texture or grain size and ground ice content. An illustrative rule could be:

- bedrock = Low TII;
- coarse-grained sediment with low ground ice = Low TII;
- fine-grained sediment with low ground ice = Moderate TII; and
- sediment with high ground ice = High TII.

These combinations demonstrate the logic. The specific relationships among material type, grain size, and ground ice would require local borehole information, geophysical evidence, calibration, and validation. This type of conditional classification is informed by the decision-flow approaches used by Daanen et al. (2011) and Karjalainen et al. (2019).

Establishing rating rules: Thresholds, categorical rankings, and conditional rules should be developed using the following order of evidence:

1. Local measured relationships and observed ground response in Iqaluit.
2. Published physical relationships from comparable permafrost settings.
3. Structured expert judgement where local observations are incomplete.

The procedure for establishing a rating rule is:

1. Define the physical condition represented by the indicator within its assigned branch.
2. Compile relevant Iqaluit observations and published relationships from comparable settings.
3. Propose numerical thresholds, categorical rankings, or conditional rules that reflect the expected physical behavior.
4. Apply the proposed rule within a representative pilot area.
5. Test how reasonable changes to the rule affect indicator ratings, branch results, and final classes.
6. Calibrate the rule using representative local evidence.
7. Validate the adopted rule using observations that were not used during calibration.

Oldenborger et al. (2022) provide a comparable Nunavut example in which seasonal subsidence and ground conditions were used to establish thaw-sensitivity classes. Allard et al. (2023) demonstrate how boreholes, geophysics, thermistors, laboratory information, terrain mapping, and calibrated modelling can support community-scale classification. Broad regional classifications may inform initial rating rules, but they are not treated as Iqaluit-specific thresholds.

Branch-specific ratings: Each rating method produces a branch-specific ordinal rating:

- 0 = Low
- 1 = Moderate
- 2 = High

These numbers are calculation codes for ordered classes. A rating of 2 does not represent twice the physical condition represented by a rating of 1. The term branch-specific means that the rating is assigned according to the role of the indicator within TRI, GTS, or TII. The same indicator may receive different ratings in different branches because it represents a different physical relationship. The branch-specific rating is the output of the rating method. It is not a separate rating method. For example:

- A MAGT value is compared with locally established quantitative thresholds and assigned a GTS rating of 0, 1, or 2;
- A drainage category is compared with ranked classes and assigned a TRI rating of 0, 1, or 2; and

- A material and ground ice combination is evaluated using a conditional rule and assigned a TII rating of 0, 1, or 2 or class.

Combining rated indicators within each branch: After the individual indicators have been rated, the ratings are combined within TRI, GTS, or TII. Rating and weighting are separate steps. A rating describes the condition represented by an indicator. A weight describes the relative influence assigned to that rated indicator within its branch. Where the indicators have an additive relationship, their ratings may be combined using a normalized weighted sum:

$$S^b = \sum(W_{ib} \times r_{ib}), \text{ where } \Sigma w_{ib} = 1$$

where:

- S_b is the score for branch (b);
- r_{ib} is the rating assigned to indicator (i) within that branch; and
- W_{ib} is the normalized weight assigned to the indicator.

Illustrative TRI Calculation: Assume that three TRI indicators receive the following ratings: snow rating = 2, organic-cover rating = 1, and drainage rating = 0. If the illustrative weights are 0.40, 0.30, and 0.30, the TRI score would be:

$$TRI = (0.40\times2) + (0.30\times1) + (0.30\times0)$$

$$TRI = 1.10$$

Illustrative GTS Calculation: Assume that MAGT and ALT receive the following ratings: MAGT rating = 2, and ALT rating = 1. If the illustrative weights are 0.60 and 0.40, the GTS score would be:

$$GTS = (0.60\times2) + (0.40\times1)$$

$$GTS = 1.60$$

The relative influence of MAGT and ALT, and the class assigned to a score of 1.60, would require local calibration, sensitivity testing, and validation.

Weighted multi-indicator approaches have been used in permafrost hazard and susceptibility mapping by Hong et al. (2014), Karjalainen et al. (2019), and Mohammadi and Hayley (2023).

The normalized weighted sum proposed here is informed by those approaches. It is not derived directly from Smith and Burgess (2004). Where empirical estimates are incomplete, the Analytic Hierarchy Process (AHP) may be used to compare the relative importance of indicators and derive normalized weights through structured expert judgement (Saaty, 2008). AHP is applied after indicators have been rated. It can inform indicator weights, but it does not establish the thresholds used to rate MAGT, ALT, snow, or other variables. Equal weights may be used as an initial comparison during pilot testing. No weighting method should be adopted without sensitivity testing and validation. Closely related indicators should also be examined to avoid double counting.

Rule-based combination within TII: A weighted sum is not required where the physical relationship is conditional. TII may be better represented by a decision rule because the meaning of ground ice depends on material type and grain size. Using the illustrative rule described above:

- bedrock would produce a Low TII class;
- coarse grained sediment with low ground ice would produce a Low TII class;
- fine grained sediment with low ground ice would produce a Moderate TII class; and
- Sediment with high ground ice would produce a High TII class.

In this case, the rule may produce the TII class directly rather than first producing a numerical TII score. This is why Figure 7.4 refers to either a weighted sum or rule-based logic within a branch. The method used should reflect the physical relationship among the indicators rather than applying the same mathematical procedure to every branch.

Converting branch results into classes: Where a weighted sum is used, the resulting TRI or GTS score is converted into a Low, Moderate, or High branch class using locally calibrated class breaks. Indicator thresholds and branch class breaks perform different functions:

- Indicator thresholds convert an individual value or category into a rating of 0, 1, or 2.
- Branch class breaks convert a combined branch score into a Low, Moderate, or High TRI or GTS class.

For example, the illustrative TRI score of 1.10 cannot be labelled Low, Moderate, or High until the TRI class breaks have been established. Similarly, a GTS score of 1.60 does not automatically correspond to a particular class. Where a conditional decision rule is used, as illustrated for TII, the rule may assign the branch class directly.

Combining branch classes into TPI and PHSI: After the TRI, GTS, and TII classes have been established, TRI and GTS are combined through the TPI matrix. The resulting TPI class is then combined with TII through the PHSI matrix. The matrices therefore operate only after indicator rating, within-branch combination, and branch classification have been completed. Smith and Burgess (2004) provide the conceptual basis for keeping thermal response, ground thermal condition, and physical ground response distinct before combining them into an overall susceptibility interpretation. Their study does not provide the exact three-by-three matrices shown in Figure 7.5.

The matrices in Figure 7.5 are proposed in this thesis. The TPI matrix gives greater influence to GTS where the GTS class is High. A High TRI combined with Low GTS produces Moderate TPI, while High GTS produces High TPI even where TRI is Low. This treatment is proposed because GTS represents the existing thermal condition of the ground and therefore its proximity to thaw, while TRI represents the rate and magnitude at which surface and near-surface conditions may transmit atmospheric warming to the ground. Smith and Burgess (2004) found that areas could exhibit a High thermal response but retain lower thaw potential where the underlying permafrost was colder than approximately −5°C. In contrast, ground temperatures warmer than approximately −2°C were associated with High thaw potential because less additional warming would be required to initiate thaw. The proposed matrix therefore treats High GTS as the more immediate control on thaw potential, while High TRI over comparatively cold ground produces a Moderate class. This is proposed conservative planning rule rather not reproduced from Smith and Burgess (2004), and it requires local calibration, sensitivity testing, and validation.

The PHSI matrix similarly gives greater influence to TII. A High TPI combined with Low TII produces Moderate PHSI, while High TII produces High PHSI even where TPI is Low. Giving greater influence to the physical ground response is consistent with Smith and Burgess (2004), although the exact matrix cells remain proposed. The remaining combinations are interpreted as follows:

- Low combined with Low produces Low;

- Moderate combined with Moderate produces Moderate;
- Moderate combined with High produces High; and
- Low combined with Moderate produces Moderate.

The final matrix rules must be selected through physical interpretation, local calibration, sensitivity testing, and validation.

A branch or final PHSI class is assigned only where the minimum evidence requirements are met. If an essential indicator or branch cannot be supported, the result is Unknown / Insufficient Data. Missing evidence is not assigned a Low rating, and its weight is not transferred automatically to the remaining indicators. Confidence is reported separately from the branch and PHSI classes. It describes the strength of the evidence supporting the assigned result and does not change the susceptibility class.

7.5.3 Spatial units, resolution and parcel queries

The spatial part of the framework distinguishes four concepts:

- Source resolution: the level of detail in the original dataset, such as its cell size, map scale, positional accuracy, or the spacing between observations.
- Analytical unit: the grid cell or terrain unit within which indicators are rated and combined.
- Minimum mapping unit: the smallest area retained as a separate feature in the final overlay.
- Effective resolution: the smallest spatial pattern that the available evidence and validation can reasonably support.

These concepts describe different parts of the mapping process. Using smaller grid cells does not automatically produce more detailed or accurate information. For example, dividing a regional dataset into smaller pixels changes how it appears on the map, but it does not add new local evidence. The detail shown in the final overlay should therefore reflect the quality, accuracy, and coverage of the information used to create it (Hengl, 2006). The analytical unit and effective resolution should be established through pilot work in representative neighborhoods within the populated area. The pilot would compare different grid sizes and terrain units by considering:

- the detail and accuracy of the available datasets;
- differences in terrain and surficial materials;

- the number and distribution of boreholes and monitoring locations;
- whether mapped class boundaries remain stable; and
- how well the resulting classes agree with independent observations.

The framework may use a grid, mapped terrain units, or a combination of both. Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT) may be represented as continuous prediction surfaces. Material type, soil texture or grain size, and ground ice may be represented through terrain or material units supported by boreholes and other subsurface information. These layers can be combined in the GIS, but the final overlay should not show more detail than the supporting evidence can justify.

MAGT and ALT are generally measured at individual monitoring locations. Additional analysis is therefore needed to estimate conditions between those locations. A locally calibrated model could use the point measurements together with relevant mapped information to produce continuous MAGT and ALT surfaces. These surfaces would represent modelled estimates, not direct measurements at every location. Section 7.5.4 explains how current and future MAGT and ALT surfaces could be produced.

TII would more likely be mapped using terrain or material units. Boreholes, cores, exposed materials, laboratory results, and geophysical surveys could be used to determine whether a unit consists of bedrock or sediment, identify its soil texture or grain size, and describe its ground ice content. A TII class should be assigned only where the available evidence supports those conditions for the relevant unit and depth. Where the minimum evidence requirements are not met, the unit should remain Unknown / Insufficient Data.

Regional maps cannot simply be enlarged and treated as neighborhood-scale information. The products developed by Karjalainen et al. (2019), for example, are useful for circumpolar assessment, but they do not provide the local ground information required for municipal development review. Oldenborger et al. (2022) show that finer-scale prediction is possible where suitable local training data are available. They also show that a model developed from observations in one area may not perform equally well in different terrain. Hinkel and Nelson (2003) similarly document substantial local variation in ALT. These studies support the use of local data, testing of the proposed map detail, and independent validation.

After TRI, GTS, TPI, and TII have been combined, each analytical unit is assigned one final PHSI class for the selected planning horizon:

- Low;
- Moderate;
- High; or
- Unknown / Insufficient Data.

These classes are mutually exclusive. The final PHSI layer should therefore consist of non-overlapping mapped units or grid cells. Adjacent units may have different classes, but only one PHSI class should be displayed at any location for a selected planning horizon.

7.5.4 Climate scenario and ground thermal state (GTS) projection

The future PHSI requires a supported estimate of future Ground Thermal State (GTS). In this framework, GTS is represented by Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT). As explained in Section 7.4.3, future PHSI changes mainly through projected GTS. Baseline TRI and TII are retained unless reliable information supports a different future treatment. MAGT and ALT are generally measured at individual monitoring locations. These point observations must therefore be used with mapped environmental and climate information to estimate conditions between the monitoring locations. The resulting maps represent modelled estimates rather than direct measurements at every location.

Karjalainen et al. (2019) provide the main methodological precedent. They linked observed MAGT and ALT with mapped variables that help explain ground thermal conditions. They then tested several statistical and machine learning models and applied projected climate information to estimate future MAGT and ALT. Their circumpolar model cannot be transferred directly to Iqaluit, but the general procedure can be adapted using local observations and higher-resolution mapped information. The proposed procedure is:

1. Compile and review the observations: Assemble available MAGT and ALT records, including their locations, measurement depths, observation periods, dates, methods, and

site conditions. A common baseline period should be selected, and records that cannot be compared directly should be identified.

2. Link each observation to relevant mapped variables: At each MAGT and ALT monitoring location, identify the corresponding values of mapped variables that may help explain the observed condition. These may include:

- air temperature;
- precipitation;
- freezing degree days (FDD), which represent accumulated cold below 0°C;
- thawing degree days (TDD), which represent accumulated warmth above 0°C;
- potential solar radiation;
- soil organic carbon;
- terrain;
- moisture;
- surface cover; and
- other locally relevant variables.

These mapped variables are referred to as predictors because they are used to estimate MAGT and ALT across locations where direct measurements are not available.

3. Set aside information for independent testing: Some observations should be kept separate and should not be used to build the models. These observations can later be used to test how well the models perform at locations they have not already seen.
4. Develop several possible models: Different statistical and machine learning methods should be compared. Possible methods include:
    - generalized linear models;
    - generalized additive models;
    - random forest models; and
    - boosted regression models.

The appropriate method will depend on the number, location, and quality of the available observations.

5. Test the MAGT and ALT models separately: MAGT and ALT describe different ground conditions and should not be assumed to have the same level of accuracy. Each model should be tested using:

- spatial cross-validation, which checks performance at locations not used to build the model;
- held-out observations;
- hindcasting, which checks whether the model can reproduce earlier observed conditions;
- measures of prediction error; and
- maps showing where model errors are concentrated.

6. Select the best-supported model: The model that performs most reliably should be selected separately for MAGT and ALT. Several models may be combined where the combined result performs better, but only where this does not hide important disagreement among the individual models.
7. Select the climate scenario and planning horizon: The future assessment should identify:
   - the selected emissions or climate scenario;
   - the future period being assessed;
   - the climate-model source;
   - the method used to translate regional climate information to the local scale; and
   - the baseline period used for comparison.

These choices should be recorded for each future GIS layer.

8. Prepare the future predictor information: Future air temperature, precipitation, freezing degree days, thawing degree days, and other supported predictors should be obtained or calculated for the selected scenario and planning horizon. Where a variable cannot be projected reliably, the baseline condition should be retained and the assumption should be stated.
9. Produce future MAGT and ALT maps: The future predictor values are entered into the selected MAGT and ALT models. This produces continuous maps of projected ground temperature and active layer thickness. The results should also identify:
   - the expected range of values;
   - areas where the model is less reliable;
   - areas where the model is being applied beyond the conditions represented by the observations;
   - differences among the supported models; and

- differences among climate scenarios.

10. Convert the projected values into future GTS classes: Projected MAGT and ALT are rated using locally calibrated thresholds and combined to produce a future GTS class. The minimum evidence requirements must be met before a Low, Moderate, or High class is assigned. Confidence is then reported separately for the selected scenario and planning horizon.

Karjalainen et al. (2019) found that MAGT could be predicted more reliably than ALT using the available circumpolar observations. They used several model types for MAGT but a more limited model for ALT because fewer ALT observations were available. This distinction is important for Iqaluit. A reliable MAGT map does not mean that the ALT map is equally reliable, and the performance of the two variables should be reported separately. Daanen et al. (2011) provide an example of using regional climate projections to drive a ground thermal model. Allard et al. (2023) demonstrate how local thermistor records and site information can be used to calibrate community-scale ground thermal models under future climate conditions. Ni et al. (2021) also show how projected permafrost conditions can be incorporated into geohazard mapping. Together, these studies provide several possible methods for developing and testing future GTS estimates.

If the available observations, mapped predictors, climate projections, or model results cannot support future GTS at the selected map scale, a future GTS class should not be assigned for that area. The corresponding future PHSI result should remain Unknown / Insufficient Data rather than present an unsupported class.

7.5.5 Calibration and validation

Calibration and validation serve different purposes. Calibration uses local evidence to establish or adjust the ratings, thresholds, weights, class breaks, matrix rules, and map detail used in the framework. Validation tests whether those decisions perform well using evidence that was not used during calibration.

Calibration should begin in pilot areas that represent the main terrain, material, drainage, and ground thermal conditions within the populated area. Relevant evidence may include boreholes and cores, laboratory results, geophysical surveys, thermistor records, repeated Active Layer Thickness (ALT) measurements, terrain mapping, DInSAR, surveyed ground movement, and documented ground performance. The pilot would be used to refine the indicator ratings, branch class breaks, weighting methods, TPI and PHSI matrices, minimum evidence requirements, and effective map resolution.

Short et al. (2014) demonstrate how DInSAR can be compared with field observations and terrain information at Iqaluit Airport. Oldenborger et al. (2022) show how local deformation and ground-condition data can support thaw-sensitivity classification, while also showing that a model may not transfer reliably beyond the terrain represented by its training data. Allard et al. (2023) provide a community-scale example of combining boreholes, geophysics, thermistor records, laboratory information, terrain mapping, and modelling.

Validation should use independent observations that were kept separate from calibration and, where possible, are located in different parts of the study area. It should test both the MAGT and ALT models and the resulting TRI, GTS, TII, TPI, and PHSI classes. Suitable methods include held-out observations, spatial cross-validation, hindcasting, class-specific accuracy, and sensitivity testing of thresholds, weights, map resolution, and matrix rules. Particular attention should be given to whether High and Unknown / Insufficient Data areas are identified correctly (Karjalainen et al., 2019; Oldenborger et al., 2022).

Future conditions cannot be observed directly when the overlay is created. Future GTS should therefore be evaluated by testing whether the models can reproduce current and earlier conditions, comparing the results of supported models, and examining how the projections change across climate scenarios. MAGT and ALT performance should be reported separately. Where validation shows that a model, rating rule, matrix, or mapped unit performs poorly, it should be revised, assigned lower confidence, or shown as Unknown / Insufficient Data

7.5.6 Evidence requirement, uncertainty, and confidence

A Low, Moderate, or High PHSI class should be assigned only where the essential evidence for TRI, GTS, and TII is sufficient at the adopted map scale and, where relevant, at the depth affected by thaw. At minimum, the framework requires:

- suitable surface and terrain information for the indicators included in TRI;
- observed or locally modelled Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT) for GTS, together with information on model performance; and
- material type, soil texture or grain size, and ground ice information for TII.

If an essential branch cannot be supported, the mapped unit should be classified as Unknown / Insufficient Data. Missing information should not be treated as a Low rating, and its weight should not be transferred automatically to the remaining indicators.

Uncertainty describes limitations in the evidence or analysis. These may result from sparse or older observations, differences in the scale of the input data, reliance on indirect indicators, uncertain mapped boundaries, model error, disagreement among evidence sources, future climate scenarios, or sensitivity to thresholds, weights, and matrix rules. The model testing, sensitivity analysis, and comparison methods described in Sections 7.5.4 and 7.5.5 provide ways to examine these sources of uncertainty (Karjalainen et al., 2019; Oldenborger et al., 2022; Allard et al., 2023).

Confidence describes how strongly the available evidence supports an assigned PHSI class. It is reported separately and does not increase or reduce the susceptibility class.

Table 7.5. Proposed confidence criteria

Confidence	Proposed interpretation
High	The class is supported by current, direct local evidence with suitable coverage and map detail. The main evidence sources agree, and validation shows acceptable performance.
Moderate	The class is supported by a mixture of direct local evidence and suitable indirect information. Some gaps or scale limitations remain, but validation is acceptable and there is no major unresolved disagreement.
Low	The minimum evidence requirements are met, but the class relies mainly on sparse, indirect, older, or unevenly distributed information. Validation is limited or disagreement among evidence sources or models affects the result.

Unknown / Insufficient Data is not a confidence level. It is used where the minimum evidence requirements are not met and a susceptibility class cannot be assigned. Low confidence means that a class can be assigned, but the supporting evidence has important limitations. The confidence assessment should consider the quality, coverage, timing, agreement, and validation of the evidence. The overall confidence level should reflect the least well-supported factor that materially affects the class. For future conditions, confidence should also consider the length of the projection period, model performance, agreement among climate scenarios and models, and which variables were projected or retained at their baseline condition.

7.6 GIS Overlay and Development Review Use

7.6.1 How the planner facing GIS overlay should work

The proposed municipal output is a single map layer named Permafrost Hazard Susceptibility. It would appear alongside other municipal map layers used during development review, such as roads, parcels, zoning, servicing, watercourses, and planning boundaries.

A staff member would search for an address or location using the GIS search function. The map would move to and mark the selected location. When the Permafrost Hazard Susceptibility layer is turned on, the user would immediately see the susceptibility class assigned to the mapped unit containing that location. For each selected planning horizon, every mapped unit would be displayed as one of four mutually exclusive classes:

- Low;
- Moderate;
- High; or
- Unknown / Insufficient Data.

The PHSI colors would not overlap. The interaction among the indicators and analytical branches would already have been resolved through the PHSI calculation before the result is displayed. Other municipal reference layers could remain visible, but the PHSI layer itself would show only one susceptibility class at each location.

The baseline PHSI layer would be shown by default. A planning-horizon selector would allow staff to view supported future conditions. Selecting another horizon would replace the displayed PHSI classification with the classification produced for that horizon. Confidence would remain separate from susceptibility. It could be shown through an optional pattern, outline, or field in the information panel. It would not replace, combine with, or change the color of the PHSI class. Selecting the mapped unit containing the searched address would open an information panel showing:

- the PHSI class;
- the selected planning horizon;
- the planning area or mapped-unit identifier;
- the main supporting evidence;
- the confidence level;
- the main limitation;
- a brief planning note; and
- access to further technical information or relevant technical staff.

The intermediate TRI, GTS, TPI, and TII results would not need to appear in the main map view. These results could remain available as supporting information where a technical reviewer needs to understand how the final PHSI class was produced.

Figure 7.4 illustrates how the proposed overlay could appear within a municipal GIS viewer. The interface includes an address search, the PHSI legend, a planning-horizon selector, confidence information, municipal reference layers, and an information panel. The figure is conceptual and does not represent a functioning portal or actual PHSI conditions in Iqaluit.

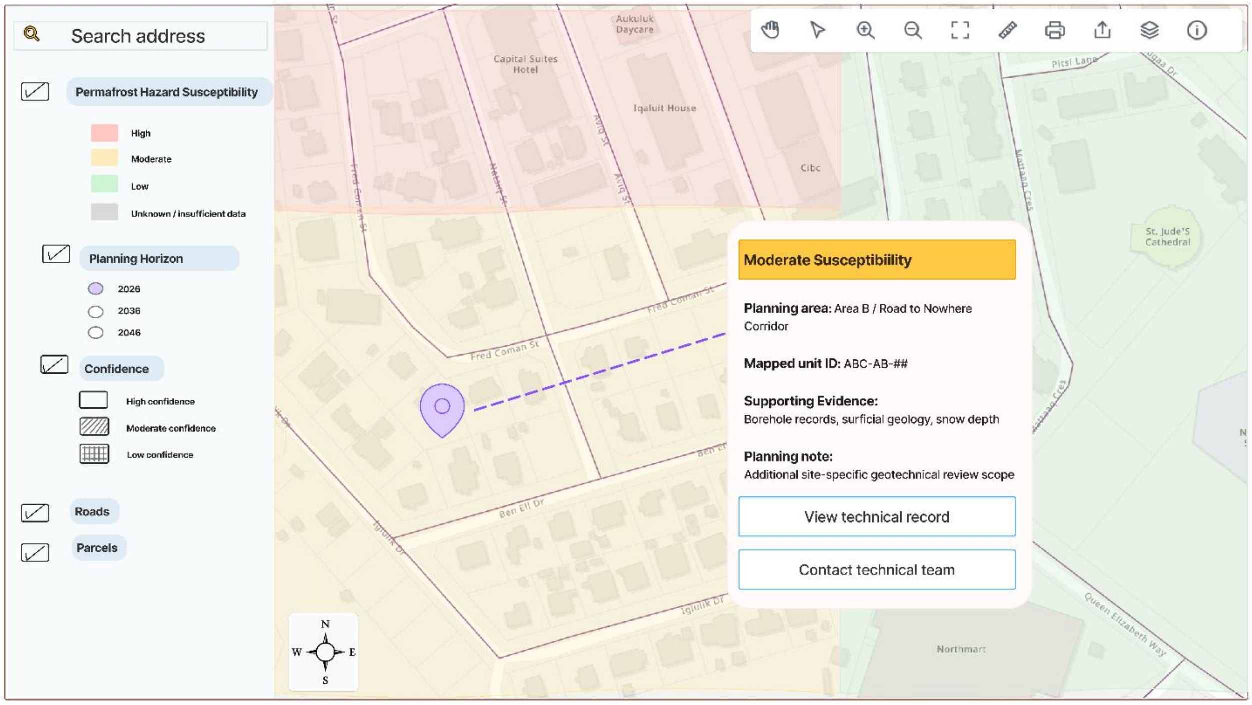

Figure 7.4. Conceptual planner-facing PHSI overlay within a municipal GIS viewer

7.6.2 Class meanings and review responses

The PHSI class communicates the relative susceptibility of the land for the selected planning horizon. It does not describe land as safe, conditionally safe, or unsuitable.

Table 7.6. Proposed PHSI classes and municipal review responses

PHSI class	Planning-scale meaning	Proposed review response	Important limit
Low	Available evidence supports comparatively lower thaw-related land susceptibility	Continue routine review and confirm the applicable technical, servicing, drainage, permit, and professional requirements	Low does not establish site safety or remove project-specific investigation requirements
Moderate	Thaw-related ground conditions may affect the proposal	Review the conditions controlling the class and the confidence level. Determine whether additional technical	Moderate is not a prediction of failure

		information or closer review may be needed	
High	Available evidence supports comparatively stronger thaw-related land susceptibility	Begin technical review early. Consider detailed site-specific permafrost and geotechnical assessment and examine the implications for siting, servicing, grading, drainage, and design	High does not prohibit development or determine the engineering solution
Unknown / Insufficient Data	Available evidence does not support a defensible Low, Moderate, or High class	Identify the missing information and determine what investigation is needed before a susceptibility class is relied upon	Unknown / Insufficient Data must not be interpreted as Low

The PHSI class is one input to municipal review. Staff must also consider the proposed use and design, planning policy, zoning, infrastructure, servicing, drainage, technical submissions, consultation, and other applicable requirements. The overlay does not replace professional/expert judgement, community consultation, site-specific geotechnical investigation, engineering design, permitting, or inspection.

7.7 Implementation Requirements and Methodological Limitations

7.7.1 Requirements before implementation

The proposed framework should first be reviewed by the intended municipal users, including development review staff and relevant technical staff. This initial review would determine whether the framework is understandable, whether the proposed classes and information are useful, and whether its intended role fits the City's development review process. The framework should then be revised where necessary before steps towards implementation begin. These steps include:

1. Review the proposed framework with intended users: Development review staff and relevant technical staff should assess the framework's structure, class meanings, proposed

GIS interface, and intended use. They should identify unclear elements, missing information, unnecessary features, and any changes needed to make the framework practical for municipal review.

2. Refine the framework: The analytical structure, terminology, class descriptions, information displayed in the GIS, and proposed review responses should be revised based on the initial staff assessment. Major changes should be resolved before the technical method is developed further.
3. Confirm the intended scope and responsibilities: The City would need to confirm the area covered by the framework, its role in development review, the staff who would use it, and the technical expertise required to support it. Responsibility for overseeing the technical work should also be identified.
4. Compile and review the available information: Available terrain and surficial geology maps, climate information, Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT) observations, borehole records, geophysical surveys, DInSAR, and relevant municipal GIS data should be collected and reviewed.
5. Identify data gaps and minimum evidence requirements: The available information should be compared with the evidence needed to support TRI, GTS, and TII. Areas or indicators with insufficient information should be identified before classification begins.
6. Select representative pilot areas: Pilot areas should represent the main terrain, material, drainage, and ground thermal conditions within the populated area. The pilot would be used to test the framework before broader mapping is considered.
7. Determine the appropriate map detail: Different analytical units, grid sizes, and minimum mapping units should be compared. The selected level of detail should reflect what the available information and validation results can support.
8. Calibrate and validate the framework: Local evidence should be used to establish or adjust indicator ratings, thresholds, weights, class breaks, matrix rules, and the MAGT and ALT models. The results should then be tested using independent evidence.
9. Develop and test the GIS overlay: Once the analytical method performs adequately, the PHSI layer, address search, planning-horizon selector, confidence display, information panel, and supporting technical information could be configured in the municipal GIS. The interface should then be tested with the intended users.

10. Decide whether the framework is ready for operational use: The framework should move into operational use only after the analytical results and GIS interface have been reviewed and accepted. Responsibilities for approval, maintenance, updating, version control, and periodic review would also need to be established.

The overlay should be updated as important new information becomes available, including boreholes, thermistor records, ALT observations, geophysical surveys, DInSAR, improved terrain mapping, or revised climate projections. Each update should identify the information used, changes made to the analytical method, and the validation completed.

7.7.2 Methodological limitations

The proposed framework has several limitations:

1. The framework has not yet been reviewed by its intended municipal users. Development review staff and relevant technical staff may identify changes needed to its structure, terminology, class meanings, GIS interface, or intended use before technical implementation begins.
2. The thesis does not produce a completed or City-approved GIS overlay. The figures show how the overlay could work and appear, but no operational municipal system has been developed or tested.
3. The analytical rules have not been finalized for Iqaluit. Indicator thresholds, weights, branch class breaks, TPI and PHSI matrix rules, minimum evidence requirements, and confidence criteria still require local calibration and validation.
4. The appropriate map detail has not yet been established. The analytical unit, grid size, minimum mapping unit, and effective resolution would need to be determined through pilot testing. The final overlay should not show more detail than the available information can support.
5. Local information may be uneven. Borehole, ground ice, geophysical, thermal, snow, drainage, and deformation information may vary in coverage, quality, and age. Modelled Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT) surfaces would be estimates between observation locations rather than direct measurements at every mapped location.

6. Regional datasets cannot be used directly for local mapping. They may help guide the method, but they cannot simply be enlarged and treated as neighborhood or site-level information.
7. Future PHSI classes depend on assumptions and model performance. The results would vary according to the selected climate scenario, planning horizon, projected climate information, and the performance of the MAGT and ALT models. Baseline TRI and TII are retained unless suitable information supports a different treatment. The framework also does not simulate the gradual loss of ground ice or changes to the ground after thaw.
8. The class shown at a searched address is a planning-scale interpretation. It represents the mapped unit containing that location, not a direct measurement of subsurface conditions at the address.
9. The PHSI represents susceptibility, not risk. It does not include the design of a proposed development, building heat, grading, fill, drainage changes, loading, exposure, vulnerability, or consequences.
10. The overlay does not determine site safety, engineering design, permit compliance, or development approval. Municipal judgement, community consultation, site-specific investigation, and professional engineering assessment remain necessary.

Where the available information or model performance does not support a defensible class, the mapped location or future planning horizon should remain Unknown/Insufficient Data rather than display an unsupported result.

7.8 Chapter Summary

This chapter described the research design used to develop the proposed Permafrost Hazard Susceptibility Index (PHSI) framework for the populated area of Iqaluit. It identified the case study context, intended municipal users, evidence base, and literature supporting the main design decisions. The framework uses one common analytical structure for baseline and future conditions. The Thermal Response Index (TRI) and Ground Thermal State (GTS) are combined to form the Thaw Potential Index (TPI). TPI is then combined with the Thaw Impact Index (TII) to produce the final PHSI class. The baseline assessment uses current TRI, GTS, and TII information. The future assessment retains baseline TRI and TII unless suitable future information supports a different treatment, while projected Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT) are used to update GTS.

The chapter explained how indicators would be selected, rated, combined, and classified. Quantitative thresholds, categorical rankings, and conditional rules translate different forms of evidence into ratings of 0, 1, or 2, corresponding to Low, Moderate, and High. Rated indicators may be combined within TRI and GTS using weighted sums, while TII may be determined through rule-based logic that considers material type, soil texture or grain size, and ground ice content. The resulting branch classes are combined through the proposed TPI and PHSI matrices. The framework also defines the spatial and technical work needed to support the final classification. This includes determining an appropriate map resolution, producing current and future MAGT and ALT surfaces, calibrating the analytical rules with local information, validating the results with independent evidence, and reporting uncertainty and confidence. A Low, Moderate, or High class is assigned only where the minimum evidence requirements are met. Where the available information is not sufficient, the result remains Unknown / Insufficient Data.

The final PHSI classes would be displayed through a municipal GIS overlay. For each selected planning horizon, every mapped location would show one mutually exclusive class: Low, Moderate, High, or Unknown / Insufficient Data. Staff could search for an address, turn on the overlay, and view the class assigned to the mapped unit containing that location. Confidence and supporting information would be shown separately from the susceptibility class.

The framework is not ready for immediate implementation. It should first be reviewed and refined by the intended development review and technical staff. Further work would then include compiling and reviewing local information, identifying data gaps, selecting pilot areas, calibrating and validating the framework, developing the GIS overlay, testing it with municipal users, and establishing responsibility for its maintenance and updating. The proposed framework supports early municipal development review process, but it does not replace site-specific investigation, engineering design, community consultation, or expert judgement. The following chapter demonstrates how the framework and proposed GIS overlay could be used through an illustrative application in the populated area of Iqaluit.

Chapter 8: Illustrative Application of the Framework

8.1 Introduction

Chapter 7 presented the proposed planning-scale framework and explained how it produces Permafrost Hazard Susceptibility Index (PHSI) classes that would be displayed through the Permafrost Hazard Susceptibility Overlay. The purpose of this chapter is to demonstrate how the framework, its analytical process, and the resulting overlay could operate through an illustrative application.

The application is not intended to produce a validated site-specific hazard map or an actual development decision. Instead, it uses a hypothetical but technically plausible location in Area B to show how the mapped PHSI class, supporting planning information, analytical process, and planning interpretation could work together during municipal review.

The chapter proceeds in four steps. Section 8.2 defines the purpose, boundaries, and assumptions of the illustrative application. Section 8.3 presents the planner-facing view of the selected location and explains how existing planning information would be considered alongside the overlay. Section 8.4 demonstrates how selected inputs could be interpreted through the analytical branches of the framework. Sections 8.5 and 8.6 then explain what the baseline and future readings could mean for planning use and what the example demonstrates about the proposed framework.

8.2 Purpose, Boundaries, and Analytical Assumptions

The illustrative application is bounded in three ways. First, it is situated in the populated area of Iqaluit, where building-related development review, municipal servicing, and future development pressures are most concentrated. Second, it is hypothetical rather than site-specific. The example demonstrates how the proposed framework could support review, but it does not classify an actual property for regulatory use. Third, it begins with existing planning information and then shows how a PHSI class could provide an additional land-based screening input.

For this purpose, the illustrative location is placed within Area B, near Road to Nowhere and west of the Niaqunnguk River. The Area B Development Scheme provides the relevant neighbourhood planning context, including a land-use concept plan, water and sanitary servicing information, and a transportation plan (City of Iqaluit, 2015). These materials are used to situate the example within an existing planning context. They are not presented as layers that would automatically form part of the susceptibility overlay. Within these boundaries, the application demonstrates five parts of the proposed approach:

1. how an illustrative location can first be understood using maps and planning information already available to staff;
2. how the overlay adds a planner-facing susceptibility class;
3. how selected inputs are interpreted through the analytical branches;
4. how baseline and future PHSI classes may differ; and
5. how the result could support a more spatially informed planning response.
6. The values, ratings, classes, and confidence levels used in this chapter are illustrative. They are not raw field measurements, calibrated site-specific thresholds, or final municipal classifications. Their purpose is to demonstrate the framework in a realistic review setting.

Consistent with Chapter 7, the future assessment retains the baseline Thermal Response Index (TRI) and Thaw Impact Index (TII). Future local snow, vegetation, organic cover, drainage, and moisture conditions are not projected in this example, while the material type, soil texture or grain size, and ground ice conditions represented by TII are treated as the existing physical ground setting. The future change is introduced through projected Ground Thermal State (GTS), represented by Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT).

The example also assumes that projected ALT remains within the same general soil or material layer. If future thaw were expected to reach a deeper layer with different soil texture, grain size, or ground ice conditions, TII would need to be reconsidered using the properties of that deeper layer.

8.3 Planner Facing View of the Selected Site

Before introducing the susceptibility information, it is useful to begin with the types of planning information that development review staff may already consult. Figure 8.1 situates the illustrative location within the broader populated-area context using the City's populated-area land-use map, populated-area zoning map, and a simplified local locator panel.

In broader land-use terms, the location falls within the Area B future-development context addressed by the Area B Development Scheme, which is intended to accommodate residential growth together with associated institutional, commercial, open-space, servicing, and movement functions (City of Iqaluit, 2015).

In zoning terms, the location lies within an area designated MR, or Municipal Reserve, on the populated-area zoning schedule. This indicates that the land is reserved for future development planning rather than already being zoned as a developed residential area (City of Iqaluit, 2022c). The local locator panel narrows the focus to the illustrative location near Road to Nowhere and west of the Niaqunnguk River.

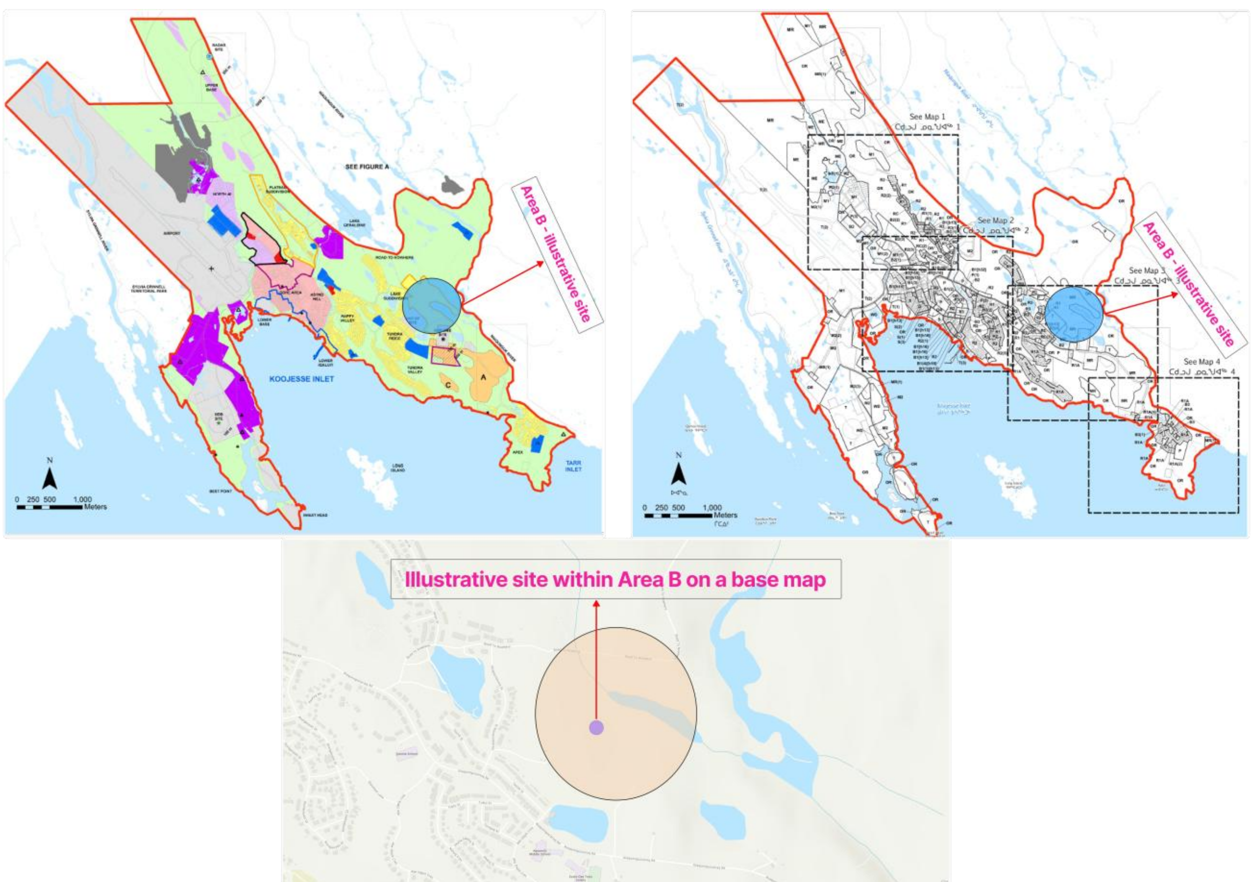

Figure 8.1. Illustrative site in the broader populated-area context. Source: adapted from City of Iqaluit (2022b, 2022c) and ArcGIS Pro basemap

Figure 8.2 presents a closer view of the same location within the planning and infrastructure context provided by the Area B Land Use Concept Plan, Water and Sanitary Distribution Network, and Transportation Plan. These materials represent the types of supporting documents that development review staff may review when considering development applications. They provide information about the intended neighbourhood structure, land uses, servicing layout, and movement network.

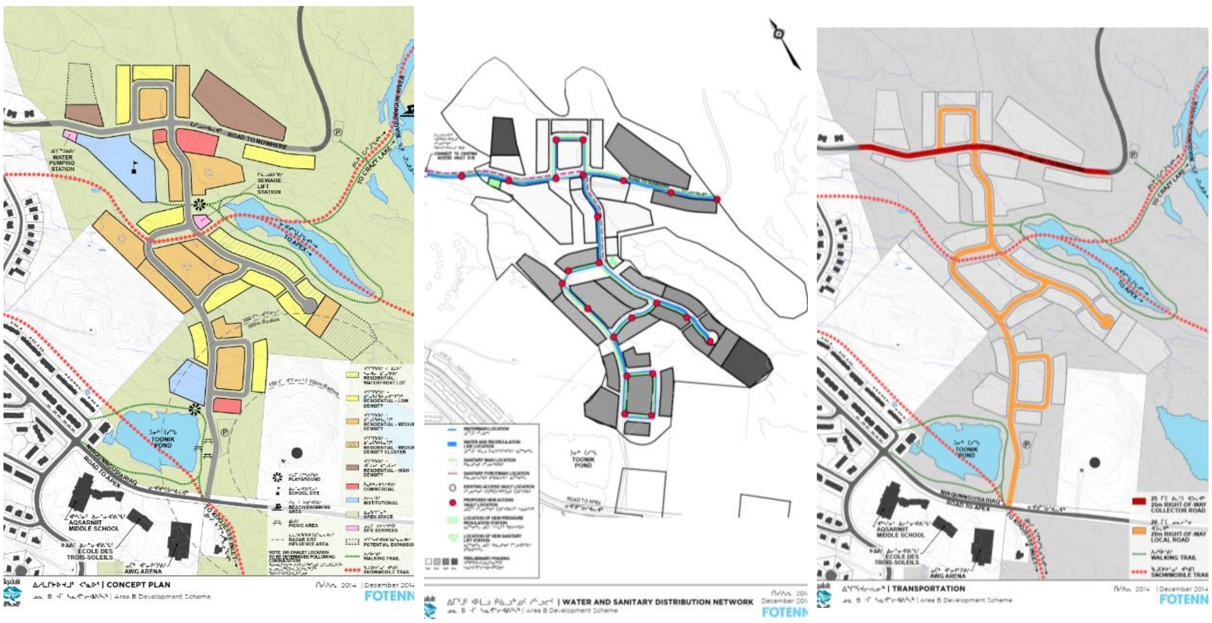

Figure 8.2. Illustrative site in the local Area B planning and infrastructure context. Source: adapted from City of Iqaluit (2015)

The distinction between these planning materials and the susceptibility information is important. The overlay would be one internal planning screening layer viewed alongside other city planning instruments and municipal servicing information, such as land use, zoning, roads, servicing, parcels, and planning boundaries. Concept plans, servicing plans, transportation plans, and applicant materials would continue to be reviewed as supporting planning or application documents. They do not become part of the PHSI calculation itself.

Figure 8.3 presents the susceptibility classes in the proposed planner-facing form on a simplified base map. In this illustrative example, the selected Area B location falls within a Low PHSI class with High confidence under the baseline condition. Under the future 20-year planning horizon, the same location shifts to a Moderate PHSI class with Moderate confidence.

For each planning horizon, the searched location displays one final PHSI class. The colors do not overlap because the relationships among TRI, GTS, TPI, and TII have already been resolved before the final class is displayed.

Figure 8.3. Standalone PHSI overlay for the selected Area B site under present and future planning horizons

Figure 8.4 places the same illustrative classes over the Area B concept-plan background. This comparison helps show how the susceptibility information could be interpreted alongside the local planning context. It does not imply that the concept plan is equivalent to zoning, forms part of the normal municipal interface or is incorporated into the PHSI calculation.

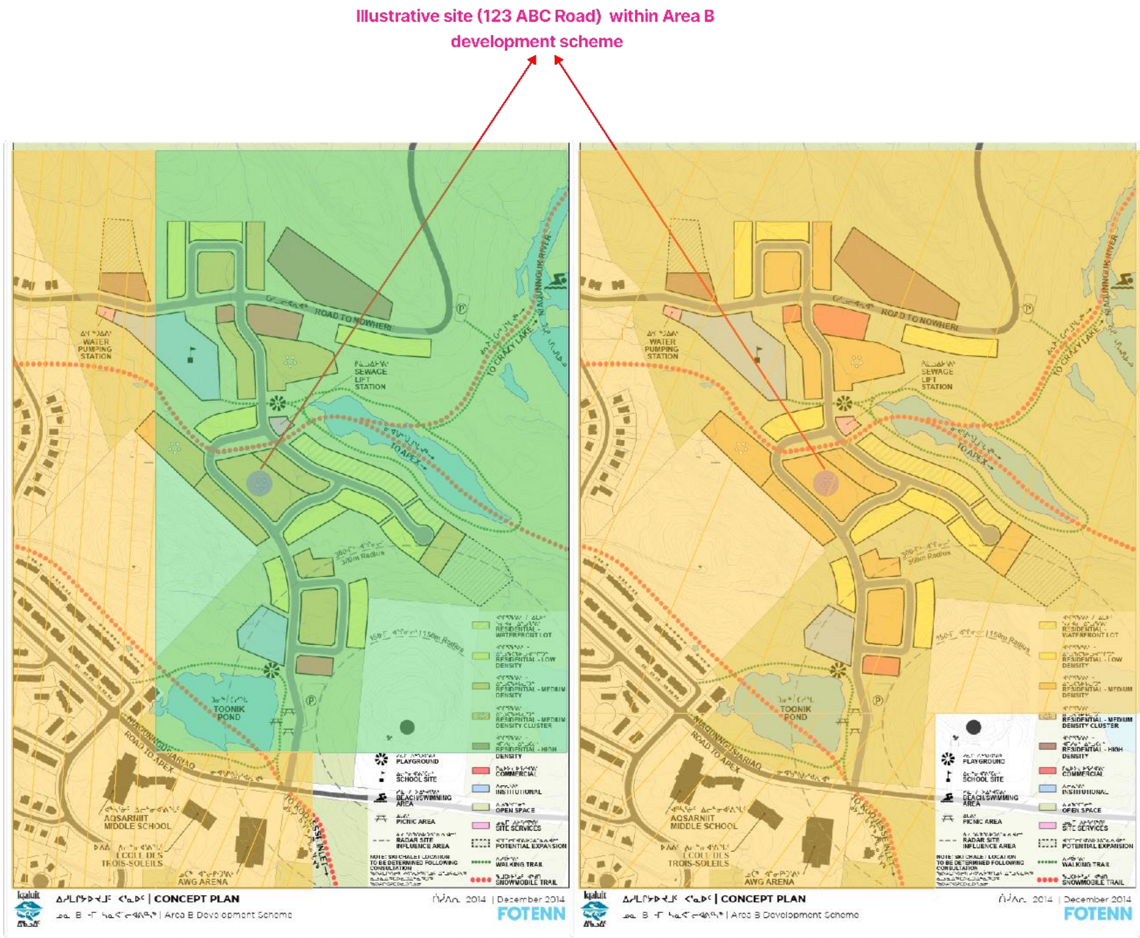

Figure 8.4. Illustrative PHSI readings over the Area B concept plan background. Source: adapted from City of Iqaluit (2015)

Note: this figure is included for thesis interpretation only. It does not represent the normal live interface of the proposed GIS overlay tool.

8.4 Analytical Construction of the Site Class

8.4.1 Reclassification of selected inputs

To demonstrate the analytical process, Table 8.1 presents illustrative ratings for selected inputs under two planning horizons: the baseline condition and a future 20-year horizon. The values shown are not raw field measurements or calibrated site-specific thresholds. They are illustrative ratings assigned after quantitative thresholds, categorical rankings, or conditional rules have been applied. The three-level rating system established in Chapter 7 is used:

- 0 = Low;
- 1 = Moderate; and
- 2 = High.

Table 8.1. Illustrative reclassification of selected inputs for the hypothetical site under

Branch	Example input	Baseline condition and rating	Future condition and rating
TRI	Snow conditions	Snow depth, duration, and retention interpreted as supporting a Low thermal-response rating, rating 0	Baseline snow rating retained because future local snow conditions are not projected, rating 0
TRI	Vegetation and surface organic cover	Surface cover interpreted as supporting a Low thermal-response rating, rating 0	Baseline vegetation and organic-cover rating retained, rating 0
TRI	Surface material	Surface material interpreted as supporting a Low thermal-response rating, rating 0	Baseline material and TRI rating retained, rating 0
GTS	Mean Annual Ground Temperature	Comparatively colder baseline ground condition, rating 0	Warmer projected MAGT, rating 1
GTS	Active Layer Thickness	Comparatively limited seasonal thaw depth, rating 0	Projected increase in ALT, rating 1
TPI	Combined TRI and GTS class	Low TPI based on Low TRI and Low GTS	Moderate TPI based on Low TRI and Moderate GTS

TII	Material type and soil texture or grain size	Ground material interpreted as having comparatively lower thaw-impact potential, rating 0	Baseline material and soil-texture rating retained, rating 0
TII	Ground ice content	No illustrative indication of high ground ice content, rating 0	Baseline ground ice rating retained, rating 0
Final PHSI class	Combination of TPI and TII	Low PHSI with High confidence	Moderate PHSI with Moderate confidence

The rating system allows information recorded in different forms to be interpreted within a common analytical structure. Under the baseline condition, the selected location is assumed to have a Low TRI, a colder GTS, and a Low TII. Under the future 20-year horizon, TRI and TII remain Low because their baseline conditions are retained. The change occurs in GTS, where projected MAGT and ALT move from Low to Moderate. Under the proposed TPI matrix, Low TRI combined with Moderate GTS produces Moderate TPI. Under the proposed PHSI matrix, Moderate TPI combined with Low TII produces Moderate PHSI.

Table 8.1 should not be read as a simple arithmetic average. The indicators are first rated and interpreted within their respective branches. The branch classes are then combined using the TPI and PHSI matrices described in Chapter 7.

8.4.2 Thermal response, ground thermal state, and thaw potential

On the thaw-potential side of the framework, the selected location is interpreted through TRI, GTS, and the resulting TPI. Under the baseline condition, the location is assumed to have snow conditions, surface cover, and surface material that produce a Low TRI class. The baseline GTS is also assumed to be Low. MAGT represents comparatively colder ground, while ALT represents relatively limited seasonal thaw. Low TRI combined with Low GTS therefore produces Low TPI.

Under the future 20-year horizon, TRI remains Low. The example does not assume that snow, vegetation, organic cover, drainage, or surface material become less protective simply because the climate becomes warmer. Their baseline ratings are retained because suitable future information is not available at the required local scale.

The projected change occurs in GTS. MAGT becomes warmer and ALT increases, producing a Moderate GTS class. Under the proposed TPI matrix, Low TRI combined with Moderate GTS produces Moderate TPI. The shift in the future PHSI class is therefore driven by a more critical projected ground thermal condition rather than by assumed changes to every part of the framework.

8.4.3 Thaw impact

TII represents the potential physical ground response if thaw occurs. Under the baseline condition, the selected location is assumed to have a material type and soil texture or grain size associated with comparatively lower thaw-impact potential. The available illustrative information also does not indicate high ground ice content. Together, these conditions produce a TII rating of 0, corresponding to Low.

The same Low TII class is retained under the future 20-year horizon. The material type, soil texture or grain size, and baseline ground ice conditions are treated as the existing physical ground setting. They are not assigned a higher rating simply because future ground temperatures are warmer. This does not mean that ground ice cannot thaw or that the ground would remain physically unchanged after thaw. It means that TII represents the potential response of the existing ground setting if thaw reaches that material. The framework does not model progressive ground ice loss, post-thaw consolidation, or later changes to the ground.

If projected ALT were expected to reach a deeper soil or material layer with different grain-size or ground ice conditions, TII would need to be reconsidered. That condition is not assumed in this example.

8.4.4 Final class and confidence

Table 8.2 summarizes the branch classes for the baseline and future conditions and shows how the TPI and PHSI matrices produce the final class. Table 8.1 presents the illustrative ratings assigned to the individual indicators, while Table 8.2 shows the next stage of the process, where those ratings have already been combined into TRI, GTS, and TII classes. For this illustrative example, the minimum evidence requirements are assumed to be met for both planning horizons. Confidence is reported separately and does not form part of the TPI or PHSI matrix calculation.

Table 8.2. Illustrative derivation of baseline and future PHSI classes for the selected area B location

Analytical step	Baseline condition	Future 20-year horizon	How the result is derived
TRI	0, Low	0, Low	The illustrative snow, vegetation and organic-cover, and surface-material ratings are Low. The baseline TRI is retained for the future horizon because suitable local projections of these surface conditions are not available.
GTS	0, Low	1, Moderate	Baseline MAGT and ALT are both rated Low. Under the future horizon, projected MAGT and ALT are both rated Moderate, producing a Moderate GTS class.
TPI matrix	Low TRI × Low GTS = Low TPI	Low TRI × Moderate GTS = Moderate TPI	The TRI and GTS classes are combined using the proposed TPI matrix from Chapter 7.
TII	0, Low	0, Low	The illustrative material type, soil texture or grain size, and ground ice information support a Low TII class. The baseline TII is retained because the example assumes that projected ALT does not reach a deeper material layer with different conditions.
PHSI matrix	Low TPI × Low TII = Low PHSI	Moderate TPI × Low TII = Moderate PHSI	The TPI and TII classes are combined using the proposed PHSI matrix from Chapter 7.

Confidence	High	Moderate	Confidence is reported separately from PHSI. The future confidence is lower because the future GTS depends on projected MAGT and ALT rather than direct observation.
Planner-facing result	Low PHSI with High confidence	Moderate PHSI with Moderate confidence	This is the final class and confidence information that would be displayed through the overlay for each planning horizon.

Note: the ratings, classes, confidence levels, and matrix results are illustrative. They demonstrate the proposed framework and do not represent a calibrated classification of Area B.

Under the baseline condition, the selected location combines Low TRI, Low GTS, and Low TII. Low TRI and Low GTS produce Low TPI, and Low TPI combined with Low TII produces a final Low PHSI class. The baseline confidence level is assumed to be High because the example assumes a comparatively strong evidence base from mapped information and direct or nearby local subsurface observations.

Under the future 20-year horizon, TRI and TII remain Low, while projected MAGT and ALT move GTS to Moderate. Low TRI combined with Moderate GTS produces Moderate TPI. Moderate TPI combined with Low TII then produces a final Moderate PHSI class. The future confidence level is assumed to be Moderate because the future result depends on projected ground thermal conditions and therefore has less direct evidence base than the baseline result.

Table 8.2 demonstrates a possible transition from lower baseline susceptibility to a more cautious future class.

8.5 Illustrative Planning Interpretation

The practical value of the example lies in how the same location is interpreted under different planning horizons. Under the baseline condition, the selected Area B location is assumed to have a Low PHSI class with High confidence. This indicates comparatively lower thaw-related land susceptibility than locations assigned Moderate or High. It would support a relatively routine early review, while the need for site-specific investigation would still depend on the nature, scale, and intensity of the proposed development.

The future 20-year horizon is interpreted differently. Under that horizon, the same location shifts to a Moderate PHSI class with Moderate confidence. This does not mean that the location becomes unsuitable for development or that the mapped class replaces engineering judgement.

The Moderate future class results from the projected change in GTS. TRI and TII remain Low, but warmer MAGT and increased ALT raise TPI to Moderate. As summarized in Table 8.2, Low TRI and Moderate GTS produce Moderate TPI, which then combines with Low TII to produce the final Moderate PHSI class. Confidence is reported separately and does not form part of either matrix calculation.

Having both baseline and future PHSI information would give the City its own consistent, planning-scale understanding of the mapped ground conditions before and during development review. Municipal staff would not need to rely solely on the applicant's technical submission to first identify whether thaw-related conditions may be relevant. The PHSI class, confidence level, and supporting information would provide an internal municipal reference that could be considered alongside the applicant's site-specific evidence.

This information could support a more focused discussion between the City, the applicant, and the applicant's planning, engineering, and geotechnical consultants. The discussion could consider whether the proposed height, density, building form, servicing approach, and overall development intensity are appropriate for the mapped conditions and the expected service life of the development. Where the future condition indicates greater susceptibility, staff could also ask how the proposal addresses projected warming, increased ALT, drainage, snow management, and other conditions that may affect long-term ground performance.

The framework would not establish an acceptable height or density, determine the final development intensity, or prescribe a particular mitigation measure. These conclusions would continue to depend on the planning context, the proposed development, site-specific investigation, and professional engineering and geotechnical advice. The overlay would instead help the city identify the questions that should be addressed and engage more effectively with the applicants' consultants regarding the scope of additional investigation, possible mitigation measures, and changes that may be needed to the proposal.

Depending on the mapped class, confidence level, and information already submitted, additional work could include more detailed borehole investigation, ground-temperature monitoring, ground-ice characterization, assessment of future thaw conditions, drainage and snow-management analysis, or further review of the proposed foundation, grading, and servicing approach. The purpose would be to provide a clearer basis for assessing whether the proposal can meet the applicable statutory, technical, and safety requirements and whether it can be revised, where necessary, into a form that the planning and development review team can support.

The City's planning-scale information and the applicant's site-specific studies would therefore serve related but different purposes. The overlay would provide a consistent municipal reference for early review, while the applicant's investigations would provide the detailed evidence needed to confirm conditions at the site and recommend appropriate design or mitigation measures. Considering both sources together would support a more informed and constructive review process.

The PHSI class would not be used in isolation. Staff would interpret it together with the broader land-use and zoning context shown in Figure 8.1, the Area B planning information shown in Figure 8.2, and proposal-specific materials submitted by the applicant.

The main planning implication is not that the location moves from acceptable to unacceptable. The level of caution and the type of discussion required during review change. The baseline Low class with High confidence would support a relatively routine early review. The future Moderate class with Moderate confidence could support earlier technical coordination, more focused discussion of height, density, and overall development intensity, and a clearer basis for requesting additional information, mitigation, or revisions before the application advances further.

8.6 What the Application Demonstrates about the Tool

This illustrative application demonstrates four main features of the proposed framework. First, the figures show how the proposed susceptibility information would be introduced within the City planning and development review context. Figure 8.1 locates the illustrative site within the broader land-use and zoning context of the populated area. Figure 8.2 provides the more detailed Area B planning and infrastructure context. Figure 8.3 then shows the additional planner-facing PHSI class that the proposed framework would make available during development review process. Together, these figures move from the location of the illustrative example to its planning context, and finally to the susceptibility information added by the proposed framework.

Second, Tables 8.1 and 8.2 show how the final PHSI class is produced. Table 8.1 presents the illustrative indicator ratings used within TRI, GTS, and TII. Table 8.2 then shows how the resulting branch classes are combined through the TPI and PHSI matrices. The final class displayed to municipal staff is therefore not arbitrary. It is produced through a clear sequence of indicator rating, branch classification, and matrix-based combination.

Third, the example shows why planning horizons matter. Under the baseline condition, the selected location has comparatively lower thaw-related susceptibility. Under the future horizon, projected MAGT and ALT move GTS and the final PHSI into a more cautious class. The future result does not require every branch to change. TRI and TII retain their baseline Low classes, while projected GTS changes from Low to Moderate. That change is sufficient to move TPI and the final PHSI from Low to Moderate under the proposed matrix rules. This future perspective is relevant because development review often concerns buildings and infrastructure expected to remain in service over long periods in a climate sensitive permafrost setting.

Fourth, the example distinguishes the susceptibility information from the other planning documents used during review. Area B concept plans, servicing plans, transportation plans, and applicant materials provide the planning and proposal context. The overlay provides an additional land-susceptibility class that staff can consider alongside those materials. Figure 8.4 is included as an analytical comparison to show how the illustrative PHSI class relates spatially to the Area B concept-plan context, it does not suggest that the concept plan forms part of the overlay or the

PHSI calculation.

The application also demonstrates how the framework could strengthen the City's position during development review without replacing the role of the applicant's consultants. The City would have its own planning-scale information about baseline and future ground susceptibility, while the applicant and their consultants would remain responsible for site-specific investigation, design, and mitigation. This shared information base could support a clearer discussion about whether the proposed height, density, building form, servicing, and overall intensity are appropriate, what additional studies may be required, and what changes may be needed to support the approval of the development proposal.

This approach could also make the reason for requesting additional information more transparent. Rather than making a general request for further geotechnical work, staff could relate the request to the mapped PHSI class, future planning horizon, confidence level, and the specific ground conditions requiring clarification. The resulting discussion would remain subject to the applicable statutory, technical, safety, and professional requirements.

The application also shows the limits of the framework. The ratings and class combinations shown in Tables 8.1 and 8.2 are illustrative rather than calibrated site-specific results. The mapped classes shown in Figures 8.3 and 8.4 are not part of a validated or operational municipal overlay. The purpose of the chapter is to demonstrate how the framework could operate, not to determine the actual classification of the Area B example.

Altogether, the illustrative application demonstrates the intended role of the framework in municipal development review process. It does not determine engineering acceptability or development approval. It supports earlier recognition of thaw-related land conditions by connecting the planning context and planner-facing mapped result to a separate, clear, and reviewable analytical process

8.7 Chapter Summary

This chapter demonstrated the proposed framework through an illustrative application in Area B within the populated area of Iqaluit. It first placed the selected location within the broader land-use and zoning context and then within the more detailed planning and infrastructure context of the Area B Development Scheme.

The chapter showed how the PHSI class could be displayed as a planner-facing screening layer and interpreted alongside existing planning materials. It also explained how selected inputs could be rated and combined through TRI, GTS, TPI, TII, and the final PHSI.

Under the baseline condition, the selected location was assumed to have a Low PHSI class with High confidence. Under the future 20-year horizon, TRI and TII remained Low, while projected MAGT and ALT moved GTS to Moderate. As summarized in Table 8.2, Low TRI and Moderate GTS produced Moderate TPI, and Moderate TPI combined with Low TII produced a final Moderate PHSI class. Future confidence was reported as Moderate because the result relies more strongly on projected ground thermal conditions.

The future change was therefore driven by a more critical projected ground thermal condition rather than by assumed changes in surface conditions or the physical ground setting.

The application also showed how baseline and future PHSI information could give the City an internal planning-scale reference for discussions with applicants and their consultants. This information could help staff consider whether the proposed height, density, servicing, and overall development intensity are appropriate for the mapped conditions, identify where additional investigation or mitigation may be required, and assess whether the proposal can be advanced in a form that meets the applicable statutory, technical, and safety requirements.

The overlay would not replace site-specific geotechnical investigation, engineering design, or professional judgement. Its value would be in helping the city ask more focused questions, explain the basis for additional information requests, and engage in a more informed review of the proposal and any recommended mitigation measures.

The application therefore shows how the framework could support a mapped result that remains simple for municipal staff while being based on a clear analytical process. It also demonstrates how baseline and future PHSI classes could help identify where additional technical information, mitigation, or a more cautious review approach may be appropriate.

PART IV: Synthesis and Implications

Chapter 9: Discussion and Conclusion

9.1 Introduction

This thesis addressed a practical problem within the City's planning and development review process in a permafrost setting. In Iqaluit, decisions concerning land use, building height and density, servicing, site layout, and overall development intensity are influenced not only by planning policy and infrastructure capacity, but also by the condition of the ground and the possibility that thaw-related concerns may become more significant under continued warming.

The research did not begin from the assumption that scientific knowledge, engineering guidance, or formal review procedures are absent. Substantial knowledge already exists concerning permafrost processes, ground ice, ground temperature, Active Layer Thickness (ALT), thaw settlement, terrain conditions, and climate change. Engineering standards and technical guidance also establish expectations for site investigation, design, construction, and professional responsibility. The city already has an established planning and development review process supported by the General Plan, Zoning By-law, technical submissions, internal review, professional judgement, applicant revisions, and development-permit decisions.

The gap addressed by the thesis is therefore one of translation. Relevant information exists, but it is distributed across scientific literature, regional and national mapping, local observations, engineering standards, technical studies, and planning documents. It is not yet brought together in a consistent planning-scale form that City planning and development review staff could use early in the review of a proposed development.

The thesis responds to this gap by proposing a framework for producing a Permafrost Hazard Susceptibility Index (PHSI) and presenting the resulting classes through a planner-facing overlay. The framework defines the analytical process. The PHSI is the classified analytical result produced through that process. The overlay is the mapped representation through which City planning and development review staff would view the final Low, Moderate, High, or Unknown / Insufficient Data class for a selected planning horizon.

The contribution is methodological and applied. The thesis does not produce a completed citywide map, an operational portal, final Iqaluit-specific thresholds and weights, or an engineering determination for any site. It identifies what such a framework would need to assess, how different forms of information could be rated and combined, how baseline and future conditions could be represented, how uncertainty and confidence should be communicated, and how the resulting information could support the City's planning and development review process.

This chapter discusses the principal findings and contribution of the research, the implications for City planning and development review, the strengths and limitations of the proposed framework, the work required before implementation, and the main directions for future research.

9.2 Principal Findings and Contribution

The first research question asked which subsurface, environmental, and climate-related factors are most relevant for characterizing planning-scale thaw-related hazard susceptibility in Iqaluit. The research found that no single indicator can adequately represent thaw-related land susceptibility. The relevant factors operate through different physical pathways and must be interpreted according to the role they play within the assessment.

Surface, terrain, and near-surface conditions influence how heat is transferred between the atmosphere and the ground. These include snow, vegetation and organic cover, surface moisture, drainage, terrain, and the thermal properties of surface materials. Within the proposed framework, these conditions inform the Thermal Response Index (TRI).

The thermal condition of the ground must be represented separately. Mean Annual Ground Temperature (MAGT), Active Layer Thickness (ALT), and relevant thermal trends indicate how warm or cold the ground is and how deeply seasonal thaw extends. These indicators inform Ground Thermal State (GTS).

The potential physical response of the ground if thaw occurs depends mainly on the existing material and ground ice conditions. Within the proposed Thaw Impact Index (TII), the core factors are the surficial setting or material type, soil texture or grain size, and ground ice content.

Cryostructure and other local subsurface observations can support the interpretation of those factors.

The framework therefore separates two related questions. TRI and GTS are combined to represent the potential for thaw-related change through the Thaw Potential Index (TPI). TPI is then combined with TII to represent overall land susceptibility through the PHSI:

$$TPI=f\,(TRI,\ GTS)$$

$$PHSI=f\,(TPI,\ TII)$$

This structure is informed conceptually by Smith and Burgess (2004), who distinguished the thermal response of permafrost from the physical response of the ground. The thesis adapts that general distinction to a planning-scale framework for Iqaluit rather than transferring their national map units, ratings, thresholds, or weights directly.

The second research question asked how existing engineering standards, technical guidance, mapping approaches, and planning processes address permafrost-related decision needs and where important gaps remain. The review found that existing knowledge is substantial but divided by scale, purpose, and audience. National and circumpolar mapping approaches provide useful methods for identifying broad patterns in thermal conditions, active-layer change, settlement potential, terrain sensitivity, and ground ice. Community-scale and infrastructure studies demonstrate how local boreholes, thermistors, geophysics, DInSAR, terrain mapping, and modelling can improve the interpretation of ground conditions. Engineering standards and technical guidance establish more detailed expectations for project-specific investigation, foundation design, drainage, construction, and professional responsibility.

These approaches do not, however, answer the same question. Some map thermal conditions, some estimate potential settlement, some identify observed deformation, and others address risk, infrastructure vulnerability, or engineering design. Their output cannot be treated as interchangeable. The literature also shows that a high nominal map resolution does not necessarily represent detailed local evidence, especially where the underlying climate, soil, or ground ice information remains coarse.

The City's planning and development review process addresses another part of the problem. It provides the pathway through which a proposal is reviewed against land-use policy, zoning, servicing, site design, infrastructure, technical information, and other requirements. Project-specific geotechnical studies can be requested and reviewed within that process. What is not currently provided by these sources collectively is one consistent planning-scale framework that gives City planning and development review staff an early spatial reference for thaw-related land susceptibility.

The principal gap is therefore located between broad screening and site-specific engineering. It is not a replacement for either. The proposed framework occupies this intermediate scale by translating relevant ground, terrain, climate, and local evidence into a form intended to support the earlier stages of the City's planning and development review process.

The third research question asked how existing scientific and engineering knowledge could be translated into a planning-scale susceptibility framework that is understandable and usable during development review. The thesis found that this translation requires both analytical clarity and a simple visible result. A single unstructured score would make it difficult to understand whether a final class was driven by surface heat transfer, warm ground, deep seasonal thaw, fine-grained material, or high ground ice. The proposed framework therefore retains separate analytical branches and combines them only after the indicators have been interpreted within their relevant physical role.

The analytical process begins by rating individual indicators. Quantitative indicators are rated using locally supported numerical thresholds. Categorical indicators are rated using ranked classes. Conditional indicators are interpreted through process-specific rules where one condition changes the meaning of another. These methods produce branch-specific ratings of 0, 1, or 2, corresponding to Low, Moderate, and High.

Rated indicators may then be combined within TRI and GTS using a weighted sum where an additive relationship is appropriate. TII may be better represented through a rule-based structure because the significance of ground ice depends on material type and soil texture or grain size. The resulting TRI, GTS, and TII branch classes are then combined through the TPI and PHSI matrices.

The proposed matrices make the class-construction rules visible rather than hiding them within an overall average. The TPI matrix gives greater influence to GTS where the ground is already thermally warm or seasonal thaw is more critical. The PHSI matrix gives greater influence to TII where the existing ground material and ground ice indicate a stronger physical response if thaw occurs. The exact thresholds, weights, class breaks, and matrix cells remain proposed rules that require local calibration, sensitivity testing, and independent validation.

The framework also recognizes that not every mapped unit will have enough information to support a class. Minimum evidence requirements are therefore applied before a Low, Moderate, or High PHSI class is assigned. Where an essential part of TRI, GTS, or TII cannot be supported, the result remains Unknown / Insufficient Data. Confidence is reported separately and describes how strongly the available information supports the assigned class. Unknown / Insufficient Data is not a confidence level and must not be interpreted as Low.

The visible result is intentionally simpler than the analytical process behind it. For each planning horizon, the overlay displays one mutually exclusive PHSI class at each mapped location. City planning and development review staff could search for an address, activate the overlay, and view the class assigned to the mapped unit containing that location. Confidence, the main supporting evidence, and a brief planning note could be made available separately without requiring routine users to interpret the full TRI, GTS, TPI, and TII structure.

The fourth research question asked how the proposed framework could support more informed decisions regarding site suitability, development intensity, and the need for additional geotechnical investigation.

The research found that the main value of the framework lies in the timing and quality of the questions it could support. The PHSI class would not determine whether land is suitable, establish an acceptable height or density, select a foundation type, or decide whether a development should be approved. It would give the city planning and development review team its own consistent planning-scale information about mapped ground susceptibility before and during its review of the applicant's proposal.

This information could support more focused discussion with the applicant and the applicant's planning, engineering, and geotechnical consultants. Depending on the class, confidence level, and planning horizon, the discussion could consider whether the proposed height, density, building form, servicing approach, and overall development intensity are appropriate for the mapped ground conditions. It could also help staff determine whether additional boreholes, ground-temperature monitoring, ground ice information, future thaw assessment, drainage and snow-management analysis, or further review of the proposed foundation and servicing approach may be needed.

The illustrative application in Area B demonstrated this role. The figures moved from the location of the illustrative example to its broader and local planning context, and then to the additional planner-facing PHSI information produced by the framework. The tables separately demonstrated the analytical sequence from indicator ratings to branch classes, to the TPI and PHSI matrices.

Under the illustrative baseline condition, the selected location was assigned Low TRI, Low GTS, and Low TII, producing Low TPI and a final Low PHSI class with High confidence. Under the future 20-year horizon, baseline TRI and TII were retained, while projected MAGT and ALT moved GTS from Low to Moderate. Low TRI combined with Moderate GTS produced Moderate TPI, and Moderate TPI combined with Low TII produced a final Moderate PHSI class with Moderate confidence.

The example did not validate the framework or classify Area B in practice. It demonstrated how the proposed method could produce a different review posture for the same location under baseline and future conditions. The future Moderate class did not mean that the location had become unsuitable. It indicated that projected ground thermal change could justify earlier technical discussion, more focused review questions, or additional evidence over the expected life of the development.

Taken together, these findings show that the main contribution of the thesis is not another regional permafrost map or a completed municipal software product. The contribution is a planning-scale translation framework that:

- organizes relevant permafrost information according to clear physical roles;
- distinguishes the analytical framework, the PHSI, and the overlay;
- separates thaw potential from the potential physical ground response;
- provides a process for rating, weighting, classifying, and combining different forms of evidence;
- includes baseline and future conditions within the same analytical architecture;
- retains Unknown / Insufficient Data and reports confidence separately;
- connects the mapped result to questions that arise within the City's planning and development review process; and
- identifies the technical and institutional work required before operational use.

The contribution is therefore conceptual, methodological, and applied. It defines what could be built, how the result should be interpreted, and how it could be tested. It does not claim that the resulting system has already been calibrated, validated, adopted, or implemented by the City.

9.3 Implications for Development Planning and Review

The City's planning and development review process is the stage at which a proposed development is assessed, discussed, and refined. The plans and technical information submitted by an applicant represent a proposal rather than an approved final form. During completeness review, coordinated technical and statutory review, and subsequent re-review, City planning and development review staff may identify concerns, request additional information, and work with the applicant and their consultants through revised plans, supplementary studies, mitigation measures, and resubmissions.

These revisions are a normal part of the review process. They allow the city to consider whether the proposed height, density, building form, site layout, servicing approach, drainage strategy, and overall development intensity are appropriate. They also allow the applicant and the City planning and development review team to determine what changes, technical studies, mitigation measures, or possible approval conditions may be needed before the proposal can be supported.

The proposed framework and overlay would be most useful during this iterative review period. They would give City planning and development review staff an internal planning-scale understanding of baseline and future thaw-related land susceptibility while changes to the proposal can still be considered. This information could be introduced during pre-application discussions where appropriate, but its main role would be during completeness review, coordinated technical and statutory review, applicant revisions, resubmissions, and re-review.

The purpose would not be to avoid revisions or move an application more quickly toward approval. Rather, the framework could help make the review-and-revision process more focused, transparent, and informed by the mapped ground conditions. It could help staff identify the relevant questions earlier within the review, explain why additional information may be needed, and assess whether revised plans and technical submissions respond adequately to the concerns identified.

The overlay could also provide a shared starting point for discussion among the City planning and development review team, the applicant, and the applicant's planning, engineering, and geotechnical consultants. The City's PHSI information and the applicant's site-specific studies would serve different but related purposes. The overlay would provide a consistent planning-scale view of the broader mapped conditions, while the applicant's investigations would provide the detailed evidence needed to confirm conditions at the site and recommend appropriate design or mitigation measures.

This distinction could place the city in a stronger position to participate in technical discussions without replacing the role of the applicant's consultants. City planning and development review staff could use the mapped class, confidence level, planning horizon, and supporting information to consider whether the submitted studies address the ground conditions identified by the framework and whether the proposed development responds appropriately to those conditions.

Where the overlay shows a Low PHSI class with strong confidence, the proposal may proceed through a comparatively routine review, subject to the technical, statutory, servicing, drainage, professional, and other requirements that would otherwise apply. A Low class would not remove the need for project-specific investigation or design where it is required.

Where the overlay shows Moderate or High susceptibility, the result could support closer discussion of the proposed height, density, building form, site layout, servicing, grading, drainage, and overall development intensity. It could also help determine whether the scope of the submitted geotechnical work is sufficient or whether further information is needed. Depending on the mapped conditions and the proposal, additional work could include:

- more detailed borehole investigation;
- Mean Annual Ground Temperature or Active Layer Thickness monitoring;
- further characterization of soil texture, material type, and ground ice;
- assessment of projected future thaw conditions;
- drainage and snow-management analysis;
- review of the proposed grading, foundation, and servicing approach; or
- comparison of alternative siting, layout, or development-intensity options.

The framework would not determine an acceptable height or density, prescribe a particular foundation system, or select the required mitigation. Those conclusions would depend on the planning context, the characteristics of the proposal, site-specific investigation, and professional planning, engineering, and geotechnical advice. The overlay would instead help the City identify the questions that need to be addressed and provide a clearer basis for discussions about revisions, further studies, mitigation, and possible conditions.

Where the result is Unknown / Insufficient Data, the lack of a supported class would itself provide useful information. It would indicate that the available evidence is not sufficient to rely on a Low, Moderate, or High interpretation. The City planning and development review team could then identify what additional information is needed before the ground conditions are treated as adequately understood.

The inclusion of baseline and future PHSI classes has a further benefit during review. Buildings and infrastructure are expected to remain in service beyond present ground conditions. A proposal may appear comparatively straightforward under the baseline condition but require a more cautious interpretation where projected Mean Annual Ground Temperature and Active Layer Thickness produce a higher future GTS and PHSI class.

The future class would not predict an exact failure or determine one design solution. It could help City planning and development review staff ask whether the applicant's studies assess how projected permafrost thaw may affect the site over the expected service life of the development, including changes in Mean Annual Ground Temperature and Active Layer Thickness, drainage and snow-management conditions, and the measures proposed to maintain long-term ground and foundation performance.

The PHSI would remain one source of information within a broader review. City planning and development review staff would continue to consider the General Plan, Zoning By-law, servicing and infrastructure, drainage, transportation, environmental conditions, community considerations, applicant submissions, and other applicable requirements. The overlay would not create a separate approval pathway or transfer professional engineering responsibility to City planning and development review staff.

Once a Development Permit is issued, the approved form of the proposal is established. Material changes to that approved proposal would normally require further review or authorization. The main value of the framework therefore lies in supporting the period before permit issuance, when additional information, revisions, mitigation measures, and possible conditions can still be considered through the City's planning and development review process.

9.4 Strengths, Limitations, and Cautions

A principal strength of the proposed framework is its clear separation of physical questions. Surface and terrain controls, ground thermal condition, thaw potential, and physical ground response are not treated as interchangeable. Keeping TRI, GTS, TPI, and TII distinct makes it easier to understand why a location receives its final PHSI class. A second strength is the distinction between the analytical process and the visible overlay. City planning and development review staff would not need to interpret numerous technical layers during routine use. They would see one PHSI class for the selected planning horizon, while the supporting analytical information would remain available where further technical review is needed.

A third strength is the treatment of different forms of evidence. The framework does not assume that continuous map layers, categorical terrain information, boreholes, thermistors, geophysics, laboratory results, and DInSAR observations all provide the same type of spatial information. It identifies different roles for mapped indicators, local classification evidence, model calibration, and validation. A fourth strength is the explicit treatment of uncertainty. The minimum evidence requirements prevent missing information from being assigned a Low rating. Unknown / Insufficient Data is retained as a valid result, while confidence is reported separately from susceptibility. This helps prevent the mapped output from presenting more certainty than the supporting evidence can justify.

A fifth strength is the use of the same conceptual architecture for baseline and future conditions. The future framework does not create an unrelated second index. It retains the same relationship among TRI, GTS, TPI, TII, and PHSI, while updating the component that can be projected most directly: GTS.

The proposed treatment of future conditions is also intentionally cautious. Baseline TRI is retained unless reliable future information is available for local snow, vegetation, organic cover, moisture, drainage, or other surface conditions. Baseline TII is retained as the existing physical ground setting unless projected ALT is expected to reach a deeper soil or material layer with different grain-size or ground ice conditions. Future PHSI therefore changes mainly through projected MAGT and ALT.

This approach is transparent, but it is also a limitation. Surface conditions may change over time even where the framework retains their baseline ratings. Ground ice may thaw, drain, and contribute to settlement after thaw begins. The framework does not simulate progressive ground ice loss, post-thaw consolidation, or the changing physical condition of the ground after thaw. These processes would require a more detailed ground thermal and geomechanical model.

The thesis also has important empirical limitations. It is based on document analysis, literature synthesis, mapping precedents, planning documents, and an illustrative application. It did not collect new field data, construct a complete Iqaluit database, select an operational map resolution, or produce current and future MAGT and ALT surfaces for the populated area. The proposed indicator thresholds, weights, branch class breaks, TPI and PHSI matrix cells, minimum evidence requirements, and confidence criteria have not been calibrated and independently validated using representative Iqaluit observations. They remain proposed components of the framework.

The framework has also not yet been reviewed or tested by the intended City planning and development review staff. Their assessment may identify changes needed to the terminology, class meanings, analytical structure, interface, information shown, or intended role within the review process. The Area B example is illustrative rather than site-specific. Its ratings and classes were selected to demonstrate the sequence of the framework. They do not establish the actual baseline or future susceptibility of Area B and should not be used for a planning or engineering decision.

The framework also remains limited to susceptibility. It does not calculate risk. It does not include the exposure or vulnerability of a proposed building, the consequences of failure, project costs, occupants, service criticality, or the effects of a specific foundation design. Building heat, loading, clearing, grading, fill, drainage changes, snow management, and servicing are proposal-specific conditions that remain outside the land-only PHSI. Several cautions therefore apply to interpretation:

- A Low PHSI class does not establish whether a site is safe or suitable.
- A Moderate class is not a prediction of failure.
- A High class does not prohibit development or determine the required engineering solution.
- Unknown / Insufficient Data must not be interpreted as Low.
- Low confidence is not the same as Unknown / Insufficient Data.
- The class shown at an address is a planning-scale interpretation for the mapped unit, not a direct subsurface measurement at that address.
- The overlay does not replace site-specific investigation, professional engineering and geotechnical judgement, community consultation, permitting, inspection, or the City's

decision-making authority.

These limitations do not remove the value of the framework. They define the boundary within which it can be used responsibly and identify the work needed before the proposed approach could become operational.

9.5 Implementation, Considerations and Future Research

The next stage is not immediate operational implementation. The proposed framework should first be reviewed by the city planning and development review staff and the relevant technical expertise expected to use or support it. This review should assess whether the structure is understandable, whether the class meanings are useful, whether the proposed interface provides the right information, and whether the framework fits the City's planning and development review process. The implementation pathway can be understood in three stages.

- Initial review and refinement: The intended City planning and development review staff should assess the proposed framework, terminology, PHSI classes, confidence information, and overlay interface. The framework should be revised where the review identifies unclear language, missing information, unnecessary complexity, or a poor fit with the existing development review process. The city would also need to confirm the intended area of application, the role of the overlay, and the responsibilities of planning and technical staff.
- Technical development and pilot testing: Once the framework has been refined, the available terrain, climate, thermal, borehole, geophysical, monitoring, and GIS information should be compiled and reviewed. Important gaps should be identified against the minimum evidence requirements for TRI, GTS, and TII. Representative pilot areas should then be selected to test the analytical unit, effective map resolution, indicator ratings, thresholds, weights, decision rules, TPI and PHSI matrices, MAGT and ALT models, and confidence criteria. Calibration should use representative local evidence, while validation should use observations that were not used to establish the rules.
- GIS development, user testing, and governance: An operational overlay should be developed only after the analytical method performs adequately. The address search, planning horizon selector, PHSI classes, confidence display, information panel, and

supporting technical information should then be tested with the intended City planning and development review staff. Responsibility would also need to be established for approval, technical oversight, data ownership, version control, updating, maintenance, and periodic revalidation.

Future research should support each of these stages.

- One priority is the development of a stronger local ground thermal dataset. Additional MAGT and ALT observations distributed across representative terrain conditions would support the current and future GTS models. Different statistical and machine learning approaches should be compared using spatially separated validation. MAGT and ALT should continue to be evaluated independently because they may not be predicted with the same reliability.
- A second priority is improved information on material type, soil texture or grain size, ground ice content, and subsurface layering. This would strengthen TII and help determine whether future ALT may reach a deeper layer with different ground-response conditions.
- A third direction is the treatment of future TRI. The present framework retains baseline surface conditions where suitable future projections are not available. Future work could examine whether local snow, vegetation, moisture, drainage, or organic-cover conditions can be projected at a scale suitable for the City's planning and development review process. Any such additions should improve the analysis without creating unsupported precision.
- A fourth direction is the evaluation of alternative rating, weighting, and matrix rules. Sensitivity testing should identify which decisions have the greatest effect on the final PHSI class. Alternative PHSI matrices could also be compared to test how much influence TII should have on the final result.
- A fifth direction is the assessment of practical use. Research with City planning and development review staff should examine whether the overlay improves understanding, supports clearer information requests, and fits the timing of the review process. The evaluation should consider not only whether users understand the classes, but whether the information helps them ask better questions, coordinate technical review earlier, and explain the basis for requests or recommendations.
- A sixth direction is the consideration of implementation within the wider planning and

community context. The overlay should not be treated as a stand-alone technical product. Its development and use should remain consistent with the City's planning instruments, community priorities, Inuit knowledge and participation, and the broader governance context within which land-use decisions are made in Iqaluit.

- Finally, future research could consider how the general structure might apply in other northern communities. Transferability should be assessed at the level of the framework rather than the numerical rules. The separation of thaw potential and thaw impact, the treatment of minimum evidence requirements, and the distinction between the PHSI and the overlay may be broadly useful. The actual indicators, thresholds, weights, mapped units, confidence criteria, climate projections, and review responses would need to be developed locally.

9.6 Closing Conclusion

Permafrost-informed planning in Iqaluit is not solely a technical exercise and not solely a land-use exercise. It is a city planning and development review challenge located at the intersection of variable ground conditions, climate change, housing and development pressure, infrastructure constraints, and the need to make decisions before every technical question has been resolved.

The central finding of this thesis is that the required knowledge is not absent. Scientific studies explain the processes controlling permafrost warming and ground response. Mapping studies provide approaches for representing thermal and terrain conditions. Engineering standards and technical guidance establish expectations for investigation and design. The City's planning and development review process provides the institutional pathway through which a proposal is assessed, revised, supported, conditioned, or refused.

What is missing is a consistent planning-scale translation among these forms of knowledge. The proposed framework offers one way to provide that translation. It organizes relevant evidence through TRI, GTS, TPI, TII, and the final PHSI. It provides a common structure for baseline and future conditions, retains Unknown / Insufficient Data where the evidence is inadequate, reports confidence separately, and presents the final result through a simple overlay that City planning and development review staff could interpret alongside other planning and application information.

The framework is not a completed operational map, a site certificate, an engineering design method, or an approval decision. Its contribution is a structured and transparent path from technical evidence to earlier planning-stage understanding.

For the City, the potential value lies in having an internal planning-scale reference that can support more focused discussion with applicants and their consultants. It could help staff consider whether proposed height, density, servicing, and overall development intensity are appropriate for the mapped conditions, identify where additional investigation or mitigation may be required, and explain why a more cautious review posture is warranted under baseline or future conditions.

The value of the framework is therefore not that it removes uncertainty. Its value is that it makes susceptibility, uncertainty, and evidence limitations more visible at a stage when they can still inform the direction of the review. In that sense, the thesis contributes not a final answer for development in permafrost terrain, but a clearer way to ask the right questions earlier.

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APPENDICES

Appendix A: Framework Summary and Application in Iqaluit

Summary of the Permafrost Hazard Susceptibility Index (PHSI) Framework

Its application to planning, zoning and development review in Iqaluit

The project: Beginning with the translation gap shown in Figure A1, this thesis develops a planning-scale framework that translates available permafrost evidence into a consistent reference for planning, zoning and development review in Iqaluit.

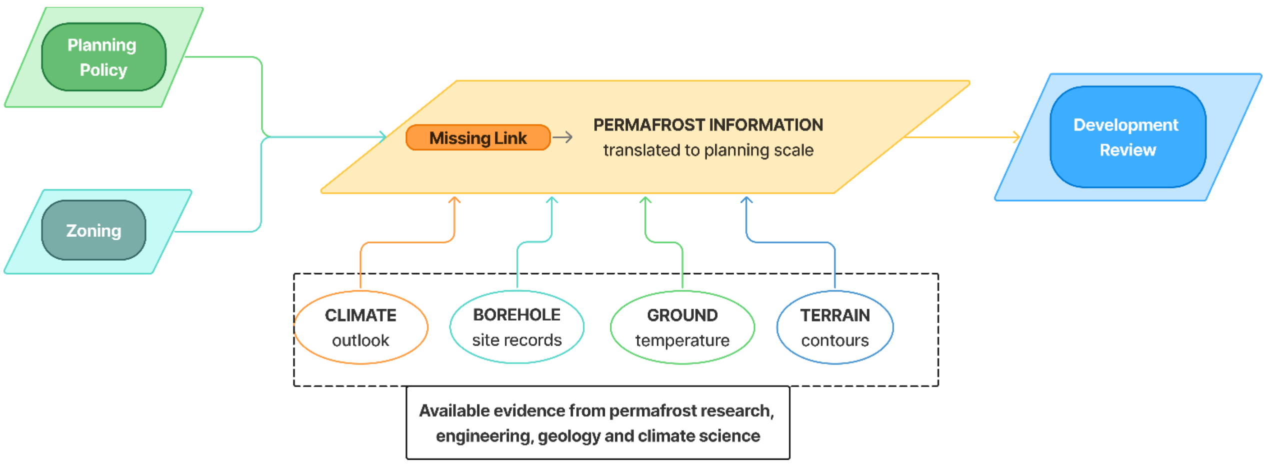

Figure A1. The planning-scale permafrost information gap

Understanding permafrost and ground response: Permafrost is ground that remains frozen for at least two consecutive years. Each summer, the upper "active layer" thaws and then refreezes. Conditions below the surface vary: some areas contain bedrock or coarse material, while others contain frost-sensitive soil or ground ice. As the climate warms and seasonal thaw deepens, the way the ground responds can also vary from place to place.

What the City is already deciding: The General Plan and Zoning By-law guide land use, height, density, building form and development intensity. During development review, staff examine a building proposal, coordinate comments, identify required information, review revisions and prepare a recommendation or decision. These choices also connect to grading, drainage, roads, water and sewer servicing, and the long-term performance of buildings and public infrastructure.

The planning gap: Figure A1 summarizes the starting problem. Relevant evidence and methods already exist, including borehole data, frozen-ground engineering knowledge, and permafrost hazard and susceptibility mapping approaches developed for different scales. However, this information has not been consolidated and translated into a reference suited to City planning and development decision-making in Iqaluit. The PHSI provides a framework for that planning-scale translation while development proposals are being reviewed.

How the PHSI is developed

Figure A2 shows how available evidence becomes a susceptibility class while preserving confidence and the supporting record

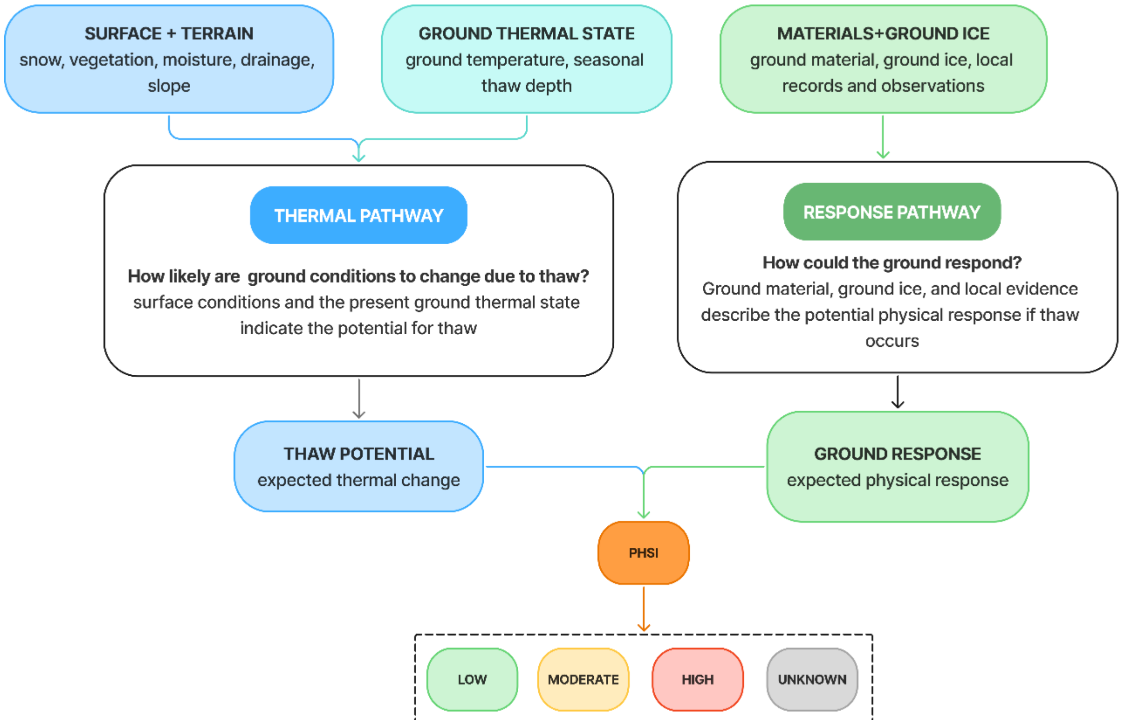

Figure A2. Conceptual structure of the PHSI

How the framework works

1. Describe thaw potential	2. Describe ground response	3. Produce the PHSI result
Surface and terrain conditions, ground temperature and seasonal thaw depth describe the expected potential for thaw-related change.	Ground material, ground ice and local records describe how the land could physically respond if thaw occurs.	The two pathways are combined through transparent rules. The result is Low, Moderate, High or Unknown / Insufficient Data, with confidence and supporting evidence recorded separately.

What accompanies the mapped result

- City staff can see whether the classification is driven by thaw potential, expected ground response, or both.
- Every class can be traced back to the evidence and rules that produced it.
- Confidence is shown separately, indicating how strongly the available evidence supports the class.
- Unknown / Insufficient Data identifies locations where additional information is needed.

From framework to mapped output: The process in Figure A2 produces more than a susceptibility class. The pathway results, confidence, supporting evidence and any information gaps are carried into the planner-facing overlay shown in Figure A3, turning separate technical records into a planning-scale view for use in City planning and development review process.

The planner-facing overlay - and where it enters the development review process

Figures A3 and A4 show how the PHSI could be viewed and where it could support the City planning and development review process

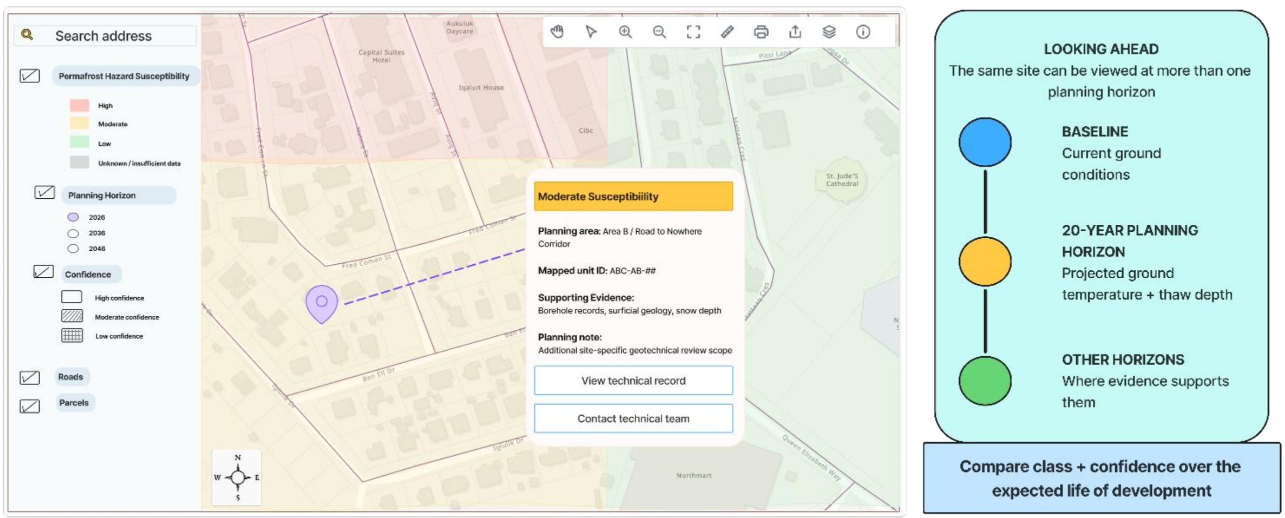

Figure A3. Planner-facing PHSI overlay and planning horizons

Planner-facing view and future feasibility: Figure A3 shows how staff could locate a proposal area, view its mapped class, confidence and supporting evidence, and compare baseline conditions with conditions projected for a 20-year planning horizon. Additional 30-, 40- or 50-year horizons could be included where the climate projections, local model performance and supporting evidence are sufficiently robust, allowing staff to consider how mapped susceptibility could change over the expected life of a building or infrastructure investment.

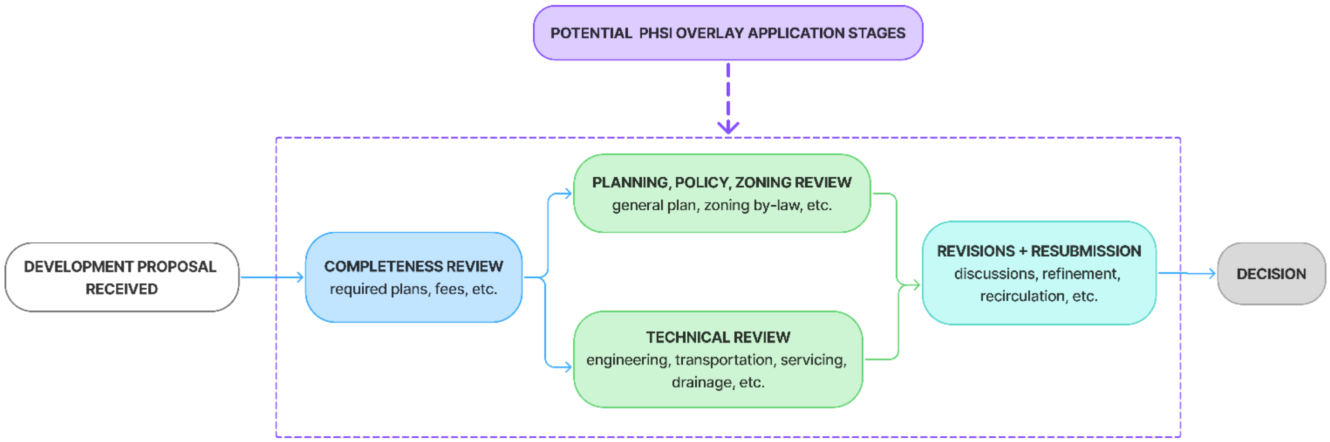

Figure A4. PHSI overlay use in development review

Use in development review: As Figure A4 shows, the overlay's primary application begins at completeness review, where it could help City planning and development review staff identify permafrost-related plans, reports and supporting information that may be required. It would then serve primarily as a technical screening and reference layer during the concurrent planning policy, zoning and technical reviews, supplementing applicable plans, policies, by-laws, submitted studies and professional judgment. The overlay would remain useful during any revisions or resubmissions by providing a consistent basis for reviewing updated materials before a decision is made.

The contribution: City planning and development review staff could gain a consistent basis for considering permafrost across planning, zoning and development review. Nunavut Housing Corporation and other developers and investors gain earlier insight into site conditions and likely technical requirements for site selection and project preparation. Engineers and researchers could gain a clearer basis for connecting technical evidence to planning decisions and supporting future framework refinement. Together, Figures A1 to A4 show how the thesis translates permafrost evidence into a planning-scale reference for planning, zoning and building-development review in Iqaluit.

Appendix B: Draft Survey to Inform Future PHSI Development

Draft Survey: Status and Purpose

This draft survey arises from the thesis and identifies questions that could inform future validation and refinement of the PHSI framework, the needs of City of Iqaluit Planning and Development Review staff, and the potential integration of a planner-facing overlay into the City planning and development review process. It was not submitted to or approved by the City of Iqaluit, was not administered, and no thesis findings are based on survey responses. Any future refinement, translation, distribution or administration will occur with the City's prior consent, collaboration and approval, and in accordance with applicable research-ethics, privacy, data-governance and informed-consent requirements.

City of Iqaluit Planning, Zoning and Development Review Staff Survey

Section 1 - Your role and workflow

1. Which areas are part of your work? Select all that apply.

☐ Planning policy and long-range planning ☐ Zoning administration or by-law review
☐ Development application review ☐ Development permit decisions
☐ GIS or spatial data ☐ Municipal engineering or infrastructure
☐ Management or interdepartmental coordination ☐ Other: ____________________________

2. How long have you worked in planning, zoning or development review in northern communities?

☐ Less than 2 years ☐ 2–5 years ☐ 6–10 years ☐ More than 10 years

3. How often do you review building-development proposals?

☐ Weekly or more often ☐ Monthly ☐ Several times each year
☐ Rarely ☐ Not part of my current role ☐ Other: ____________________________

4. Which proposal types do you commonly encounter? Select all that apply.

☐ New residential buildings ☐ Housing subdivisions or multi-unit housing
☐ Commercial or institutional buildings ☐ Building additions or redevelopment
☐ Rezoning or zoning amendments ☐ Subdivision or site-layout proposals
☐ Municipal infrastructure connected to development ☐ Other: ____________________________

5. At which stages are you usually involved? Select all that apply.

☐ Pre-application discussion ☐ Application completeness review
☐ Coordinated staff review ☐ Applicant comments and revisions
☐ Staff recommendation ☐ Permit or decision
☐ Post-decision follow-up ☐ Other stage: ____________________________

6. Which systems do you use during review? Select all that apply.

☐ City GIS or map viewer ☐ Paper or PDF maps
☐ Application-tracking or permitting system ☐ Shared drive or document system
☐ Email and internal comments ☐ Staff-report template
☐ External technical reports ☐ Other: ____________________________

7. Briefly describe the usual path of a building-development application through your team.

8. At what point can staff most effectively influence site layout, building density and height or proposal supporting documentation requirements?

Current use of permafrost information

Where information enters the process - and where staff experience difficulty

Section 2 - Current practice and the translation gap

9. When is permafrost information usually considered? Select all that apply.

☐ Long-range or growth planning
☐ Pre-application discussion
☐ Coordinated staff review
☐ After an applicant submits a geotechnical report
☐ After a ground or building problem is observed
☐ Zoning or rezoning
☐ Application completeness review
☐ After an engineering comment
☐ During building design or territorial permitting
☐ Other point in the process: ___________________________

10. Which information sources do you currently use? Select all that apply.

☐ Geotechnical reports
☐ Surficial geology or terrain maps
☐ City GIS layers
☐ Scientific or government studies
☐ Community or Inuit knowledge
☐ Other: ___________________________
☐ Borehole or test-pit records
☐ Ground-temperature or thaw-depth records
☐ Consultant or engineering comments
☐ Staff knowledge and previous project experience
☐ Climate projections

11. How is the need for more permafrost information usually identified?

☐ A standard application requirement
☐ A staff member recognizes the issue
☐ The proposal type or intensity raises a concern
☐ There is no consistent approach
☐ The site location or terrain raises a concern
☐ An engineer or consultant recommends it
☐ Information from a nearby project is available
☐ Other: ___________________________

12. Rank the three greatest current challenges. Use 1-3 for ranking (1 representing the greatest challenge)

Item	Top 3
Permafrost information is stored in different places	
Coverage of permafrost data varies across the city	
Existing permafrost evidence is difficult to interpret at planning scale	
Permafrost conditions are considered too late in the review process	
Permafrost related submission requirements vary between applications	
Staff cannot easily determine why an area may be sensitive to thaw	
Future permafrost conditions are difficult to consider	
Uncertainty or gaps in permafrost data are difficult to communicate	
Technical permafrost information is difficult to communicate to applicants	
Other challenge: _________________________	

13. Describe a recent type of application where earlier permafrost information (reports and studies) provision by the applicant would have improved the review.

14. What information do staff most often request from an applicant when ground conditions are a concern?

15. Where do delays, repeated comments or inconsistent expectations most often occur?

Where a planning-scale overlay could add value
Decisions, stages and building-development questions

Section 3 - Priority uses

16. Rank the five most valuable uses for a future overlay. Use 1 for the highest priority.

Item	Top 5
General Plan, growth-area or neighborhood planning	
Zoning review and zoning amendments	
Early site selection for housing or public projects	
Pre-application discussion with an applicant	
Application completeness review	
Coordinated city staff technical review and comments	
Review of applicant revisions/resubmissions	
Staff recommendation or development-permit conditions	
Capital planning and municipal servicing coordination	
Communication with Nunavut Housing Corporation, developers or investors	
Other use: ___________________________	

17. Which building-development questions should the overlay help staff examine? Select all that apply.

- ☐ Development-ground compatibility
- ☐ Building footprint
- ☐ Overall development intensity
- ☐ Drainage and surface-water management
- ☐ Water and sewer servicing
- ☐ Comparison of alternative sites or layouts
- ☐ Building location on the lot
- ☐ Height and density
- ☐ Grading and site disturbance
- ☐ Road access and circulation
- ☐ Need and scope for further technical information
- ☐ Other question:____________________________

18. For each review stage, show how useful the overlay could be.

1 = Not useful 2 = Slightly useful 3 = Moderately useful 4 = Very useful 5 = Essential NS = Not sure

Statement	1	2	3	4	5	NS
18. Pre-application discussion	☐	☐	☐	☐	☐	☐
19. Application completeness review	☐	☐	☐	☐	☐	☐
20. Coordinated staff technical review and comments	☐	☐	☐	☐	☐	☐
21. Applicant revisions and staff re-review	☐	☐	☐	☐	☐	☐
22. Staff recommendation or decision	☐	☐	☐	☐	☐	☐
23. Long-range planning or zoning work	☐	☐	☐	☐	☐	☐
24. Other review stage: ____________________________	☐	☐	☐	☐	☐	☐

25. What would an overlay need to show before it could meaningfully change a planning or zoning discussion?

26. Which users outside the City should be able to see or receive the information, and in what form?

Designing the planner-facing experience

The information, evidence and workflow connection staff would need

Section 4 - Interface and information requirements

27. Rank the five most important functions. Use 1 for the highest priority.

Item	Top 5
Search by address, parcel or proposal area	
See all susceptibility classes across a site	
Switch between current and future planning horizons	
See confidence or data sufficiency	
Read a short explanation of the class	
See the main factors affecting the result	
See evidence sources and dates	
See missing evidence	
Open a technical record	
Print or export a site summary	
Compare two sites or proposal layouts	
Other function: ___________________________	

28. Where should staff access the overlay? Select all acceptable options.

☐ Existing City GIS or map viewer
☐ Internal planning map portal
☐ Standalone web map
☐ Printable map or PDF report
☐ Other: ___________________________

29. What is the minimum information needed when staff select a site?

☐ Susceptibility class
☐ Class meaning
☐ Planning horizon
☐ Confidence or data sufficiency
☐ Main factors behind the class
☐ Evidence sources and dates
☐ Missing evidence
☐ Planning note
☐ Suggested technical coordination
☐ Mapped-unit identifier
☐ Other information: ________________________

30. How should the class be displayed? Select all that would improve understanding.

☐ Color plus the class word
☐ Pattern or symbol as well as color
☐ Short explanation
☐ Class visible across the full site
☐ Separate confidence display
☐ Separate Unknown / Insufficient Data class
☐ Other display method:______

31. Please rate the following statements.

1 = Strongly disagree 2 = Disagree 3 = Neither agree nor disagree 4 = Agree 5 = Strongly agree NS = Not sure

Statement	1	2	3	4	5	NS
31. The four classes are easy to understand.	☐	☐	☐	☐	☐	☐
32. The planning-horizon selector would support future-oriented decisions.	☐	☐	☐	☐	☐	☐
33. A separate confidence display would improve interpretation.	☐	☐	☐	☐	☐	☐
34. A short explanation of why the site is classified would help staff.	☐	☐	☐	☐	☐	☐
35. Links to source evidence would increase trust.	☐	☐	☐	☐	☐	☐
36. A printable site summary would support files, comments or staff reports.	☐	☐	☐	☐	☐	☐

Planning for future conditions

Which horizons matter, what should change, and what evidence staff would need

Section 4 continued - Planner-facing experience

37. What should a site summary contain?

38. What wording, colour or symbol could be misunderstood by staff, applicants or the public?

Section 5 - Future planning horizons and feasibility

39. Which planning horizons would be useful to view? Select all that apply.

☐ Baseline / current conditions
☐ 10 years into the future
☐ 20 years into the future
☐ 30 years into the future
☐ 40 years into the future
☐ 50 years into the future
☐ Another horizon: ___________________________
☐ The useful horizon depends on the development type

40. Which decisions would benefit most from future-condition information? Select all that apply.

☐ General Plan or growth-area planning
☐ Zoning review or zoning amendments
☐ Housing or public-facility site selection
☐ Review over the expected life of a building
☐ Road, water and sewer investment
☐ Drainage and surface-water planning
☐ Comparison of alternative sites or layouts
☐ Applicant information requirements
☐ Other decision: ___________________________

41. What should staff be able to compare between baseline and future horizons? Select all that apply.

☐ PHSI class
☐ Confidence or data sufficiency
☐ Projected mean annual ground temperature
☐ Projected seasonal thaw depth
☐ Main factors causing the change
☐ Factors retained at baseline
☐ Climate scenario and climate modelling version
☐ Planning note or review response
☐ Other comparison: __________________________

42. What would make a future layer credible and usable? Select all that apply.

☐ A clearly stated climate scenario
☐ Locally calibrated ground-thermal models
☐ Model performance reported for each horizon
☐ Agreement or differences among scenarios
☐ Confidence shown separately
☐ Evidence sources, dates and assumptions
☐ A regular update schedule
☐ Ability to compare scenarios
☐ Other requirement: _________________________

43. How far into the future should the City look for different types of buildings or infrastructure proposals, and why?

Validation and pilot design

What must be tested, with whom, and how success should be judged

Section 6 - Evidence, trust and validation

44. What would make you trust and use the overlay? Select all that apply.

- ☐ Clear explanation of the method
- ☐ Local borehole and geotechnical evidence
- ☐ Local ground-temperature and thaw-depth monitoring
- ☐ Comparison with known building or ground-performance locations
- ☐ Independent technical review
- ☐ Visible evidence dates and sources
- ☐ Clear confidence or data-sufficiency rating
- ☐ Documented update schedule
- ☐ Staff training and examples
- ☐ Successful testing in a pilot area
- ☐ Other requirement: ________________________

45. Who should participate in refinement and validation? Select all that apply.

- ☐ City planning staff
- ☐ City zoning and development review staff
- ☐ City engineering and infrastructure staff
- ☐ City GIS and data staff
- ☐ Geotechnical and permafrost engineers
- ☐ Nunavut Housing Corporation
- ☐ Government of Nunavut departments
- ☐ Developers and design consultants
- ☐ Inuit knowledge holders and community representatives
- ☐ Academic or research partners
- ☐ Other participant: _________________________

46. Which geography would make the most useful first pilot?

- ☐ A representative neighborhood
- ☐ A planned growth area
- ☐ A housing-development area
- ☐ A corridor with servicing or drainage questions
- ☐ Several areas with contrasting terrain
- ☐ Other: ___________________________

47. How should pilot success be measured? Select all that apply.

- ☐ Staff understand the classes and confidence
- ☐ Permafrost questions arise earlier in the review process
- ☐ Information requests are more consistent
- ☐ Applicants understand expectations earlier
- ☐ Repeated comments or rework decrease
- ☐ The overlay agrees with independent local evidence
- ☐ Staff can explain the result to decision-makers
- ☐ The overlay fits existing systems and time demands
- ☐ Other measure: ___________________________

Next research and implementation priorities

The work *that would turn the concept into a locally tested planning resource*

Section 7 - Research priorities and practical conditions

48. Rank the five most important next research tasks. Use 1 for the highest priority.

Item	Top 5
Confirm staff needs and workflow requirements	
Compile and standardize local geotechnical records	
Expand ground-temperature and active-layer monitoring	
Define evidence-sufficiency and confidence rules	
Test thresholds and combination rules	
Develop a pilot PHSI map	
Compare the map with independent field evidence	
Test the interface with real review scenarios	
Test supported future planning horizons	
Develop governance, updating and data-stewardship arrangements	
Other research task: ___________________________	

49. Rank the three greatest implementation barriers. Use 1 for the greatest barrier.

Item	Top 3
Data coverage or quality	
Data access, ownership or confidentiality	
Staff time and capacity	
GIS or technical capacity	
Funding	
Responsibility for maintenance	
Policy or legal authority	
Coordination across organizations	
Public communication and translation	
Other barrier: ___________________________	

50. What is the most important question the next phase of research must answer?

51. What would make the overlay unsuitable for everyday City use?

52. If this work succeeds, what practical difference should it make for staff, applicants and building projects?

53. Additional comments or recommended contacts, data sources or pilot locations: