LIVING ON UNSTABLE GROUND: IDENTIFYING PHYSICAL LANDSCAPE CONSTRAINTS ON PLANNING AND INFRASTRUCTURE DEVELOPMENT IN NUNAVUT COMMUNITIES

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Living on unstable ground:
Identifying physical landscape constraints on planning and infrastructure development in Nunavut communities

by
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Abstract

This thesis develops and tests a research framework that assesses constraints imposed by the physical environment, in particular landscape hazards on infrastructure development and community planning in Arctic environments. The framework uses a multi-hazard, multi-tool approach, and was operationalized in the community of Clyde River, Nunavut. Data were accessed through a range of sources including: community consultations, air photo interpretation, topographic surveys, sediment sampling, inventory of existing infrastructure, permafrost coring, and landscape and landform assessment. Data were analyzed, interpreted and integrated to produce individual landscape hazard layers and then combined to create a composite physical landscape constraint map. The constraint map categorized the community landscape into a tiered classification scheme of low, moderate and high risk. An assessment of how projected climate changes may modify the risk level associated with individual landscape hazards was also undertaken. Research suggests that flooding, erosion, slope instability and permafrost dynamics are the main landscape hazards occurring in Clyde River and that the risk level associated with these hazards will be enhanced due to climate change. The spatial distribution of these hazards varies, and is dependent on the physical environment and human modifications to the landscape. Both adaptations and maladaptations are altering the vulnerability of the community towards landscape hazards. The research framework devised in Clyde River is considered applicable to other arctic communities, and will provide useful guidance for community planning and sustainable infrastructure development.

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Chapter 1 Introduction

1.1 Introduction

The purpose of this thesis is to develop and test a research framework that assesses the nature and distribution of constraints imposed by the physical landscape on infrastructure and community planning in the Arctic. Although methodologies exist to assess how terrain may limit and influence infrastructure development, these have not been applied at length in northern environments (Van Westen et al., 1999; Cronin et al., 2004). The present framework was designed and operationalized using a case study of Clyde River (Kangitugapik), a community of 820 people on the east coast of Baffin Island, Nunavut (Fig. 1.1).

Landscape hazards are considered to be components of the physical environment that directly constitute potential risks to human life and/or infrastructure stability, and can impede or constrain development (Coch, 1995). Examples include erosion, thermokarst (ground subsidence), landslides, flooding and sea-level changes. Hazards exist in a number of reference frames, including magnitude and frequency, and spatial and temporal scales. This thesis will focus on assessing all landscape hazards originating in the study area, regardless of the level of impact, how often they occur, the area they cover, and their duration. Both slow on-going changes and extreme hazards are included, although those events considered external to the field area, such as earthquakes, tsunamis and fiord wall failures, are excluded.

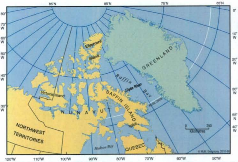


Figure 1.1A Clyde River, Nunavut is located at 70° 27'45''N, 68°37'44''W. Map source C. Conway.

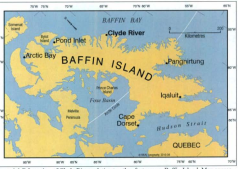


Figure 1.1 B Location of Clyde River relative to other features on Baffin Island. Map source C. Conway.

Causative factors leading to landscape instabilities include substrate characteristics, terrain morphology, climate variables, hydrology, and human and natural disturbances. Techniques and tools used to understand and assess these factors vary, and have included: surficial geological mapping, permafrost coring, remote sensing, and numerical and climate models. Data collection methods are also site specific, for instance mapping ground ice conditions will be applicable for continuous and discontinuous permafrost, whereas nearshore surveys will only be relevant for communities built along the coast.

For this thesis, research efforts focus on areas of existing and proposed urban development in Clyde River, Nunavut (NU). Only hard infrastructure, defined as built structures such as buildings, utility poles and roads, is examined. Soft infrastructure such as trails or hunting grounds is not included in this assessment. This thesis uses field data collected during the summers of 2007 and 2008, and analytical data processed between 2007 and 2010. Fieldwork involved community consultations, field mapping, surveying, permafrost drilling, and sediment sampling.

This thesis is principally focused on assessing current landscape hazards and risk. However, it is also recognized that various constraints and risks associated with the present environment will likely be exacerbated by climate change, and that future planning and development need to take these future considerations into account. Projections and changes in various identified risk elements are discussed at the end of the thesis. Without an appreciation of the degree of climate changes that may occur in the future, it is not possible to quantify actual changes in risk, which are instead discussed in more general terms of relative frequency of occurrence and magnitude of potential impact.

Initially the focus of this thesis was on the investigation, assessment and mapping of physical landscape constraints and development of a framework that can inform and provide guidance to the planning process in Clyde River. Time constraints resulted in a focus on an understanding of the physical environment, compared to understanding whom the individuals and organizations involved in the planning process are, their roles and responsibilities, and the structure of the planning process in the community and Nunavut. As such, the process of how to integrate the research into the planning process could not be fully investigated, and there is greater emphasis in this thesis on physical landscape constraints in Arctic environments.

The Geological Survey of Canada (GSC) branch of Natural Resources Canada (NRCan) and Canada-Nunavut Geoscience office (CNGO) provided financial and logistical support for the field research under its program "*Enhancing Resilience of Canadian Communities in a Changing Climate.*" Additional logistical support for the permafrost coring was provided by the Centre d'études Nordiques at Laval University and L'Institut National de la Recherche Scientifique (INRS) in Quebec City. Community consultation visits occurred during March 2008 and 2010, and were supported by NRCan, CNGO, and Indian and Northern Affairs Canada (INAC), and included attendees affiliated with NRCan, Canadian Institute of Planners (CIP), INAC, Government of Nunavut (GN), Nunavut Research Institute, University of British Columbia and the Office of the Auditor General of Canada. Community consultations and project support was facilitated by Ittaq Heritage and Research

Centre, a local non-governmental organization located in Clyde River. This thesis also uses additional information made available by NRCan team members.

1.2 Contribution to other research projects

This research contributes to a sub-project of the *Integrated Assessment of Climate Change Impacts and Adaptation Options in Nunavut Communities* project, led by the GN and the Earth Sciences Sector of NRCan, in conjunction with Memorial and Laval universities, the CIP and the CNGO. By working in Nunavut communities with local community groups, this project aims to combine traditional and scientific knowledge to improve the capacity at the community level to cope with the impacts of a changing climate. Project findings will help inform and guide regional planners, community members, government decision makers and other stakeholders on how landscape hazards and climate-related environmental changes may impact communities and their infrastructure. For example, by working with the Government of Nunavut and the Canadian Institute of Planners, research will be incorporated into climate change action plans for specific communities and will provide guidance to planning and development decision-making in all communities. A multidisciplinary team is an important component of this work. This research is based in science, but the ultimate success of the project requires that the science is communicated into a language that is understood by communities, government agencies and community planners. This will allow the information to be incorporated into planning principles, documents and policies.

This thesis also contributes to the *International Polar Year* (IPY) *Community Adaptation and Vulnerability in Arctic Regions* (CAVIAR) project. The aim of IPY-

CAVIAR is to increase the understanding of processes that shape vulnerability across the circumpolar region. Research using a similar methodological framework is being conducted in numerous communities across the Arctic and project results will be compared between case studies (Fig 1.2).

Preliminary results from the CAVIAR project suggest a few trends. Vulnerability varies between and within communities, and is strongly influenced by environmental and social conditions. Change is not new in the Arctic, and northern peoples have always had to deal with and adapt to changes, and this needs to be taken into account when investigating current risks and adaptations. Coping mechanisms to infrastructure risks need to be employed by local and territorial governments and institutions.

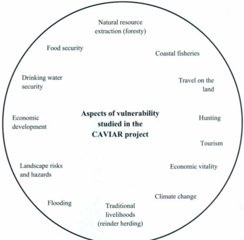


Figure 1.2 In the CAVIAR project, vulnerability in relation to a range of factors is being studied, which together provides an overall assessment of human security in the Arctic. This study provides a case study of vulnerability in relation to landscape risks and hazards, infrastructure and community development.

1.3 Research rationale

There are tremendous population pressures in Nunavut communities driving infrastructure expansion, which shows the need to have long-term development plans for communities. Communities in Nunavut are generally small, young and growing. More than two-thirds of residents of Nunavut live in communities with less than 1000 people, with the capital, Iqaluit, being the sole community with a population exceeding 5,000 people (Prowse and Furgal, 2009b). The population of Nunavut is young; 54.3% of the inhabitants are under the age of 15, and in smaller communities, this percentage is often greater. In comparison, the percentage of the population under 15 for Canada is 38.8%, and 37.6% and 30.8% for the Yukon and Northwest Territories, respectively (Furgal and Prowse, 2008). Nunavut has one of the highest population growth rates of any province or territory in the country, with a 10% increase from 2001 to 2006. As the population will remain youthful, the dependency ratio is projected to remain the highest out of any territory or province (Prowse et al., 2009a). As Nunavut communities continue to grow, additional residential, transportation, utility and community infrastructure will need to be developed.

Already, there is an infrastructure deficit and over-crowded housing situation in Nunavut. Over half of Nunavut's Inuit population is considered to be living in overcrowded conditions, with 38% identified as having core needs (Government of Nunavut and Nunavut Tunngavik, 2004). Core needs are defined as not living in, or having access to, suitable, adequate or affordable housing. In the Qikiqtaaluk (Baffin Island) region of Nunavut, housing shortages are of particular concern, with an average of 6.1 occupants per house (Kovesi et al., 2007). Insufficiencies are not limited to housing, much of the air and road transportation service is also outdated or unsuitable (Government of Nunavut, 2007).

One of the hurdles to development in Nunavut is the high cost of infrastructure construction and maintenance (Departments of Transportation, 2008). Contributing factors include small, remote populations (Couture et al., 2003; Furgal and Prowse, 2008), a short construction season, lack of rail and road access to communities (Dore and Burton, 2001), long shipping times with the high potential for goods to be damaged, limited access to large equipment, and the high costs of labour and materials (Strub, 1996).

The physical environment onto which infrastructure is built also poses significant constraints due to the Arctic's extreme climate, the sensitive and dynamic nature of the landscape, and the strong influence that the physical environment has on development (Instanes et al., 2005; Furgal and Prowse, 2008). Seasonally variable, extreme and harsh climate conditions affect Nunavut communities. The Baffin Island region is characterized by long, cold winters, and short, cool summers (Prowse et al., 2009a). This cold climate translates into challenges for infrastructure due to heat loss from buildings, contraction and expansion of building materials, and freezing of water in pipes and other confined places (Strub, 1996). Additionally, strong winds result in snow drifting and damage to infrastructure (Strub, 1996). Abrupt changes in climate conditions can lead to further instabilities in the landscape, impacting infrastructure development (Prowse and Furgal, 2009b). For instance, rapid snowmelt on frozen ground can cause flooding, or saturated unfrozen sediments overlying frozen ground can fail on low to moderate slopes causing landslides.

Temperatures in Nunavut are cold, with daily averages during the winter months generally below -30°C. These cold temperatures result in the formation of permafrost conditions, which is defined as ground that remains below 0°C for two or more years. Above the permafrost is the active layer, which is the layer of ground that thaws and freezes on a yearly basis. Frozen ground can serve as a stable building foundation, so long as conditions do not change (Prowse et al., 2009c). However, as permafrost is a thermal condition, anthropogenic and natural disturbances may destabilize the permafrost environment (Nelson et al., 2001). For instance, as discussed in detail in Chapter 2, permafrost may contain varying amounts of ice, which upon melting may cause uneven ground subsidence. Periglacial processes, which occur in cold, non-glaciated environments, also cause disturbances to the terrain surface. These include the formation and degradation of ice-wedge polygons, frost heave and thermokarst (French, 2007).

Most Nunavut communities are coastal and occupy glacio-isostatically uplifted areas formerly inundated by postglacial high sea levels. Communities situated atop raised marine sediments may be underlain by saline permafrost, considered more sensitive to environmental change than other types of permafrost (Biggar and Sego, 1993). The coastlines themselves may be composed of easily erodible sediments, which when coupled with rising sea levels and increased wave action can be prone to instability and failure (Dolan and Walker, 2004). In addition, some Nunavut communities are huddled between steep bedrock slopes and the shoreline and thus are potentially affected by issues of slope failure and rockfall.

Hydrology is another potential challenge to building in permafrost environments. Flooding and gullying can occur during snowmelt or heavy rainfall, and can be rapidly accentuated where erosion intersects ice-rich sediments. Areas of water ponding can also cause thermal erosion of permafrost, resulting in subsidence of the ground surface. This will create further depressions, allowing more water to collect, causing the cycle to intensify. If vehicles disturb the ground, permanent channels can develop which erode and enlarge over time as water collects in, and is channeled along, the vehicle tracks.

Snow distribution also plays an important role in shaping the landscape. In areas of perennial snow accumulation, water logged conditions often develop downslope. Snowdrifts also insulate the ground, preventing cold winter temperatures from penetrating into the ground, resulting in warmer permafrost temperatures, and thickening of the seasonal active layer.

The Canadian Arctic is a region projected to experience amongst the greatest and earliest impacts under global climate change scenarios (Serreze et al., 2000; Prowse and Furgal, 2009b). Projected changes include alterations in air and ocean temperature, precipitation patterns, wind direction and intensity, timing and duration of seasons, and increased variability and decreased predictability of weather conditions. Indigenous peoples and scientists have already observed such climate-related changes. On Baffin Island for example, Inuit have noticed seasonal and magnitude changes in temperature, wind and precipitation (Fox, 2003). This is leading to modifications in snow, ice, and terrain conditions, increasing the potential for landscape hazards (Meier et al., 2006). As a result of dynamic feedback mechanisms in the environment, climate-related landscape hazards may well be enhanced in the future, resulting in increased risk to communities with implications for infrastructure development (Anisimov and Reneva, 2006).

Climate changes present specific challenges for infrastructure in arctic landscapes. Northern infrastructure generally depends on the stability of the permafrost to provide a secure foundation for buildings, pipelines, roads, waste containment and other structures. Although in the short term the impact of disturbances associated with the construction of infrastructure will outweigh those of warming climate, changes due to warmer thermal regimes could become significant over decadal time frames (Furgal and Prowse, 2008).

1.4 Research objectives

In order for Arctic communities to develop appropriate planning and development guidelines, they must be aware of local constraints imposed by the physical environment. As such, two key objectives were established for this project:

(1) Devise a research framework that assesses the nature and spatial extent of landscape hazards on infrastructure planning and development in Nunavut communities as they exist today, and under projected climate change scenarios.

(2) Test the developed framework in a Nunavut community to gauge its effectiveness, level of community acceptance, accuracy in delineating landscape risks, and potential application to other arctic communities.

A series of research questions were developed to address the above objectives:

- *What types of landscape hazard impact infrastructure development in the Arctic?*
- *How will landscape hazards change under projected climate changes?*
- *What infrastructure adaptations and maladaptations are used in arctic communities, and what are the implications for landscape and community development?*

- *What modifications to landscape hazard assessments must be employed to ensure they are applicable and appropriate for different arctic communities?*
- *How can the risk level for specific landscape hazards be mapped and ranked?*
- *How can hazard mapping be presented and communicated in a manner appropriate for people with different cultural and educational backgrounds?*

1.5 Thesis structure

This thesis presents information to address the two main research objectives and is structured in the following manner: Chapter 2 provides relevant background information on the nature of Arctic environments and the fields of hazard and risk assessment as they have been applied to arctic environments and elsewhere. Building on this context, a framework that assess the role of Arctic landscapes in community development is formulated and described. Chapter 3 describes the application of the research framework in Clyde River. This chapter begins by explaining the physical and social characteristics of Clyde River that are relevant to the assessment of landscape hazards and risks and then applies the research framework for landscape hazard assessment to Clyde River. The creation of individual landscape hazard layers and the composite landscape hazard map are explained, and the implications of the physical environment on infrastructure and community development in Clyde River are discussed. Chapter 3 concludes by exploring the implications of climate change on identified landscape hazards. In Chapter 4 the research framework is critiqued, and the accuracy, acceptance and transferability of this approach is evaluated. The thesis concludes with Chapter 5, in which a summary of the key research findings are presented, suggestions for future research needs are outlined and this research contribution to other projects is explained.

Chapter 2 Background information

This research assesses conditions in the physical landscape that impact infrastructure planning and development in Nunavut communities. It includes the creation and application of a research framework to study landscape hazards and constraints. The purpose of this chapter is to situate the context of the thesis into the hazards and risk literature and to familiarize the reader with factors that need to be considered when planning infrastructure development in Arctic environments. This is followed by a description of the methodology employed through the research framework.

2.1 Thesis terminology

Landscape hazards

Landscape hazards are defined as those components of the physical environment that can detrimentally affect the safety of humans and/or the integrity of infrastructure (Coch, 1995). They are most commonly associated with the interaction of several properties of the physical environment, such as coastal proximity, altitude, topography, climate, hydrology and surficial geology. Examples of landscape hazards include erosion, flooding, and specific to Arctic environments, permafrost thaw and degradation.

Risk

This thesis investigates landscape hazards in the context of risk to infrastructure. Risk within geoscience is considered to be the probability and magnitude of an impact (Dow, 1992; Brooks, 2003). Although similar risks can occur in different environments, the potential impact will depend on the sensitivity of the system in which they operate. Sensitivity measures the degree of change that may occur due to the risk, and results can either be positive or negative (O'Brien et al., 2004).

Adaptation

The potential impact of risk is also a function of the ability to cope with exposure, termed capacity of response (Gallopin, 2006; Bernard and Ostländer, 2008). Gallopin (2006) provides a useful summary of the variations in the usage of this term; however, in this study, adaptation is defined as the ability to make changes to practices, livelihoods or structures to either lessen the impact of change or to best take advantage of change (Bernard and Ostländer, 2008). In this context, the capacity of response includes two components: (1) short term coping mechanisms referred to as coping ability; and (2) adaptive capacity or resilience, which encompasses longer term strategies that allow for minor changes to occur while sustaining the livelihood of a community or system (Dow, 1992; Dolan and Walker, 2004; Ford and Smit, 2004).

Adaptation strategies assessed within this project focus on the range of infrastructure modifications employed to cope with landscape constraints. Infrastructure design approaches in the Arctic are generally geared to minimize environmental disturbances or to compensate for a dynamic environment, and are selected based on factors including infrastructure function and size, climate conditions, hydrology, subsurface materials, and cost and availability of labour, equipment and materials (Andersland and Ladanyi, 2004).

Maladaptations are defined as responses or actions that enhance the risk and/or have negative results (Scheraga and Grambsch, 1998). Maladaptations studied in the project often have negative impacts in both the immediate area and other areas in the community.

Vulnerability

The notion that the impact of risk is a balance between exposure and the capacity of response is termed vulnerability (Dow, 1992; Zimmerer and Bassett, 2003; Gallopin, 2006). The notion of vulnerability is applied by many different disciplines, including geology, economics, political science and anthropology, although its exact meaning, as illustrated in Table 2.1, is variable (cf., Dow, 1992; Cutter, 1996; Fussel, 2005; Gallopin, 2006; Neukum and Hotzl, 2007; Bernard and Ostländer, 2008; McLaughlin and Dietz, 2008).

Table 2.1 Examples of different definitions of vulnerability.

Definitions of vulnerability	Source
Ability to cope with and adapt to external stresses	Kelly and Adger, 2000
As a static end point, notably the impact of a hazard minus adaptation	O'Brien et al., 2004a
As starting point, specifically the state produced by numerous physical and social processes	O'Brien et al., 2004a
A system's susceptibility to threat	Ezell, 2007
Multilayered and multi-dimensional social space that is governed by the capabilities of the people in a particular time and space	Watts and Bohle, 2003
Likelihood of an occurrence and resulting impact of events on areas	Nicholls et al., 1999
Both the exposures affecting a community or individual and the adaptive capacity or ability to deal with the exposure(s)	Ford and Smit, 2004
Potential for loss	Cutter, 1996
Inherent susceptibilities and resiliencies which are part of both biophysical and social environments	Dolan and Walker, 2004

Specific applications of vulnerability studies have been made in relation to natural hazards (Clark et al., 1998; Nicholls et al., 1999; Brown and Damery, 2002), food and water security (Dow, 1992; Watts and Bohle, 1993; Leichenko and O'Brien, 2002; Baro, 2006; Ezell, 2007), climate change (Kelly and Adger, 2000; Dolan and Walker, 2004; Ford and Smit, 2004; Ford et al., 2006; Ford et al., 2007), poverty (Kabeer, 2002), and livelihood (Eakin and Bojorqueez-Tapia, 2008). There is a direct link between physical vulnerability and other components of the social environment, such as economic stability, which shape how individuals, groups or communities may react to risks and the nature of the risks themselves.

This research focuses on assessing physical vulnerability, which encompasses risks attributed to the physical environment, response to risks, site characteristics that alter this risk, and technological and management strategies designed to minimize the impact (McCarthy and Martello, 2005; Adger, 2006).

2.2 Previous risk and adaptation assessments in the Canadian Arctic

Researchers have studied risks and adaptations related to a range of factors in the Canadian Arctic. Berkes and Jolly (2001) examined how the community of Sachs Harbour, Northwest Territories is responding to climate change in the context of land-based activities such as hunting and fishing. Their approach involved repeated, long-term visits to the community, in-depth interviews and community-driven workshops. Ford and Smit (2004) developed a framework to assess community-scale vulnerability in the Canadian Arctic, which considers vulnerability to be a function of the stresses influencing a system and the adaptive capacity to cope with such stresses. This framework has been applied to studies in Igoolik, Nunavut (Ford et al., 2006), Arctic Bay, Nunavut (Ford et al., 2006), Ulukhaktok, Northwest Territories (Pearce, 2006) and in communities elsewhere in the circumpolar region, such as Norway and Russia (Keskitalo and Kulyasova, 2009).

It is noted, however, that these studies focused primarily on assessing social vulnerability. For example, working with the community of Arctic Bay, Ford et al. (2006a) studied vulnerability related to resource harvesting and climate change. The researchers determined that community members have modified harvesting practices in response to a changing environment, and adaptation was facilitated by a strong level of Inuit knowledge, social networks, flexibility, economics and modern technology. Pearce's (2006) research in Ulukhaktok used in-depth interviews to study the vulnerability of livelihood activities, such as hunting, to climate change.

A vulnerability approach that assesses multiple landscape hazards has not been applied at length in the Arctic and considered into planning. This study provides the first systematic case study of its kind. The nature of the physical geography and geology of the Arctic has the potential to significantly constrain development, and currently is not considered to be adequately included in infrastructure planning and development. Communities in the Arctic both share and possess unique landscape constraints as dictated by their physical environment. The physical characteristics of communities make them susceptible to different landscape risks and alter the risk level. The dominant landscape risk(s) occurring in one community may be absent from another, or impacting the area to a lesser or greater degree.

For instance, in Arviat, Nunavut, on the western shore of Hudson Bay, many of the potential sites for community development are on low-lying drained ponds, which are prone to inundation, resulting in standing water and a risk of flooding (Canada Mortgage and Housing Corporation, 2006; Forbes et al., in press).

Arctic Bay on northern Baffin Island, Nunavut, is surrounded by steep hills and at risk to mudslides and other slope instabilities (Ford and Smit, 2004). The shoreline along Tuktoyaktuk, Northwest Territories, is dynamic and undergoing inland migration. The area is also characterized by very low relief, and the community is built on fine to medium sand with high ice content. Coastal erosion is a major problem, with sediment loss of several metres occurring after large storm events (Manson et al., 2005).

On June 8th 2008 the community of Pangnirtung, in eastern Nunavut, experienced significant sediment loss due to heavy rains and erosion of ice-rich sediment, which resulted in damage to a community bridge, and loss of access to the sewage lagoon and water supply for a significant portion of the community (Windeyer, 2008). This example shows how susceptible permafrost environments are to changes in the climate, and the increased landscape instability under changing climate conditions, as heavy rain events are likely to become more common.

The hydrology, topography, geology and climate are all factors influencing the type and severity of landscape risks. Therefore, landscape hazard assessments in the context of community infrastructure planning conducted at a local level are of particular importance and merit research attention.

2.3 Assessing planning constraints

Frameworks developed to assess constraints imposed by landscape conditions on infrastructure generally examine physical factors that influence landscape stability and their spatial relationships (Anbalagan, 1992; Cabuk, 2001; Harris et al., 2001; Baillifard et al., 2003). One approach to the presentation of such spatial information is to create a landscape constraint or landscape hazard map, which categorizes areas based on the potential risk. There are two broad techniques used in this mapping approach: direct and indirect. Direct mapping involves the researcher manually classifying locations based on experience and knowledge of the area, whereas indirect mapping uses statistical analysis or models to delineate the level of hazard potential (Van Westen et al., 1999). Direct mapping can be highly subjective, while indirect hazard mapping can result in over-simplification and generalization (Huabin et al., 2005).

Many hazard assessments focus on assessing one type of risk, such as earthquakes (Cabuk, 2001), volcanoes (Cronin et al., 2004) or landslides (Anbalagan, 1992; Malkawi et al., 2000). A few studies use a multi-hazards approach to provide guidance for planning decisions. Batterson et al. (2006) created a research framework to identify and map risks from a range of landscape hazards, including landslides, avalanches, rockfalls and flooding. These are to be integrated to produce community-level hazard risk maps for regions of Newfoundland. The first stage of this framework identified criteria for risk assessment through air photo interpretation, historical research, site observations and examination of published maps. Site visits included an assessment of vegetation type, sediment texture, slope angle, surficial geology, historic events, human activities and risk potential. In cases where sufficient data existed, statistical techniques are used to determine the probability of a given event (e.g., stream flooding). This information is intended to guide the next project phase of Batterson's work, which is the delineation of hazard polygons at a community level.

Petley (1998) used a multi-hazard assessment to examine the risk associated with rockfalls, floods, landslides and erosion to roads in eastern Taiwan. He used air photo interpretation and geomorphological mapping to assess the nature of the terrain, and the location, type and size of landscape hazards. Each hazard was classified into a four-tier classification system based on the likelihood of occurrence. To assess the accuracy of the research, hazard map predictions were compared with observations after a period of extended rain, and results indicated that the approach was generally successful.

Environmental planning is the study and assessment of features, processes and systems of the landscape to direct decisions and solve issues (Nicol, 2006). An assessment of physical landscape constraints can provide guidance to planning decisions through assessing and mapping which areas of the physical environment impose high, medium and low risk to infrastructure, and how the risk level will likely change due to climate change

2.4 Landscape processes and hazards in arctic environments

The geography of arctic environments supports a range of landscape processes that constrain infrastructure and community development. Topographic form and relief of the terrain significantly influences the landscape through factors such as slope movement, distribution of permafrost, surface drainage, snow accumulation and active layer movement (Fig. 2.1). In this section, the factors that can cause landscape hazards are discussed in detail and adaptations and maladaptations are described.

Figure 2.1 In arctic communities housing design is adapted to construction on steep slopes such that long steel piles are used to elevate the house off the ground and establish a level foundation (photo M. Irvine, July 2007).

2.4.1 Slope movement

Slope movement is defined as the downslope transport of sediment, snow or rock in response to gravitational forces (Batterson et al., 2007). Factors contributing to slope stability include angle, sediment texture, moisture content, and the presence of permafrost. Categorization of slope movements is based on the rate, magnitude, and material in motion.

A widespread example of slow mass movement in arctic environments is gelifluction. Gelfluction is the slow movement of thawed surface sediment over frozen ground. It is reflected on the landscape by lobes appearing as tongue-like deposits composed of non-sorted sediment. Frost creep is also a slow moving slope process, wherein freeze-thaw action results in the down-slope displacement of surface material. Factors contributing to frost creep include slope gradient, sediment texture, moisture content, and daily and seasonal temperature variations. Rapid ground movements include rockfalls, which are rocks or boulders that free fall or roll down a slope (Coch, 1995). Active-layer failure is another process occurring in terrain underlain by permafrost, and describes when sediments and rocks comprising the active layer becomes detached from the underlying permafrost and slide downslope (Van Everdingen, 2005).

2.4.2 Permafrost characteristics and degradation

Throughout the arctic islands of Nunavut, permafrost is classified as continuous, meaning that frozen ground underlies over 90% of the landscape (Van Everdingen, 2005). Thermokarst refers to melting of ice-rich permafrost, which results in some combination of subsidence, erosion, collapse or instability of the terrain surface. This process is common in regions with high ground ice content, such as ice-wedges. Ice-wedges are wedge-shaped bodies of ice extending vertically into the ground and are common in poorly drained areas underlain by continuous permafrost. On the ground surface, ice-wedges can occur singularly, or as a network of intersecting ridges, forming polygons (French, 2007). Permafrost with high ice content will have a high potential to compact and subside if the ground ice melts. The temperature of the ground affects thaw susceptibility as warm permafrost (close to 0°C) will be more sensitive to thaw than colder permafrost (Couture et al., 2003).

The salinity of pore water within permafrost alters the bearing strength and how it is impacted by changes in ground temperature. Saline permafrost can form along coasts or in sediments previously submerged by the ocean. In the latter case, when permafrost aggraded into newly emerged marine sediments, freezing led to the formation of ice crystals between which brines were progressively trapped (Nixon and Lem, 1984; Nixon, 1988; Biggar and Sego, 1993). The brines depress the freezing point of the enclosing ground and saline permafrost will thus thaw at a lower temperature. This translates into greater susceptibility to thaw and ground subsidence and lower bearing capacity (Nixon and Lem, 1984; Biggar and Sego, 1993; Hivon and Sego, 1993; Brouchkov, 2002).

Disturbances of the ground surface, vegetation cover or micro climate can lead to permafrost degradation (French, 2007). Examples of such changes include alterations to snow accumulation, colour or texture of the ground surface, vegetation, fire, and drainage patterns (Couture et al., 2003; Anisimov and Reneva, 2006; French, 2007; Osterkamp, 2007). The construction and day-to-day use of infrastructure can cause the ground to warm and permafrost to degrade (Couture et al., 2000; Jorgenson et al., 2001; Nelson et al., 2001; National Research Council, 2003). Factors affecting heat transfer to the ground due to infrastructure include the seasonal timing of construction, the level of vegetation cover and sediment disturbance, type of material, building pad characteristics and style of building foundation.

Building pads are a critical component of infrastructure development in Nunavut communities, and are designed to act as a stabilizing interface between the overlying infrastructure and the underlying permafrost and active layer. The pad is normally constructed during the summer months and disturbances to the ground surface are restricted to reduce ground thawing. The pad is thick enough so that the active layer remains within the pad; if the active layer extends into the ground below the pad, the pad and any overlying foundations may be susceptible to ground movement. The pad is allowed to be free-draining and to settle for a year before any structure is built on the pad, to permit the permafrost table to migrate into the pad, and the pad material itself to stabilize. Gravel is the preferred pad material, compared to finer grained sediment such as silt or sand (Strub, 1996).

Buildings are commonly elevated above building pads on cribbing, in order to prevent heat from the house entering the ground (Fig. 2.2A). Adjustable jacks may be used instead of wooden cribs to compensate for differential ground movement (Fig. 2.2B). Steel pilings that extend into the permafrost to anchor the foundation on bedrock or into the underlying substrates (till or bedrock) are also commonly used (Fig. 2.2C). A more sophisticated technique is to use thermosiphons, which are tubes that extend into the ground to passively remove heat from under the building to keep the ground cold (Fig. 2.2D, Department of Community and Government Services, 2005). Another foundation type used is an adjustable, integrated tubular aluminium frame that is supported by numerous points connected to a continuous gravel pad. Although not common in Clyde River, this type is widespread in western Nunavut communities (R. Smith, pers. comm., 2010). A final foundation type is a cement pad. This foundation type is common for larger buildings such as garages that are built directly on the ground surface and is typically used in combination with thermosiphons or underlying insulation.

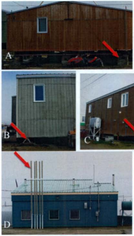


Figure 2.2 Examples of building foundation-types found in Clyde River. A) a house built on cribbing; B) a house with jacks; C) a house with steel piles; and D) building employing thermosiphons (photos M. Irvine, July and August 2007).

2.4.3 Surface drainage

The landscape morphology influences surface drainage. Flooding can occur in low-lying areas after spring snowmelt, rain-on-snow events, or periods of heavy rain (Glickman, 2000). For instance, in Pangnirtung, NU, significant erosion occurred during June 2008 after an extreme peak discharge in the Duval River following heavy rainfall on a still widely snow-covered drainage basin. Channels were deepened and significant lateral thermal erosion occurred (10s of metres), as water flowed over and melted ice-rich permafrost (Carbonneau et al., 2009). The meltwater and flood erosion were exacerbated due to the ice-rich permafrost terrain, an example of how permafrost environments can be very susceptible to erosion. Extreme events, such as the rain on snow event that occurred in Pangnirtung, are projected to increase in intensity and frequency under climate change scenarios. This will increase the likelihood of ground instability risks in the future.

Surface water pooling is common in arctic environments. As permafrost underlies the ground surface, surface water cannot penetrate into the ground beyond the depth of the active layer, preventing downward drainage and causing saturation. Water pooling is a particular concern if the sediment is ice-rich, as surface water accumulation can warm the ground, causing ice within the permafrost to melt. This will result in further subsidence of the surface, which will promote further pooling of water thus amplifying the original disturbance (Jorgenson et al., 2001; Couture et al., 2003; Anisimov and Reneva, 2006; Osterkamp, 2007). Human modifications to the environment such as constructing embankments, improperly situated drainage culverts and even vehicular disturbance to the surface may promote water pooling, or cause water to pool in new areas (Fig. 2.3; Slaughter et al., 1990).

Thermal erosion is another thaw-related process connected to the ponding of water over ice rich permafrost. Thermal erosion involves two processes: water melting ice within permafrost, and mechanical transport of material by flowing water. Flowing water will initially cause vertical erosion of the ground surface, and then lateral erosion as the bed becomes armoured with sediment (French, 2007).

Figure 2.3 Off-road and other wheeled vehicles erode the thawed terrain, exposing the underlying materials and forming depressions where water pools, both of which can change the thermal regime of the permafrost, leading to further subsidence (photo M. Irvine, July 2008).

High winds, cold winters and cool summers allow for the formation and persistence of snowpacks at the base of leeward slopes. If a snow pack remains for a protracted period of time, a nivation hollow can form. Nivation is a type of erosion that includes physical weathering and frost heave around the periphery and below the snow patch. This loosens the sediment, which is removed from the area through gelifluction or water flow, resulting in a depression (French, 2007).

Large snowdrifts can form in communities, depending on the amount of snowfall, topography, infrastructure design and layout, and wind direction and speed (Fig. 2.4). The orientation and position of infrastructure may alter the location of naturally occurring snowdrifts, as drifting may occur both on the up and down-wind side of buildings depending on their configuration. Where snow drifting occurs, the ground will be insulated from cold winter temperatures, causing it to be warmer than snow-free areas. The melt water of snowdrifts and snowpacks will also produce water saturated ground downslope in the summer.

Figure 2.4 Strong winds in winter create large snowdrifts, commonly reaching close to two stories high. Snowdrifts have important implications for underlying permafrost temperatures and local moisture conditions (photo M. Irvine, March 2008).

2.4.4 Periglacial processes

There are a range of cold climate (periglacial) processes that impact infrastructure development. For instance, frost heave is the movement of rock or soil upwards and/or outwards due to ground expansion upon freezing and ice formation in the soil. It can displace surface material by several centimetres or decimetres (French, 1996). Frost jacking can occur in infrastructure foundations, resulting in structural damage to roads, pipelines, pilings, and buildings (Williams, 1986; French, 1996). Factors contributing to frost heave and frost jacking include moisture content, sediment texture, and daily and seasonal temperature variations (Dredge et al., 1999).

Cryotubation is the movement of soil due to frost action, and involves the expansion and contraction of the soil due to temperatures change and the growth and melt of ground ice. The surface expression of these processes may lead to patterned ground that allows their present or past activity to be mapped on the surface. Ice lens formation occurs in soil or rock when water accumulates in a crack or pore in the soil. The water will cause the rock or soil to wedge apart, and the ice lens will grow parallel to the ground surface.

Patterned ground usually forms circles, polygons or stripes. A common form is a non-sorted circle that is called a hummock if it has a raised topography. Circular patterned ground is probably the result of cryoturbation, which involves the convectional movement of soil due to frost action (French, 2007). Mudboils are another example of circular patterned ground, but likely form due to water trapped between the permafrost and the ground surface, and typically form in fine-grained, water-saturated sediment (Fig. 2.5; Harris, 1977; Dredge et al., 1999; Andersland and Ladanyi, 2004).

Figure 2.5 Mudboils are a type of patterned ground formed in periglacial environments (photo M. Irvine, July 2008).

Polygonal patterned ground varies in size. The smaller form appears as nets on the ground separated by furrows and cracks that are generally between 20 and 50 cm in diameter. The larger form of polygonal patterned ground has a diameter between <1 to >10 m and forms due to thermal-contraction causing cracks on the ground surface. Striped patterned ground forms on sloped terrain. Non-sorted stripes are usually 0.3 to 1 m wide, with vegetation growing in parallel lines that separates the stripes. Sorted stripes are composed of alternating coarse and finer material. Stripes are thought to be formed by cryoturbation, similar to circular patterned ground but modified by mass-wasting processes (French, 2007).

2.4.5 Coastal processes

Communities in Nunavut were generally developed around trading posts that were typically built along the shoreline. Coastal environments are dynamic, and the coastline may migrate through either sediment progradation or erosion. Factors contributing to coastal migration include sediment texture, presence of frozen sediments, duration and extent of sea-ice cover, tidal patterns, wind speed, fetch, foreshore gradient, sea level rise and storm magnitude and frequency. For example, sea-ice cover acts as a natural protective barrier for shorelines, preventing the accumulation or removal of sediments. Infrastructure can be at risk in areas of coastline degradation due to foreshore erosion. Human modifications may alter natural sedimentation rates along a shoreline. The construction of a wharf, for instance, may cause an increase in deposition updrift, with sediment starvation downdrift.

Coastal inundation results from the flooding of the ocean onto terrestrial areas. Inundation may result in sudden changes in water levels, such as flooding due to a storm surge event, or gradual changes, such as relative sea-level rise. Factors influencing coastal inundation are similar to those of coastal migration outlined above.

2.5 Research framework

A research framework was created and tested in Clyde River to assess planning constraints imposed by the physical environment on community infrastructure development. The framework consists of a series of steps to understand the nature, and map the distribution, of landscape and environmental parameters that can limit infrastructure development in Arctic environments (Fig. 2.6). It uses a multi-hazard approach that employs several data collection methods, including direct field mapping. Individual landscape hazard maps were created based on environmental parameters, and risks associated with various hazards were integrated to produce a cumulative landscape hazard ranking. The decisions on how to rank the various risks are based on the experience, knowledge and judgment of the researchers and the community. As few studies have been completed using a multi-hazard approach, there are limited ranking schemes to use as a starting point.

An approach that uses multiple tools presents data challenges. Information may be point data, such as sediment sampling, line data, such as topographic surveys, or areal data, such as surficial mapping. Data coverage and resolution may also vary. Certain tools will cover the entire study area, whereas others techniques will only cover small areas due to logistical limitations.

The framework developed in this project is flexible and nonlinear. The framework consists of a series of steps, but the process is iterative and the steps may be repeated to ensure accurate and appropriate outcomes. For instance, steps may need to be repeated after additional knowledge is collected, when new questions or concerns arise, or if new environmental components require assessment. In addition, community consultations occur throughout the process when appropriate, and are not limited to the beginning and the end of the project. These consultations direct and provide guidance for all project stages.

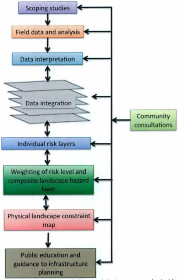


Figure 2.6 Proposed research framework design to assess physical landscape constraints in an arctic community. Community consultations feed into the entire process.

Scoping studies
The research framework begins with scoping studies that allow for project conceptualization and collection of baseline information. At this stage of the framework, all relevant information on causative factors leading to landscape risks and infrastructure adaptations is gathered for the study area. Depending on the location, the quantity and quality of data may vary. For example, in larger, more

central communities there may be a larger quantity of climate data available. Potential data sources include research papers, reports, newspaper articles, climate data, remotely sensed imagery, historical air photographs and geological, hydrological, and topographic maps. Using these types of data, it is possible to generate preliminary surficial and geological maps, document significant physiographic changes, and identify significant event/hazard occurrences.

Field data and analysis

Scoping studies provide guidance for field studies. For example, information may be collected to fill data gaps or to increase the level of detail of existing field datasets. The nature of fieldwork will depend on what type of information needs to be collected and the characteristics of the landscape. Examples of field studies include sediment sampling, vegetation mapping, permafrost coring and topographic surveys. Field data are then analyzed to establish patterns or trends using relevant techniques. For example, textual analysis may be conducted to classify surficial sediment by dominate grain size, or topographic data may be analyzed to produce slope angles and gradient maps.

Data interpretation

The next stage is data interpretation in which information compiled during fieldwork and scoping studies are combined into data layers that describe a specific component of the landscape. All of these layers can influence the probability of occurrence, distribution and magnitude of landscape hazards. Examples of these layers include the spatial distribution of ground ice, sediment texture, and slope angle.

Data integration and creation of individual risk layers

Data layers are overlain and integrated to create hazard layers for particular landscape risks. Overlaying of the classified terrain layers provides a comprehensive understanding of the relative degree of risk for a certain landscape hazard. This process is iterative, as the need for further data interpretation may become apparent after initial data integration. After the creation of relative degree of risk layers for individual landscape hazards, the general consideration of the current risk level of the hazard on community development was assessed using a risk matrix scheme (Fig. 2.7). The general consideration of the risk level is a function of likelihood of the risk occurring and the level of impact on community development. Depending on where the factor falls on the matrix, the parameter is assigned a high (red), moderate (yellow) and low (green) ranking.

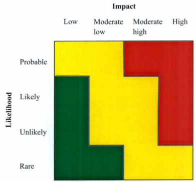


Figure 2.7 A risk matrix is based upon a combination of impact level and likelihood of occurrence of a landscape hazards. Red denotes high risk, yellow moderate risk and green low risk (Modified from Cox, 2008).

Weighting of risk level and creation of composite landscape hazard layer

After the individual hazard layers are created, they are overlaid to assess the level of overall or composite risk. The level of composite risk is subjectively determined by weighing the significance of each hazard, and (2) assessing whether the risks are cumulative, or and (3) determining whether one particular risk is of particular significance to out-weigh others that may geographically co-exist. The composite landscape hazard map uses a simple traffic light colour scheme of red, yellow and green to distinguish between areas of risk, thereby allowing for straightforward visualization by a range of different users from community members to regional planners (Cronin et al., 2004). This framework is an iterative process and the assigned classification may be modified as additional information is obtained, or through discussions with community members and other stakeholders.

Physical landscape constraint map

The creation of a physical landscape constraint map is the next step in the framework development. The physical landscape constraint map displays all constraints in the area, not just those relating to landscape processes. Non-landscape hazard constraints may include development setbacks, exclusion areas or environmentally sensitive areas. The composite physical landscape constraint map is constructed in a simplified manner, using plain language to allow a range of users, including community members, planners, decision makers and researchers from other disciplines, to easily understand and interpret the map.

The composite physical landscape constraint map should be reviewed with community members and planners for comments and suggestions. Depending on the outcomes of the community consultations, additional data may need to be collected and integrated, or modifications to data layer interpretation, integration and weighting may be required.

Public education and guidance to infrastructure planning

In order for research results to have a positive impact on community planning, findings need to be relayed back to the community, and the public must to be provided with education and information as to the significance and the meaning of the results. Following, information should be integrated into the planning process so that physical constraints can be included and considered.

Chapter 3 Case study

3.1 Background information

Chapter 3 presents the application of the research framework in Clyde River. The chapter describes the social and environmental characteristics of Clyde River to familiarize and situate the reader with the area. Next, using the research framework described in Chapter 2, trends and results from the Clyde River data are coalesced to determine the nature, spatial distribution and severity of physical landscape constraints. The types and methods of data collection are outlined, followed by a discussion of what the results mean in the context of landscape hazards and infrastructure. The creation of individual hazard layers is discussed and the rationale behind the ranking and creation of individual landscape hazard layers is justified. This leads to a discussion of the composite hazard map and its implications for Clyde River.

3.1.1 Introduction

Clyde River is located on the east coast of Baffin Island in the Qikiqtaaluk region of Nunavut, about 800 km north of the capital city Iqaluit (Fig. 1.1). Known as Kangitugapik in Inuktitut, which means "nice little inlet," the community is situated at the head of Patricia Bay, an arm of Clyde Inlet, on the Clyde Foreland (Figs. 3.1-3.2). Clyde Inlet is a 120 km-long fiord that runs from Baffin Bay to the island's interior plateau. The Clyde Foreland borders Baffin Bay, and is a flat to gently-inclined plain, with several areas of higher relief including the Black Bluffs (Briner et al., 2005).

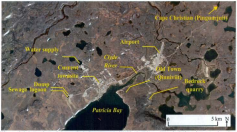


Figure 3.1 Location of the main infrastructure in Clyde River. Words in brackets are local place names in Inuktitut. Background image is a Quickbird satellite image, August 21, 2005.

Figure 3.2 View looking southeast across Clyde River towards Patricia Bay. Sand-rich marine and glacial deposits blanket the landscape around the town. The hill in the left background has an elevation of ~300 m (photo T. Bell, July 2007).

3.1.2 Glacial History and Quaternary geology

Much of the eastern Canadian Arctic is underlain by the Canadian Shield, which on Baffin Island outcrops as a range of granites, granite gneisses, migmatites, gneisses and schists. Northern Baffin Island is geologically complex and is composed of Tertiary/Cretaceous rocks and Paleozoic rocks. Central Baffin Island, which includes the Clyde Foreland, consists of undifferentiated Archean granite gneiss. Southern Baffin Island is primarily composed of Precambrian Shield rocks. East of Baffin Island, Precambrian and Paleozoic rocks are overlain by Cretaceous and Tertiary marine sediment. Quaternary sediments are thin, 0-50 m thick (Fulton, 1989).

The glacial history of the Clyde River region has had a strong influence on present day sediments and geomorphology. During the Late Wisconsinan glaciation, the Foxe Dome of the Laurentide Ice Sheet (LIS) covered Baffin Island. Outlet glaciers reached the continental shelf beyond the mouths of fiords along Baffin's east coast. Cold-based, non-erosive ice occupied upland regions and much of the coastal forelands, while warm-based, erosive ice infilled the fiords (Bierman et al., 1999; Miller et al., 2002; Davis et al., 2006). During the Last Glacial Maximum (LGM) ice inundated the Clyde Foreland around Clyde River through a northerly ice flow from Clyde Inlet into Patricia Bay that crossed the present town site of Clyde River, and extended northeast across the foreland towards Baffin Bay (Fig. 3.3; Briner et al., 2005).

Glacial retreat occurred rapidly; the outlet glacier in Clyde Inlet retreated from the fiord mouth at 10 ka (thousands of radiocarbon years before present), to the head of the fiord by 9.1 ka (Davis et al., 2006). Retreating ice influenced the course of the

Clyde River, directing it northeast, parallel to a series of recessional lateral moraines situated north of the community. There were two glacial readvances at the head of Clyde Inlet at 8.5 and 7.9 ka, although these did not reach the Clyde River area (Briner et al., 2007).

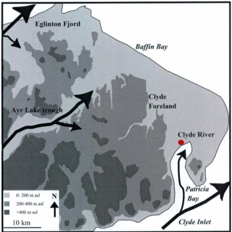


Figure 3.3 Ice flow map of the Clyde Foreland during the last glaciation. Black arrows show ice flow directions (modified from Briner et al., 2005).

Marine limit is defined as the maximum elevation reached by the sea along coastal areas following retreat of glacial ice (Benn and Evans, 1998). There are two marine limit elevations recorded in the area around the Clyde Foreland. The higher shoreline is at 80 m above sea level (asl), and is best preserved in the Cape Aston Delta on the Aston Lowlands, 50 km south of Clyde Inlet. On the Clyde Foreland, this shoreline is most evident in the Kuvinilk River area, north of Clyde River. This shoreline is considered to be older than the LGM, and exists on the landscape today in areas that were preserved by non-erosive, cold based ice (Briner et al., 2005). The lower marine limit is situated along part of the Clyde Foreland at 22 m asl, and is thought to postdate the LGM and be of early Holocene age (9-10 ka). Most of the infrastructure in Clyde River is built below the Holocene marine limit, while the newer homes and other infrastructure upslope are built on raised marine sediments of presumed older origin.

3.1.3 Climate

Clyde River has a harsh, cold climate (Table 3.1; Fig. 3.4). Summers are short and cool, and winters are long and cold. Precipitation is limited, with the majority falling during the fall months. Winds in the community are fairly constant and strong, with gusts reaching over 120 km/h.

Table 3.1 Climate normals (1971-2000) for Clyde River (Environment Canada, 2006)

Climate Variable	Value
Highest monthly average temperature (°C)	8.2 (July)
Extreme minimum (°C)	-50.1 (Jan)
Lowest monthly average temperature (°C)	-33.4 (Feb)
Extreme maximum (°C)	22.2 (July)
Average annual snowfall (cm)	202
Extreme daily snow fall (cm)	41 (April)
Average annual rainfall (mm)	52
Extreme daily rainfall (mm)	37.3 (Aug)
Average hourly wind speed (km/h)	14
Most frequent wind direction	NW
Maximum wind gust speed (km/h)	122
Maximum hourly wind speed (km/h)	102

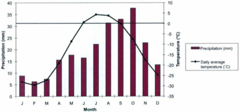


Figure 3.4 Average monthly precipitation and daily average temperatures for Clyde River for the period 1971-2000 (Environment Canada, 2006).

3.1.4 Permafrost

Climate conditions support continuous permafrost in the Clyde Foreland; actual depths of permafrost, however, are unknown. In the vicinity of the community, active layer depths vary between 0.3 m and 1.5 m (Jurello and Beckstead, 2008) and a recent study of the permafrost adjacent to the airport found the estimated thaw penetration to be at 1 m (Ednie and Smith, 2010). Ground temperatures average -10°C at 9 m depth, while surface temperatures range from -22.5°C to a maximum of 2.3°C (Nixon, 1988; Environment Canada, 2006). Recent measurements found the annual temperature range at 5 m to be 14.6°C (Ednie and Smith, 2010). Saline permafrost is widespread as much of the Clyde Foreland and the majority of the presently built-up areas of Clyde River were inundated by the post-glacial sea (Amec Earth and Environmental, 2008). Hivon and Sego (1993) documented salinity values at 0.6-44.5 parts per thousand (ppt) in permafrost cores extracted from the central part of Clyde River town site (north of the school), which ranks amongst the highest known values in the Canadian Arctic.

3.1.5 Vegetation

Vegetation in Clyde River is dominated by sedges, lichens, mosses and low shrubs typical of low tundra vegetation (Fig. 3.5; Scott, 1995). A short growing season, strong winds and cold temperatures limit vegetative growth, and the underlying permafrost condition prevents the formation of deeply rooted systems. Percentage cover varies according to surficial material characteristics, slope stability and nutrient availability, ranging from barren in areas of the townsite to 20-60% cover throughout much of the slopes bordering the town, and 80-100% cover in wet sedge meadows and downslope of the sewage lagoon. Vegetation plays an important role in reducing wind deflation of the sandy sediments that characterize the area, but does little to stabilize slope movement owing to shallow rooting systems (Department of Community and Government Services, 2005).


Figure 3.5 Vegetation west of Clyde River. Patricia Bay is visible in the background and till deposits blanket the land in the foreground (photo M. Irvine, August 2007).

3.1.6 Sea ice

Sea ice plays an important environmental role throughout much of the year in protecting the shoreline from waves and storms that can lead to coastline erosion. Sea ice in Baffin Bay is dominated by first-year ice (ice that melts during the warm season) and generally is between 0.5 and 1.5 m thick (Meier et al., 2006). In Patricia Bay, ice break-up generally occurs in July with freeze-up in November, although during recent years ice has been forming one month later and breaking up one month earlier (Gearheard et al., 2006). The surrounding fiords create a calm environment in Patricia Bay during freeze-up, allowing smooth, fast ice (ice anchored to the shore or ocean bottom) to form along the shore, extending out to the inlets and fiords where it connects with open water and pack ice (Gearheard et al., 2006).

3.1.7 Demographics

Clyde River was established in 1923 around a Hudson's Bay trading post on the eastern shore of Patricia Bay across from the present townsite. The current townsite was relocated in 1969 to have better access to fresh water and more suitable terrain for development. According to the 2006 Canadian census data, Clyde River's population of 820 is over 95% Inuit, and is characterized as youthful, with almost half of the population under the age of 19 (Fig. 3.6-3.8; Statistics Canada, 2008). The community's population growth is high, with a projected 33 % growth from 2006 to 2020.

Traditional hunting is an important driver of the local economy, providing both country food and income to residents, with ringed seal, polar bear, caribou and narwhal the most commonly hunted animals (Gearheard et al., 2006). Unemployment rates in the community are high at 24%, compared to the national average of 6% (Statistics Canada, 2008). Local people are often employed in construction, but most of the highly skilled positions are held by people from outside Clyde River.

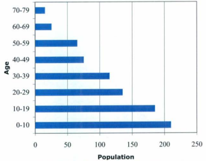


Figure 3.6 Population structure of Clyde River: this is a youthful community, with 48% under the age of 19 and less than 5% over the age of 60 (Statistics Canada, 2006).

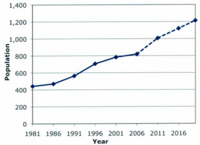


Figure 3.7 Actual and projected (dashed) population changes in Clyde River from 1981 to 2020. Growth has been steadily increasing in the community; projections of future growth exceed 20% in the next four years (Government of Nunavut, 2007; Statistics Canada, 2008).

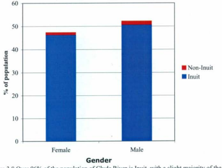


Figure 3.8 Over 96% of the population of Clyde River is Inuit, with a slight majority of the population being male (Statistics Canada, 2008).

English is not the first language of 96% of the population of Clyde River, 93% do not speak English as their primarily language in the home and 14% do not understand English (Statistics Canada 2006). Inuktitut is the primary language used in the community, especially by elders and children. This highlights the importance of the need for suitable and non-standard communication during the project.

3.1.8 Infrastructure

There are 168 residential units in Clyde River, comprised of older one and two storey single unit homes and newer one storey 5-plexes (Fig. 3.9). The community owns the majority of the homes and rents to residents at variable rates based on household income. Community infrastructure includes an airport, two general stores, a community hall, fire station, church, school, garage, RCMP station, community freezer, ice arena-sports complex, the Illisaksivik community association, and nursing station. There is a community pier for boat access, with expansion planned in the next few years. There are no road connections to other communities, but there are direct flights to and from Pond Inlet and Iqaluit several times a week, and the sea-lift serves the community annually, bringing in fuel, food, and all manner of building materials.

Figure 3.9 Houses in Clyde River are typically one-storey bungalows (photo M. Irvine, August 2007).

Water delivery and sewage removal occurs by truck every few days, rather than through utilidors as in larger arctic settlements such as Iqaluit or Inuvik. The community reservoir, a small lake basin, is situated 1 km north of Clyde River and water is brought to residents by trucks with a capacity of 20 000 litres (Fig. 3.10). The community uses approximately 70,000 l/day. This is equivalent to around 85 l/day per person, which is much lower than the 2004 national average of 329 l/day per person (Environment Canada, 2010).

Figure 3.10 Like many other Nunavut communities, water delivery is by truck to households, as permafrost conditions pose challenges to burying water-pipes underground. Note the pipe connecting the pumphouse to the water truck is insulated and heated in order to prevent freezing (photo M. Irvine, March 2008).

The community's sewage lagoon is at capacity and effluent is seeping into the retention berms. When the lagoon has reached capacity, the liquids are pumped out annually, as evidenced by the lush vegetation downslope of the lagoon. Lagoon expansion is slated for the near future, with a projected capacity to store waste for the next 20 years.

Clyde River has the third highest rate of overcrowding in Nunavut, a condition that will only be exacerbated by the projected population growth (Government of Nunavut and Nunavut Tunngavik, 2004). To meet the demand for infrastructure, over 40 new residences are projected to be built in the next four years, primarily consisting of 5-unit, one-storey multiplexes. Infrastructure constraints are not limited to housing. To provide cultural educational opportunities for Nunavut residents, the Piqqusilirivvik Cultural School is presently (August, 2010) being constructed in Clyde River, and is slated to open in the coming years (George, 2006).

The older sections of Clyde River are built along Patricia Bay on flat to gently sloping terrain. New development is progressing north up the slope towards the reservoir lake. The airport is around 3.5 km east of the community, the sewage lagoon and dump are about 1 km to the west, and the water reservoir is 1 km to the north. A landuse and zoning map was created for Clyde River in 2007 (Fig. 3.11; Government of Nunavut, 2007). The map highlights how future community expansion is spatially and topographically restricted. Much of the flat to gently sloped terrain to the east and west of the community is unsuitable due to contamination exclusion boundaries related to previous waste burial sites. The residential and commercial development that occurs within the setbacks existed prior to the establishment of the setbacks. Expansion cannot occur in a southward direction as the community is built along the shores of Patricia Bay. As such, the areas identified for infrastructure development are geographically limited to up-slope from the coast and present town site.

Figure 3.11 The 2007 landuse and zoning map for Clyde River. Yellow areas are zoned residential (R), red areas zoned commercial (C), green areas are open space (OS), purple areas are industrial sites (M) and white areas are hinterland (H). The areas in the northwest section of the community are projected for development. The two circular exclusion areas to the north and southwest of the community are the setback boundaries from former waste burial sites, and are designed Old Waste Disposal Site.

3.1.9 Observed environmental stresses and previous research

Recent research has identified perceived environmental, social, cultural and economic risks in Clyde River, providing a broader context for the current study of landscape hazards. While social issues revolving around drug and alcohol use, poverty, family cohesion and economic development may be on the forefront of people's minds, environmental concerns, especially those regarding climate change, pollution and infrastructure development, are viewed by many as being equally important (S. Gearheard, pers. comm. 2008).

Environmental changes in Clyde River are numerous and varied. Residents have detected variations in the predictability, magnitude and characteristics of different climate parameters as well as alterations in landscape conditions that directly affect their lives, such as the distribution, health and quantity of plants and animals (Fox, 2003; Huntington and Fox, 2005; Gearheard et al., 2006). Observations suggest that sea ice has undergone significant changes in duration, extent, texture, thickness and lead position. This is translating into increased hunting and travelling risks and modifications to landscape processes such as shoreline erosion (Fox, 2003; Huntington and Fox, 2005; Gearheard et al., 2006).

There are growing concerns regarding infrastructure in Clyde River. Although a community planning and zoning map was published in 2007 (Fig. 3.11), local residents want to know additional details, such as which areas are prone to risks, how the landscape may change in the future, and technological modifications that will improve the stability of buildings (S. Gearheard, pers. comm., 2008).

3.2 Application of the research framework

This section describes the application of the research framework developed in section 2.5. Although the application of each component of the framework is described separately, many of the steps in the framework occurred in a concurrent manner. For instance, the project began with meetings with community members, while community interactions and presentations with community stakeholders and regional decisions makers occurred throughout the project.

3.2.1 Scoping studies

Scoping studies are the first step in the research framework. Information is gathered that guides and directs the project, while ensuring that all baseline and preliminary data on the study area are collected. This information is then used to plan field studies.

3.2.2.1 Community interactions

Community consultations and discussions are an ongoing and vital component of the project. Initial interactions with members of the community ensured an open dialogue and facilitated the exchange of knowledge of the land on landscape conditions, processes and historical events, while providing feedback and direction to researchers (Table 3.2).

A key reason why Clyde River was chosen as a case study community was due to interest and invitation expressed by community members. Initial interest for work to be conducted in Clyde River was generated in discussions during the Nunavut climate change workshop, *Adaptation Action in Arctic Communities*, hosted by the Government of Nunavut and NRCan in Iqaluit in December 2006. This workshop explored methods to aid Nunavut communities to adapt to climate changes

(Department of Environment and Conservation, ND). At this workshop, community leaders from Clyde River expressed an interest in having research conducted in their community.

Meetings in Clyde River with key community stakeholders (e.g., Hunters and Trappers Organization) during the summer of 2007 ensured that the community had the continued desire, need and capacity for the research, and helped the refine project focus. During March 2008, researchers visited the community to present preliminary results, and through consultation with Ittaq Heritage and Research Centre and interested residents, determine the remaining project direction, community needs, concerns and suggestions. At the beginning of fieldwork in the summer of 2008, researchers met with key stakeholders such as the elders and Ittaq Heritage and Research Centre to discuss the scope of the upcoming field activities. During March 2010, the author, along with other project members, presented project results in a non-technical manner in posters, PowerPoint presentations and open discussions with the community (Table 3.2).

Informal discussions with local field assistants, bear monitors and construction workers also provided information on community development, historical landscape and environmental changes, and construction techniques. For instance, while out on the land, the bear monitors, whose families have lived in the region for generations, discussed how the landscape and associated features, such as glaciers, had changed. Within the community, contractors and construction workers provided vital information on the causes of building damages and various repair/mitigation techniques.

Table 3.2 Schedule of key meetings held by NRCan researchers with community partners regarding the Clyde River project.

Date	Partner(s)	Topic
Dec. 6-8 2006	GN community members, developers, researchers and local representatives	Climate change and adaptation actions
July 27 2007	Lands administrator	Landscape hazards in the community
July 30 2007	Hunters and Trappers Association	Community concerns, regional development and research project overview
Oct 17-19	School and community	Earthquakes and tsunamis
March 3 2008	Regional engineer	Waste management and community services
March 3 2008	Community stakeholders	Community concerns regarding environmental change
March 4 2008	Ittaq Heritage and Research Centre	Capacity building in Clyde River and Nunavut, project details and community needs
March 6 2008	Lands administrator	Community development plans
July 25 2008	Elders Association	Project logistics and direction
March 9 2010	Community	Research findings and next steps
March 10 2010	Community	Research findings

A strong partnership with Ittaq Heritage and Research Centre, a community-based organization in Clyde River, was developed, and greatly facilitated many aspects of this research. Ittaq Heritage and Research Centre acted as a liaison between the community and researchers, facilitating efficient and positive communication, organizing accommodations, project logistics, the hiring of local field assistants and in sharing and translating information. For instance, in terms of communication, the partnership with Ittaq ensured that if a problem, concern or misunderstanding arose there would be immediate action to rectify the issue. During fieldwork, certain community members were unsure of the rationale and implications of certain types of data collection. Community members had questions regarding the purpose of topographic surveying, as various pieces of unusual equipment are required to gather data. Also, there was concern regarding the implications of permafrost coring on the environment, as this tool is more intrusive than other forms of data collection and results in minor disturbance to the terrain. This issue was relayed to the research team and a member of Ittaq Heritage and Research Centre went on the community radio to address the concerns.

A key aspect of project scoping included a literature review that focused on studies pertaining to environmental and sea level history, landscape conditions, and geological, physiographic and cultural information (Table 3.3). Desktop mapping of the surficial geology, hydrology, current hazards, periglacial landforms and processes, and human and natural disturbances was conducted for the Clyde River townsite and adjoining potential areas for development. Standard classification and mapping units for surficial geology were adapted from the Geological Survey Canada (Fulton, 1993). Stereopairs of black and white, vertical air photographs at various scales were used to assess temporal changes and pre-development terrain conditions (Table 3.4). A high resolution (2.44-2.88 m accuracy) multispectral and panchromatic Quickbird satellite image from August 21, 2005 was used as a cartographic base. The satellite image was also used as a communication tool when interacting with community members because it was found that they were able to inherently better relate to material when presented in a spatial and visual context in which they could identify familiar landmarks and buildings. Compared to other images of the community, such as older, lower resolution black and white air photographs, the satellite image allowed for community members to easily locate features.

Table 3.3 Key literature references that provided background information on Clyde River

Topic	Reference
Landscape hazards	Jurello and Beckstead, 2008
Geotechnical characteristics	AMEC Earth and Environmental, 2008
Glacial history and sea level trends	Miller et al., 1977, Dyke et al., 2002; Miller et al., 2002; Briner et al., 2003; Briner et al., 2005; Briner et al., 2007.
Environmental change	Krupnik and Jolly, 2002; Fox, 2003; Huntington and Fox, 2005
Environmental characteristics	Terrain Analysis and Mapping Services Ltd, 1981; Nixon, 1988; Harris, 1991; Hivon and Sego 1993; Gearheard et al., 2006
Community planning and development	Harris, 1991; Nunavut Planning Commission, 1997; Nunavut Housing Corporation and Nunavut Tunngavik Inc, 2004; George, 2006; Government of Nunavut, 2007

Table 3.4 Air photographs used in the Clyde River study

Roll #	Date acquired	Roll #	Scale	Spectral Range
A16213	27-07-1958	33-35	60000	Black and white
A16212	27-07-1958	20-23	60000	Black and white
A16300	30-08-1958	137-141	60000	Black and white
A21157	09-08-1969	28-54	60000	Black and white
A28353	27-08-1998	79-88	10000	Black and white

3.2.2 Field activities

A range of data collection techniques were employed in order to compile current information on various components of the environment. These techniques are described in detail below.

3.2.2.1 Topographic survey

Topographic surveys of the central residential area of Clyde River were undertaken to provide an understanding of local relief and slope, and to create a digital elevation model (DEM). Using Real Time Kinematics (RTK) surveying equipment, transects throughout Clyde River were surveyed on foot and all-terrain vehicle (Fig. 3.12). RTK is a method that uses a base station with a known position and a hand-held rover, and produces highly accurate (decimeter-scale resolution) measurements (Sickle, 2001).

Figure 3.12 RTK transects surveyed by foot and ATV transposed onto a Quickbird satellite imagery, August 21, 2005.

3.2.2.2 Measurement of thaw depth

The active layer (thaw) depth was measured at 36 sites throughout the town using a hand-operated soil auger in July and August 2008; sites were selected to provide a representative sample of different surficial material (Fig. 3.13).

Figure 3.13 Location of active layer measurement sites as shown by closed red circles. Background image is a Quickbird satellite image, August 21, 2005.

3.2.2.3 Infrastructure and drainage assessment

An inventory of existing infrastructure was undertaken to assess building foundation type, and identify existing problems and deficiencies. In terms of urban hydrology, the location, size and condition of culverts, drainage channels and areas of surface ponded water were mapped and evaluated throughout the community.

3.2.2.4 Surface sediment sampling

Forty-six surface sediment samples were collected in order to characterize sediment texture in various deposits throughout the community (Fig. 3.14). Samples were taken from all landscape units to provide a representative sample of the area. Sediment sampling covered the largest geographic area compared to other techniques. Permafrost coring and topographic surveying were time intensive and required equipment that cannot readily be transported, and efforts were restricted to the townsite. Surficial mapping was also limited to the townsite, as the mapping was conducted at a detailed scale, and the research team determined that the immediate area of current and future development was sufficient for the needs of this research.

3.2.2.5 Permafrost coring

Shallow permafrost coring using a hand-held motorized permafrost drill (Fig. 3.15, cf., Calmels et al., 2005) was conducted to assess ground ice conditions and retrieve samples from permafrost substrate for chemical, compositional, and sedimentological analysis. Sites were selected based on consultations with the community, with the intention to characterize different terrain types and assess ground conditions in areas of potential future development. The drill has a hollow core barrel 40 cm in length and 10 cm in diameter, with the potential to drill to depths of 7 m under optimal conditions. Immediately after extraction, cores were photographed, logged, wrapped in thick plastic bags and kept frozen in the community freezer. Core segments were shipped as frozen cargo to a cold storage facility at Laval University, Quebec City, for analysis and laboratory testing.

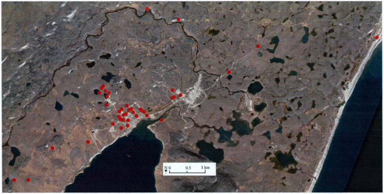


Figure 3.14 Sediment sample collection sites in Clyde River as represented by red dots. Background image is a Quickbird satellite image, August 21, 2005.

Figure 3.15 Shallow permafrost coring in a wet sedge meadow, Clyde River, Nunavut (Core 1, Appendix A, photo M. Irvine, July 2008).

Cores up to 2.83 m in length were recovered during this study, and core log descriptions are provided in Table 3.5 and Appendix A. Coring was attempted at 14 sites, from which 12 cores were successfully recovered (Fig. 3.16-3.18; Table 3.5; Appendix A). Drilling was unsuccessful in areas that contained large numbers of clasts and any amount of boulder material, or where there were high surface water contents (sites 6 and 8). Coring depth was limited by either encounters with large clasts or where cold permafrost temperatures caused the drill to freeze-in. Coring started at the bottom of the active layer (situated between 0.25 and 0.94 m below surface); cores varied in length from 0.19 to 2.83 m (Table 3.5).

Table 3.5 Permafrost core descriptions. Drill depth refers to the depth from the ground surface to the bottom of the core, and includes the active layer. Core length does not account for sediments lost during the coring process.

Site #	Site description	Drill depth (m)	Active layer (m)	Core length (m)
1	Washed till blanket, area of ponding surface water, silty-sand, 90% sedge cover	3.2	0.37	2.83
2	Washed till blanket, area of thermokarst, sand with some granules and pebbles, 90% sedge cover	2.35	0.59	1.76
3	Raised-glaciofluvial marine terrace, silty-sand, 20-30% lichen and moss cover	0.71	0.25	0.46
4	Ice-wedge polygon on raised-marine fluvial terrace, silt and sand, 20% lichen and moss cover	2.4	0.54	1.86
5	Washed till blanket, sand and scattered pebbles, 90% sedge cover	1.47	0.6	0.87
6	Till blanket, area of mud boils, boulders, 20% cover of sedge and dwarf willow	0	0	0
7	Washed till blanket, silt, sand and pebbles, 40-50% lichen and sedge cover	0.74	0.3	0.44
8	Till blanket, area of ponding water, silty sand, 70% lichen, moss and sedge cover	0	0	0
9	Raised centre of ice-wedge polygon, sand and gravel, 70% lichen, moss and sedge cover	2.18	0.84	1.34
10	Trough of ice-wedge polygon, sand, 80% lichen, moss and sedge cover	0.91	0.69	0.22
11	Washed till blanket, sand, 60% sedge cover	1.13	0.94	0.19
12	Beach, sand, 50% moss and sedge cover	1.01	0.81	0.2
13	Washed till blanket, sand with some pebbles, 70% sedge cover	2.14	0.35	1.79
14	Washed till blanket, area of ponding water, sand with some granules, 90% sedge cover	2.04	0.4	1.64

Figure 3.16 Location of coring sites within Clyde River. Background image is a Quickbird satellite image, August 21, 2005.

Figure 3.17 Location of coring sites in the area of the proposed Piqqusilirivvik Inuit Cultural Learning Facility (#3, 4) and in proximity to the community airstrip (#8-10). Background image is a Quickbird satellite image, August 21, 2005.

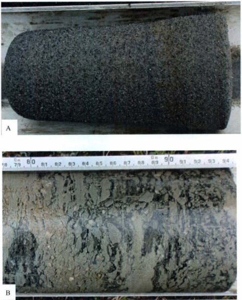


Figure 3.18 Sections of permafrost cores from site 12 (0.8-1.02 m; Fig. 3.18A) and 13 (0.78-0.95 m depth; Fig. 3.18B). The site 12 core segment (Fig. 3.18A) is composed of well-sorted, planar laminated to massive, medium to coarse sand and has low ice content. The core from site 13 (Fig. 3.18B) is composed of disaggregated massive sandy silt and minor gravel with high ice content (photo M. Irvine, July 2008).

3.2.3 Laboratory activities

Sediments collected as bulk surface or subsurface cores were analyzed for textural, sedimentological and geochemical properties. These laboratory activities are described below.

3.2.3.1 Particle-size analysis

Samples for particle-size analysis underwent wet and dry sieving following standard laboratory procedures (Syvitski, 1991). Samples were dried at 105ºC overnight, and weighed to determine total dry sample weight. The silt and clay fraction were determined on samples wet sieved through a 4 phi (0.0625 mm) sieve. The sediment remaining on the sieve was dried and then sieved for 15 minutes using a sediment shaker and a sieve nest of -2ϕ, -1ϕ, 0ϕ, 1ϕ, 2ϕ, 3ϕ, and 4ϕ sizes, corresponding to the divisions of the Wentworth scale (Table 3.6). The amount of sediment collected in each sieve was weighed and recorded. Sediment that fell through to the pan beneath the 4ϕ sieve was added to the silt and clay fraction weight from the wet sieving.

Table 3.6 Wentworth grain size classifications

Phi Unit φ	Grain size (mm)	Wentworth size class
-2	>4	Pebble or larger
-1	2-4	Granule
0	1-2	Very coarse sand
1	0.5-1	Coarse sand
2	0.25-.5	Medium sand
3	0.125-0.25	Fine sand
4	0.0625-1.25	Very fine sand
<4	<0.0625	Silt and Clay

3.2.3.2 Permafrost core analyses

Computed tomography imaging

Sediment cores underwent computed tomography (CT or CAT) imaging to document core structure and composition (Fig. 3.19). Originally used in medical research, CT scanning is now applied in a wide range of fields, including the earth sciences, where sedimentological and biological properties of both frozen and non-frozen sediment are studied (cf., Boespflug et al., 1994; Evans and Pudsey, 2002; Michaud et al., 2003; Calmels and Allard, 2008). CT scanning is a non-destructive analytical technique, allowing for the preservation of samples for subsequent analysis (Ashi, 1997).

During the CT scanning procedure, samples are placed between X-ray sources and receptors. X-ray beams pass through the sample and the reduction of the X-ray forces are measured at a variety of angles, producing a map of the attenuation (absorbance) values (Boespflug et al., 1994; Orsi et al., 1994; Boespflug et al., 1995; Geiger et al., 2009). The manner in which X-rays interact with the material is primarily dependent on the density of the material, but also reflects grain size, organic matter content, level of compaction, and chemical composition (Boespflug et al., 1995; Geiger et al., 2009).

Imagery software is used to produce a digital image of attenuation values, expressed as Hounsfield Units (HU), defined by μ, the absorption coefficient. HU is compared to μ of pure water (Boespflug et al., 1994), by the following relationship (Geiger et al., 2009).

$$HU=[(\mu-\mu_{water})/\mu_{water}] \times 1000$$

The greater the value of μ, the higher the HU value, or level of X-ray absorption (Orsi et al., 1994; Gagnoud et al., 2009). The tomographic intensities are generally displayed by processing software as a grey scale image, with pixel tone inverse to the attenuation value (Michaud et al., 2003). Areas with low X-ray attenuation (e.g., ice-rich materials) are displayed darker in CT images compared to sediment dense areas with high X-ray attenuation (Ashi, 1997).

For this study, CT imaging was conducted at the Eau-Terre-Environnement Department in the Institute National de Recherché Scientifique (INRS) in Quebec City, Quebec, using a Somerton Sensation 64 CT scanner. Frozen sediment core sections up to 50 cm in length were placed on a bench between the X-ray source and receptors. Each core segment was scanned length wise, producing a longitudinal plane. Then the core was turned 90° and a second scan was taken. The scanner's X-ray sources rotated around the core, allowing for all angles of the section to be captured. Core sections were placed in the bench in the same manner each time, with the bottom of the core section on the right hand side of the scanner. Throughout this procedure, which took approximately 2 seconds for each scan, cores remained in their plastic bags, and were only removed from the freezer for a short period. Downcore quantification of the ice, gas and sediment content of the permafrost cores was undertaken using OsiriX imaging software.

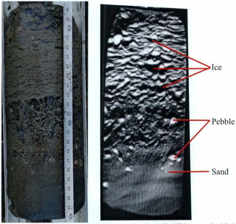


Figure 3.19 CT image of core 13, interval 1.175-1.40 m depth. The CT image on the right is of the same core segment illustrated at left, but rotated to a different viewing angle. Pebbles and other dense material are displayed as white, with less dense areas such as ice or gas displayed as very dark gray or black. The foliated structure in the upper third of this core segment is characteristic of segregated ice lenses, whereas more massive ice accumulation is seen in the middle of the core segment (photo, M. Irvine, July 2008).

Core description

Permafrost cores were described at Laval University for particle size, Munsell colour, texture, degree of sorting, presence and characteristics of ice, and the presence of shells and organic material. Core segments that were predominantly silt and ice were split lengthwise with an electric saw to preserve an archive half of the core. However, as most cores contained clast material, they had to be split with a chisel and hammer in order to extract frozen samples for chemical and particle size analysis (Appendix A).

Texture analysis

Grain size analysis was conducted on sediment extracted from the permafrost cores, and processed by the same wet and dry sieving methods described in section 3.2.3.1 (Appendix A).

Organic carbon and inorganic carbonate content

The organic content of sub-samples from the permafrost cores was measured in order to provide an understanding of the potential relative heat transfer. Organic matter can decrease heat transfer between sediment and air (Couture et al., 2003). Organic matter content was determined by loss on ignition, following the procedures of Heiri et al., (2001). Samples were dried in an oven for 24-48 hours at 105°C, weighed, combusted in a furnace at 550°C for 4 hours, and then re-weighed (Heiri et al., 2001). Following the organic matter determinations, samples were heated further at 950°C for two hours, and then re-weighed in order to determine their carbonate content (Heiri et al., 2001).

The following formulas were used to determine the organic carbon and inorganic carbonate content of the samples:

Organic carbon LOI value:

Organic LOI550° = [(dry weight 105° – dry weight 550°) /dry weight 105°] * 100

Inorganic carbonate LOI value:

Inorganic LOI 950° = [(dry weight 550° weight – dry weight 950°)/ dry weight 105°] * 100

(Appendix 2, Table B.2)

Gravimetric water content

The gravimetric water content of core sub-samples was measured to provide an estimate of ice content (Lawson, 1986; Couture et al., 2000; Nelson et al., 2001; Couture et al., 2003; Cheng, 2005). Thawed samples were weighed and then dried in an oven at 105°C for at least 24 hours and then re-weighed to determine gravimetric water content (U):

U=(Mwet-Mdry)/Mwet

where Mwet is the mass of wet sediment and Mdry is the mass of dry sediment.

(Appendix 2, Table B.2)

Pore water salinity

The salinity of the ice and pore water from the permafrost cores was measured to confirm the presence and degree of saline permafrost. Sub-samples of the permafrost cores were thawed, filtered with a vacuum pump, and then analyzed at the Geological Survey of Canada's laboratories in Ottawa. Insufficient ice/pore water contents in some samples negated their analysis. Samples were measured in milliSiemens per centimetre (mS/cm); however, to allow for comparison with other published research, results were converted to parts per thousand, by the following equation:

1 mS = 1,000 μS

μS x 0.7 = 1 ppm

1000 ppm = 1 ppt

where mS is milliSiemens, μS is microSiemens, ppm is parts per million and ppt is parts per thousand (Appendix 2, Table B.3).

3.2.3.3 Topography

A digital elevation model (DEM) was created in ArcMap using data from the RTK topographic surveys (Fig. 3.20). A Triangular Irregular Network (TIN) was used to create a raster that was gridded using Inverse Distance Weighting (IDW). A slope map displaying values in degrees was created in ArcMap using the DEM as a base layer, and running the surface analysis tool "slope." An interpreted slope map was derived from the DEM slope map, which categorizes the terrain into flat, moderate and steep slopes (Fig. 3.21).

The divisions for the slope categories were based on those used in previous studies that utilized slope maps (Malkawi et al., 2000; Harris et al., 2001). There are variations in the categorization between these studies (Table 3.7). The Harris et al. research developed four topographic zones susceptible to ground movement including landslides, debris flows and rock falls. The study by Malkawi et al. (2000) was based in a non-permafrost environment, and the ranking system is subjectively determined based on the susceptibility of different topographic zones to ground failure.

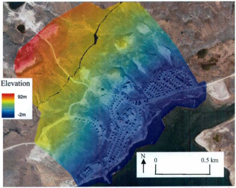


Figure 3.20 Digital Elevation Model of Clyde River, grey line is estimated maximum marine limit for the area. When integrated with other data, this map aids in the identification of areas where slope processes may pose increased developmental constraints. It also benefits analysis of meltwater and rainfall-generated runoff and snow drifting. Background image is a Quickbird satellite image, August 21, 2005.

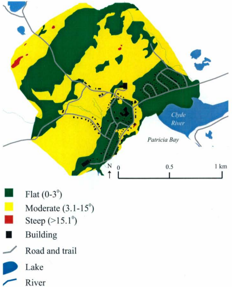


Figure 3.21 Simplified slope map derived from the topographic survey-generated DEM of Clyde River. Flat areas are prone to water pooling if water is not properly channeled. In moderate to steep gradient areas, slope processes may be more significant.

Table 3.7 Slope categorization systems

Categorization system		Source
Slope (°)	Ranking or issue	
0	Thaw settlement (fine-grained sediment)	Harris et al., 2001
<15	Thaw subsidence, solifluction, mudslides (fine-grained sediment), permafrost creep (coarse grained sediment)	
15-19	Landslide/mudflow (fine-grained sediment), permafrost creep (coarse grained)	
30-74	Debris flow	
<10	Low	Malkawi et al., 2000
10-15	Moderate	
15-20	High	
>20	Very high	

This paper uses the following topographic zones: flat (0-3°), moderate (3.1-15°) and steep (>15°). This categorization is primarily based on the research of Harris et al. (2001), as the physical environments are similar. The flat category includes values up to 3° as the survey method used in this project resulted in a coarse DEM and was not able to distinguish between terrain that was flat or had very little slope change. Slope units are in degrees as this is the standard in geotechnical work, compared to percentages commonly used in landuse planning.

3.2.4 Data analysis and interpretation

The analyses and interpretation of field and laboratory data are presented in this section. At this stage, data are examined in the context of the research questions in Chapter 1. Classified terrain layers, which are information layers that show different trends in the landscape, were generated. For this thesis, classified terrain layers include topography, surficial geology, geomorphic and natural processes and disturbances, ground ice content, sediment texture, salinity, infrastructure and infrastructure adaptations. These terrain layers are based on data gathered during scoping studies and field data collection and analysis.

Topography

The DEM created for Clyde River is limited to the townsite area (Fig. 3.20). The elevation for the area covered by the DEM ranges from -2 m to 92 m. This model includes elevations below 0 m as the surveying was conducted during low-tide. When over-layered with infrastructure, the southeast portion of the townsite is below 10 m, whereas most infrastructure in the southwest portion of the community is below 15 m elevation. The community's school is built at 15 m asl, the arena is at 17 m asl, and the oil tanks are at 7 m asl. The road leading out to the airport is around 5 m asl and the airport itself is at 25 m asl. The water reservoir is around 80 m asl, and the sewage lagoon is at 60 m asl. Most of the area of current development is below 50 m elevation. In order to understand the elevation in areas outside of the DEM, the model was compared to elevation data downloaded from GeoGratis, a portal provided by NRCan (Fig. 3.22). The DEM created for this project is considered more precise but information from the contour lines (10 m interval) can be used to provide rough elevation estimates for areas outside of the coverage of the DEM.

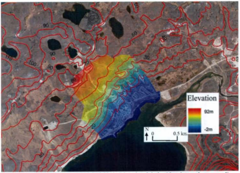


Figure 3.22 Digital Elevation Model of Clyde River overlain by 10 m interval contours lines generated from download data from GeoGratis. The DEM provides a more detailed representation of changes in relief. Background image is a Quickbird satellite image, August 21, 2005.

The slope map for Clyde River shows that the community is dominated by low sloping to flat terrain and areas of newer and proposed development on moderate slopes (Fig. 3.21). The southeast and southwest sections of the community are built on flat raised marine terraces formed during a Holocene sea level stand, and are composed of both washed till and alluvium. North of the main town site the slope is moderate with the exception of a flat area north of the road leading to the airport. These areas of moderate slope are associated with lower portions of a discontinuous moraine belt. The few areas of steep slope are north of the current townsite, and are associated with moraine ridges. The topographic survey density used in this study was too coarse to capture smaller features such as drainage channels.

Areas prone to water pooling within topographic depressions and other characteristics of the urban hydrology were mapped (Fig. 3.23). Water pooling was mapped based on visual observations of where water currently is pooling, or where there is evidence of past water pooling. In Clyde River, water is pooling in southeast parts of the community, below snow patches, along the sides of some streams, and where there is inadequate or non-existent drainage infrastructure.

Surficial geology

Bedrock is not exposed within the area of current town site development, although there are bedrock cliffs and hills along Baffin Bay east of the community and to the west of Clyde River along outer Patricia Bay (Fig. 3.24). Weathered bedrock is found across Patricia Bay and north of the community in proximity to the Clyde River. There is also a bedrock quarry southeast of the airport across the Clyde River (Fig. 3.1).

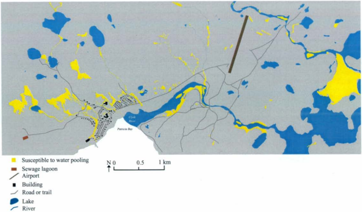


Figure 3.23 Terrain susceptible to surface water pooling.

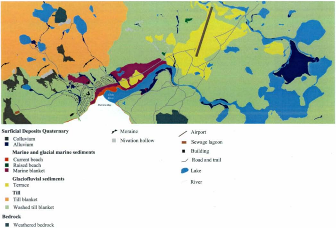


Figure 3.24 Map of Clyde River showing surficial sediment units.

Much of the area northeast of Clyde River is covered by a till blanket (thick, continuous glacial sediment). The till has a medium sand-rich matrix and consequently is prone to erosion by water and wind (Fig. 3.25A and 3.26). Below marine limit, the till is reworked and washed and where undisturbed by human activity often possesses a coarse surface lag, or armouring (Fig. 3.24).

Glaciofluvial terraces underlie the airport and extend northwards up the Clyde River where one terrace is composed of rounded cobbles (Fig. 3.27). There may be suitable lithic material and volume in this deposit necessary for generating crushed granular aggregate for construction; however, pit test would be required to determine its thickness and extent. The absence of an excavator, however, limits the community's ability to utilize this resource. Along the shore west of the mouth of the Clyde River are two small, flat raised fluvial terraces around 4 m asl, the eastern one of which is the site of the Nunavut Piqqusilirivvik cultural school currently being constructed.

The modern beach is not extensive. There is a sandy beach in front of the community fronted by a discontinuous, ice-push and man-made boulder barricade. The Clyde River enters Patricia Bay south-east of the community, and an estuarine tidal area occupies the low-lying region near its mouth. This area is vegetatively barren in many areas, reflecting frequent marine incursion. North of this region, and extending across the road to the base of the hill slopes, the area is comprised of an extensive flat, wet-sedge meadow formed atop a raised tidal plain composed of deltaic marine sediment.

In the northeast section of the community, north of the arena, an extensive and thick blanket of marine sediments is exposed (Fig. 3.25B). Other areas of marine blanket are likely to underlie portions of the community, but could not be readily identified and mapped. Local marine limit is challenging to determine, but based on air photo observations, previous studies and on the ground observations, the Holocene marine limit within the town site is estimated to be at around 50 m or 28 m higher than what is recorded on the Clyde Foreland (see Section 3.1.2). Evidence to support this include the delta formed of marine deposits within the town site found at 42 m asl (Fig. 3.25B), the washed lag surface on the landscape below 50 m and the line of discontinuous lateral moraines shown in Figure 3.24 that are situated immediately above a prominent bench. Higher glaciofluvial terraces, equating to higher marine limits, found farther north along the Clyde River above the airport suggest the sea was initially blocked from the town site by late-lying ice grounded in Patricia Bay. Permafrost in areas below marine limit may be saline, and as previously explained has implications on the sensitivity of the ground to thaw and bearing strength.

Colluvium deposits are present west of the community, in particular below nivation hollows. Alluvial deposits are found along the perimeter of rivers and creeks, in particular the Clyde River. Discontinuous lateral moraines at 50 m asl run sub-parallel to moraines at 150 m asl, and are situated on the slopes north of the community.

Figure 3.25 Quickbird satellite image of Clyde River, August 21, 2005. Letters are locations of surficial materials and processes highlighted in subsequent figures.

Figure 3.25A An example of the till blanket north of the community. Conspicuous ridge in the background is an east-west aligned lateral moraine, at the base of which is a perennial snowpack and nivation hollow. The dark green grass in the centre of the photo is a wet sedge meadow. Note abundant boulders on surface of the till blanket (photo M. Irvine, July 2007).

Figure 3.25B Massive to planar laminated, well-sorted fine to medium marine sand exposed by removal of surface cover. The surface was cleared and the sand excavated to make buildings pads for the new five-plexes seen in the background. The exposed sands have been deeply dissected over the course of one year by rain and snowmelt. Abundant paired and single bivalves (visible white material) and rare gastropods occur throughout the sediments. A radiocarbon date of a single valve from a paired, in situ *Mya truncata* yielded an age greater than 40 000 years, suggesting that these sediments date from pre-late Wisconsinan times (photo I.R. Smith, July 2007).

Figure 3.25C View looking south towards Patricia Bay. Vegetated earth hummocks, which are a form of patterned ground are common in the terrain surrounding the community. Hummocks are indicative of cryoturbation, differential heave and disturbance in the active layer. This demonstrates the necessity for construction of suitably thick granular aggregate pads for roads and buildings resting on the surface in order to mitigate differential heave (photo M. Irvine, August 2007).

Figure 3.25D Mud boils forming a sorted net in fine grained till adjacent to an area of new housing development. Mud boils are indicative of movement in the active layer related to frost heave, cryoturbation and of water-saturated sediment. Note boulders on the surface of the till (photo M. Irvine, July 2007).

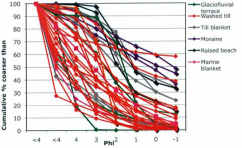


Figure 3.26 Grain size analyses of surface sediment samples from the Clyde River region. Each line represents one sample. The graph shows that the majority of the sediment falls between phi 0 and <4, which represents coarse sand to silt respectively.

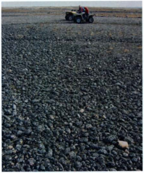


Figure 3.27 Quickbird satellite image of Clyde River, August 21, 2005. Letter A refers to photo location. North of the airport, a large glaciofluvial terrace on either side of the Clyde River contains abundant cobble-sized gravel. Depending on the quantity of material, this site could provide the community with much needed granular aggregate for building pads and other infrastructure demands (photo T. Bell, July 2007).

Geomorphic processes and disturbances

Active geomorphic processes are posing risks to infrastructure in the community and are visible on air photographs, satellite imagery and in field surveys. Thermokarst subsidence is occurring in areas around the community, near the airport

(Fig. 3.28). Human disturbance of surface material and vegetation cover relating to ATV and other vehicle traffic occurs throughout the community, and in places has led to channeling of meltwater and rain along trackways, accentuating further erosion of material. Where this exposes underlying ice-rich materials significant erosion and thermokarst processes may be expected to take place. Ice-wedge polygons visible on the 1969 air photographs have been infilled and later built upon in the northern and eastern parts of the town and are also common in the raised glaciomarine terraces in the vicinity of, and underlying, the airport (Fig. 3.29). Active ice-wedge polygons are a dynamic landscape feature, and can grow or degrade based on environmental conditions.

Earth hummocks (patterned ground) form in the till blanket, especially in areas of fine-grained material with high moisture content (Fig. 3.25C). Mud boils have formed in flat areas of fine-grained sediment, such as in the north-east of the community (Fig. 3.25D and 3.28). These form as a result of processes in the active layer and do not pose a significant constraint to community development. Gelifluction is common on the slopes surrounding the community. Thermal erosion is occurring along the banks of creeks in the community and in areas of ponded surface water where drainage/culverts are impeded (Fig. 3.30). Coastal erosion is occurring along a portion of the shoreline in the eastern section of the community in front of the elders' home.

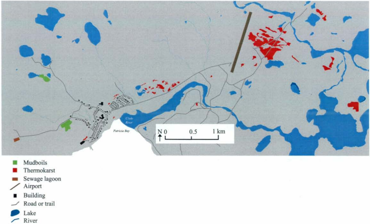


Figure 3.28 Map of Clyde River showing the distribution of mudboils and thermokarst terrain.

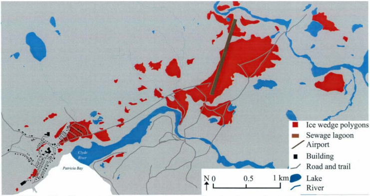


Figure 3.29 Map of Clyde River showing the location of ice-wedge polygons. Ice-wedge polygons exist under the eastern section of the community and in the terraces under and surrounding the airport.

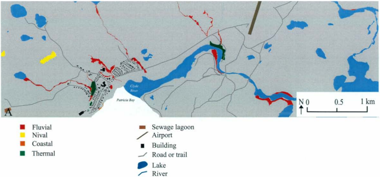


Figure 3.30A Areas of active erosion in Clyde River across the region. Other areas in the community are susceptible to these processes based on local conditions.

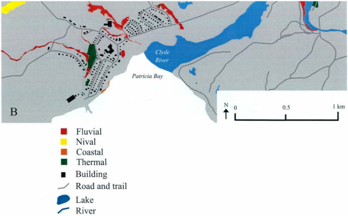


Figure 3.30B Areas of active erosion in within Clyde River. Other areas in the community are susceptible to these processes based on local conditions.

The ice composition, structure, and chemical composition of subsurface sediment

A summary of results for each core, along with a stratigraphic log including structural, sedimentary and salinity changes over depth is presented in Appendix A. Appendix B provides the analytical data in tabular form.

The ice content, grain size and salinity level of frozen ground are highly variable throughout the community (Appendices A and B). Ground ice content ranges from close to 0% to almost 100% in the cores, with an average content of 48%. Ground ice consists of structureless pore ice, segregated lenticular and layered ice (as defined by French, 2007). The gravimetric water content of the cores has a mean of 27% and a range of 4-74%. Ice-rich permafrost is variably defined as frozen ground with excess ice (Marsh and Neumann, 2001), frozen ground with ice content greater than 20% (Nelson et al., 2002), or greater than 45% (Hausmann et al., 2007). In this study, low-ice permafrost is defined as having <10% ground ice, medium-ice permafrost as 10-20% ground ice and high-ice permafrost as >20% ground ice, following the classification of Nelson et al., (2002). With the exception of the beach area in front of the community, the ground ice content of the cores generally exceeds 20% (Fig. 3.31). Landforms from which permafrost cores were extracted have their ground ice content classified on the basis of the core data, even though ice content can be spatially variable within a single sediment unit.

Sediment within the cores ranged from medium sand to silt, with silty-sand and sand comprising the predominant sediments underlying the community, and gravelly-sand in the terraces south of the airport (Fig. 3.32 and 3.33; Appendix A and B). The inorganic carbonate content of the sediment cores is very low overall, with a mean of 0.20% and a range of 0.02-1.35%. The average organic content is 1.4%, with a maximum of 12%. Similar to the ground ice content, core values were taken to be representative of the entire landform from which the core was collected.

Pore water salinity values ranged from 0.02 to 6.65 ppt (Appendix A and B). These results are similar to those recorded by Nixon (1988) in the upper 4 m of his Clyde River cores. As salinity values apparently increase with depth in the Clyde River area (Nixon, 1988; Hivon and Sego, 1993), the salinity values of the ground ice below cores recovered in this study may be greater. Previous studies suggest that salinity values greater than 2-5 ppt impose a high risk to development, and these values were used as guidance levels for this study (Nixon, 1988; Hivon and Sego, 1993). Areas with salinity values between 0-1.99 ppt are classified as low salinity, whereas salinity values 2 ppt and greater are classified as high (Fig. 3.34). All of the cores that could be analyzed from within the vicinity of the community have an upper range of salinity levels greater than 2 ppt, whereas those from south of the airport have no values above 2 ppt. Salinity measures from cores were taken to be representative of the landform from which they were sampled.

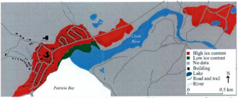


Figure 3.31 Measured and inferred ground ice contents of the uppermost permafrost terrain, community of Clyde River. The ice content of the permafrost cores from the areas in red was 20% or greater.

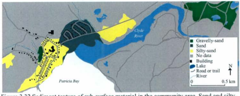


Figure 3.32 Sediment texture of sub-surface material in the community area. Sand and silty-sand are the main sediment textures in the terrain underlying the community. Coarse sediment is located in terraces south of the airport and in a small area in the community.

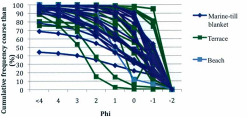


Figure 3.33 Grain size analysis of sediment extracted from permafrost cores. Note that sediment generally falls between 1 and <4 phi, corresponding to medium sand to silt, and is generally finer than that recorded in surface sediment samples (Fig. 3.26) likely reflecting the winnowing of fines from washed and deflated surfaces. Sediment from the glaciofluvial and other terraces has a greater range of grain sizes than those from the washed-till blanket.

Figure 3.34 Measured and inferred salinity content of ground ice in the terrain underlying the community. The range of salinity values of meltwater extracted from sediment cores from the community area included values greater than 2 ppt, which is considered to pose a high risk to infrastructure development. The range of pore water salinity values of water extracted from sediment cores south of the airport include values less than 2 ppt.

Infrastructure adaptations and maladaptations

In Clyde River, as in all other Nunavut communities, engineering measures dictating infrastructure design are implemented at the individual and community level. There are six different types of building foundations in Clyde River, with building function and age being strong determinants of foundation style (Fig. 3.35). Fifty-five percent (103) of buildings in Clyde River are on wood blocks with cribs that allow air to pass under the structure. Thirty-five percent (65) of buildings are built on steel piles, which extend up to 12 m into the ground, thereby anchoring the foundation into the underlying permafrost. Discussions with residents indicate that no pilings have encountered bedrock. Four percent (7) of buildings are on jacks, which can be adjusted manually to compensate for differential ground movement. Four percent (9) of the buildings are built on cement foundations on free-floating gravel pads to limit heat transfer; these buildings are typically commercial properties such as the community's garage. Two buildings – the school and nursing station – are constructed with thermosiphons. The housing unit for RCMP officers is built on a multipoint, spaceframe foundation. This foundation uses an adjustable tubular frame that is supported by numerous points connected to a continuous gravel pad, and while the only example of its kind in Clyde River, it is widespread in western Nunavut communities (R. Smith, pers. comm., 2010).

Gravel is identified as a scarce building material in Clyde River as much of the community is built on sand and silt; however, gravel should be used for infrastructure developments such as building pads because it allows for drainage and is resistant to erosion. An assessment of building pads in the community shows that medium and coarse sand are being used as pad material. Rapid and extensive erosion is occurring along the edges of many of the new pads, damaging the foundation of buildings. Sediment loss is typically occurring before building construction is complete, and results in expensive and likely perpetual repair costs (Fig. 3.36). As gravel deposits in the vicinity of the community are not common and the community does not readily have access to machinery to excavate and crush rock, the availability of gravel may become an increasingly more significant problem as infrastructure expands.

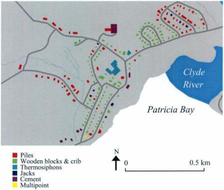


Figure 3.35 Building foundation styles in Clyde River.

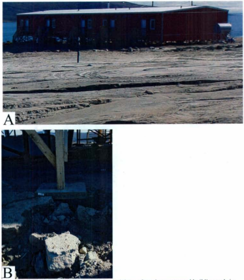


Figure 3.36 Erosion is occurring along the periphery of newly constructed building pads in Clyde River (photos M. Irvine, July 2008).
A) New housing unit built on sand building pad.
B) Close up of one support pillar of building. Note how the sediment is being eroded even before the unit is occupied.

The functionality of culverts and drainage trenches were assessed (Fig. 3.37). In the northern section of the community, culverts are sufficiently large to accommodate maximum flows and are lined with rocks in order to inhibit stream incision (Fig. 3.38A). Southeastern parts of the community have culverts that are too small to handle changes in flow, are damaged, have become blocked by debris and refuse, or have become elevationally stranded above channels feeding into them; this is leading to ponding and flooding (Fig. 3.38B and 3.38C). Areas of the lower, older town are also being impacted from development to the north, as new development is occurring up-slope, resulting in more water being diverted to the southern portions of the community. Culverts in these lower areas have not been adjusted for changes in the drainage from the new up-slope development. Where water is allowed to pond, thermal erosion and thawing of permafrost is occurring, such that culverts become raised above the terrain, necessitating their lowering through periodic maintenance.

Slope-sediment stabilization

Slope stabilization techniques should stabilize ground surface materials, minimize sediment loss and reduce the impact of flowing water and other erosive processes. Sand is commonly used as a building material in Clyde River and it is easily eroded by water. Several adaptations in Clyde River have been used to aid in slope stabilization, and the materials and the methods used influences their degree of effectiveness (Fig. 3.39). Slopes are lined with a range of material including oil drums, cobbles, plastic grid, geofabric and wood. Many slope stabilization techniques are maladaptations and are not retaining sediment, allowing for erosion.

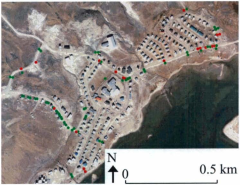


Figure 3.37 Location and condition of culverts in Clyde River as indicated by closed circles. Green circles are culverts in good condition and red circles are those that are damaged, partially to completely blocked, or are of insufficient size to handle water flows. Background image is a Quickbird satellite image, August 21, 2005.

Figure 3.38 The condition of culverts in Clyde River is variable (photos M. Irvine, July 2007.
A) This culvert in the north-eastern portion of the community is of sufficient size to withstand high water flows even during periods of heavy rain. Boulders and cobbles were placed below this culvert to minimize downstream erosion.
B) This culvert in the south-east section of Clyde River is partly blocked by sand that prevents proper flow of water.
C) This culvert in the south-east section of the community is almost completely crushed and no longer functional.

Figure 3.39 Slope stabilization techniques in Clyde River (photos M. Irvine, July 2007)
A) Originally a new residential housing unit was built on piles extending into a sandy pad, but after a period of heavy rain 4.5 m of sediment was washed away. To prevent additional sediment loss, a combination of plastic grid, geofabric and sand bags was used; the plastic grid and geofabric should aid in reinforcing the slope.
B) In the example shown here, the crushed drums are not entirely effective, as sand is still being washed downslope.

One main problem is that sand is still being used as the primary fill material and is being washed away, regardless of the other material(s) being used to hold the sediment in place. The replacement of sand with a coarse material (gravel) will rectify this problem.

Snow drifting

Precipitation is not abundant in Clyde River, but strong winds blow through the community during the winter months, forming large snowdrifts. These drifts can reach over two stories high, and can prevent residents from accessing their homes. They also act to insulate the ground from the extreme winter temperatures, so potential for permafrost thaw is greater in subsequent melt periods, particularly in areas immediately adjoining building foundations. In order to prevent snow accumulation in front of doorways, some residents have built wooden wind scoops designed to scour snow away; this is an illustration of local infrastructure adaptation to environmental conditions (Fig. 3.40).

Figure 3.40 Local infrastructure adaptations (photos M. Irvine, July 2007 and March 2010).
A) In Clyde River wind scoops are built in front of doorways to direct drifting snow away from the door.
B) The effectiveness of the wind scoop varies, and will depend on factors such as the height and distance of the wind scoop from the doorway and the wind direction.

3.2.5 Data integration and creation of hazard layers

The classified terrain layers (topography, surficial geology, geomorphic processes and disturbances, hydrology, ground ice content, sediment texture and salinity) from the Clyde River case study were integrated to map the relative risk level associated with individual landscape hazards, specifically thermokarst-related ground subsidence, flooding, erosion and slope movement. The maps classify the terrain into areas of low, moderate and high risk based on current conditions. The risk matrix presented in Figure 2.7 is used to classify the risk to community development of the four landscape hazards, based on their potential level of impact and the likelihood of occurrence. The implication of climate change on landscape hazards is explored in Section 3.3 and the level of risk is reconsidered.

3.2.5.1 Thermokarst-related ground subsidence

Terrain was classified into areas of low, moderate and high degree of risk based on likelihood of occurrence for ground subsidence based on current conditions (Fig. 3.41). The risk classification is dependent on certain characteristics of the terrain including the distribution of ice-wedge polygons (Fig. 3.29), ground ice content (Fig. 3.31), salinity (Fig. 3.34) and water pooling (Fig. 3.23).

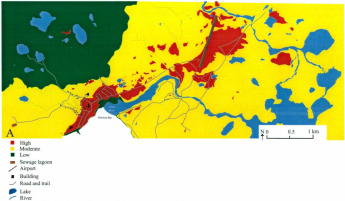


Figure 3.41A Relative risk classification for thermokarst-related ground subsidence across the region.

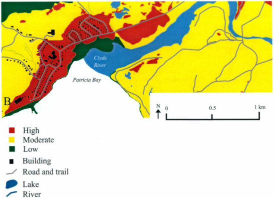


Figure 3.41B Relative risk classification for thermokarst-related ground subsidence within the community of Clyde River.

Thermokarst related ground subsidence is a concern for infrastructure development in Clyde River. Parts of the airport and southwestern portions of the community are underlain by ice-rich permafrost. As shown in Figure 3.31, in most of the area of current development, the near surface of the ground in Clyde River contains 20% or higher ice content. Cores numbered 2, 5, 10, 11, 13 and 14 (Fig. 3.16 and 3.17) contain significant amounts of pore ice and bands of interstitial layered ice; at certain depths, these cores are composed of almost 100% ice (Appendix A and B). When this ground ice melts, the ground surface will sink and deform. Further studies are required to determine the exact amount of ground surface deformation, but the structural integrity of overlying infrastructure, in particular structures that cannot be adjusted for differential ground movement, will be at risk in these areas.

Much of the permafrost in Clyde River is also saline (Fig. 3.34). The salinity of the permafrost has major implications for the likelihood of thaw. Cores 2, 4, 7 and 13 had salinity values over 2 ppt, with certain sections of the cores having salinity levels close to 7 ppt (Fig. 3.34 and Appendix A and B). Previous studies in the community found salinity levels to be some of the highest in Nunavut (up to 44.5 ppt; Hivon 1993). Biggar and Sego (1993) calculated that permafrost with salinity levels greater than 10 ppt may cause an 80-99% reduction in the adfreeze bond strength of the permafrost, or the bond strength between objects and the permafrost. Additional studies are required to determine the precise loss of strength due to the salinity of the soil in Clyde River, but in areas with high salinity levels the bond strength between the soil and building piles will be noticeably less and the permafrost will be prone to deformation. Saline permafrost primarily has implications for existing development in

Clyde River, as much of the future development is projected for areas above Holocene marine limit (50 m asl).

The salinity and ice content of the permafrost are the principal landscape factors used to map the relative degree of risk for ground subsidence. Areas of high ground ice content and high salinity are classified as high risk. In these areas the permafrost is sensitive to thaw due to the salinity of the permafrost and significant ground subsidence will occur upon thawing due to high ice content. Areas of low ground ice content, regardless of the salinity level, have low potential for thermokarst processes and therefore classified as low risk.

Ice-wedge polygons are a surface indicator of potential buried ground ice and therefore represent terrain with relatively high risk of thermokarst related ground subsidence. The southwest portion of the community and the airport's runway were built over polygonized terrain (Fig. 3.29 and 3.42). Additional research is required to determine if these polygons are still active, or if the ice within the polygons has melted. If the ground ice has melted, most of the ground subsidence will have already occurred. Coring was not allowed within the vicinity of the airport, but ground coring of ice-wedge polygons south of the airport (core 10) revealed ice contents close to 100%, suggesting ground ice is widespread (Appendix A and B).

Natural topographic setting and human alteration of slope drainage are combining to cause water pooling in different areas of Clyde River (Fig. 3.23). Development in Clyde River originated in flat backshore areas, and then proceeded upslope. The culverts in the older parts of the town are small and commonly in need of repair, upgrades or maintenance (Fig. 3.37-3.38). Increased water flows are directed towards these culverts from upslope, and water pooling results; for example along the main river running through the community (Fig. 3.43). Water is pooling alongside roads and other infrastructure in areas that necessitate a culvert, but none have been installed (Fig. 3.44). Water is also pooling below permanent snow patches, such as in the area north of the community that is zoned for development. Water pooling increases the likelihood of ground subsidence due to the transfer of heat from the water to the ground. As such, areas prone to water pooling in ice-rich permafrost are assigned a high relative risk for ground subsidence.

Figure 3.42 Ice-wedge near the airport in Clyde River (photo T. Bell, July 2007).

Figure 3.43 View looking southwest at children playing in the main stream that runs through the community. Water is accumulating on the upstream end of this culvert because it has been infilled by sediment and debris. Ground thaw in front of the culvert has lowered the ground surface below the bottom of the culvert, necessitating a lowering of the culvert in order to make it function properly (photo M. Irvine, July 2007).

Figure 3.44 View looking southeast from an area of projected development at the mid-slope above town. Water pooling is occurring along the side of the road because there is no culvert in place to drain it (photo M. Irvine, August 2008).

There is documented evidence of infrastructure damage attributed to uneven ground subsidence in Clyde River. The walls in some of the houses in the southeastern part of the community that are built on ice-rich, saline permafrost are differentially settling and cracking (Fig. 3.45). In addition, many telephone poles in the community are leaning, which suggests uneven ground subsidence (Fig. 3.46).

Overall, ground subsidence was assigned a moderate risk to infrastructure and community development in Clyde River (Fig. 3.47, Table 3.8). The likelihood of thermokarst related ground subsidence causing development problems in Clyde River depends on changes in ground temperature. The level of impact is categorized as moderately low to moderately high as the potential for thermokarst related ground subsidence is widespread, especially in the southern sections of the community and around the airport, but can be reduced through engineering and appropriate land use planning.

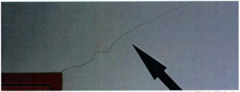


Figure 3.45 The walls in some of the buildings in Clyde River are cracking. This is likely due to uneven ground subsidence and shifting of the building foundations (photo T. Bell, August 2007).

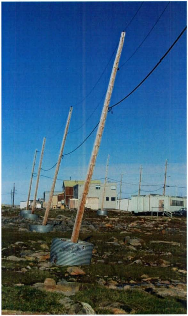
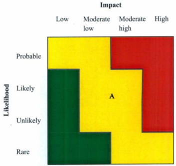


Figure 3.46 Leaning telephone poles in Clyde River illustrate differential settling and ground movement (photo M. Irvine, July 2007).



A Thermokarst-related ground subsidence

Figure 3.47 Overall classification of current risk level (indicated by letter A) of thermokarst related ground subsidence to infrastructure in Clyde River.

Table 3.8 Overall classification of risk level of physical landscape constraints on infrastructure

Parameter	Risk classification	Rationale
Thermokarst ground subsidence	Moderate	Issue widespread and moderate impact on infrastructure
Coastal flooding	Low	Restricted to small area and limited potential to impact infrastructure
Fluvial flooding	Low	Restricted to small area and limited potential to impact infrastructure
Slope movement	Low	Restricted to small area and limited potential to impact infrastructure
Coastal erosion	Low	Restricted to small area and limited level of impact on infrastructure
Fluvial erosion	Moderate	Impacts portions of the community and has a high level of impact
Thermal erosion	Moderate	Impacts portions of the community and has a high level of impact on infrastructure
Nivational erosion	Low	Impact portions of the community and has a low level of impact on infrastructure

3.2.5.2 Flooding

In general, the extent of flooding in Clyde River is geographically limited (Fig. 3.48). With the exception of the Clyde River, the streams in the community are small, with limited floodplains and low water flows for most of the year. There is some evidence of flooding along the sides of streams, but based on discussions with local residents and on ground observations, river flooding is not common in Clyde River. The potential impact of river flooding on most buildings in Clyde River is also limited as they are generally elevated above the ground on piles, jacks or other types of foundations. Where it may be of increased significance is the potential lateral erosion of ice-rich sediments that may undermine foundations.

The beach along the southeast side of the community and much of the low-lying areas extending up the mouth of the Clyde River are vegetatively barren or are covered by *Puccinellia* grass, indicating that these areas are subject to periodic salt-water inundation (Fig. 3.49). However, there is no permanent development in this area and the current flood water levels are not causing a concern to nearby infrastructure and there is no physical or anecdotal evidence of problems relating to coastal flooding.

Overall, fluvial and coastal flooding hazard was assigned a low general risk (Fig 3.50, Table 3.8). Coastal flooding has a potentially low level of impact although it has a strong likelihood of occurrence under current conditions. Coastal flooding has a very small impact on the community as only the undeveloped beach area is being inundated. Fluvial flooding has a low level of impact and a variable likelihood of occurrence. Only a small portion of the terrain has evidence of flooding, primarily in the area of the arena, which is discussed below under fluvial erosion.

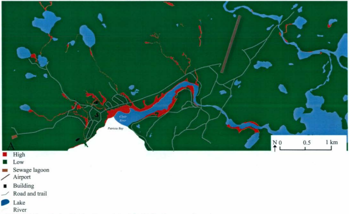


Figure 3.48A Relative risk classification for coastal and fluvial flooding across the region.

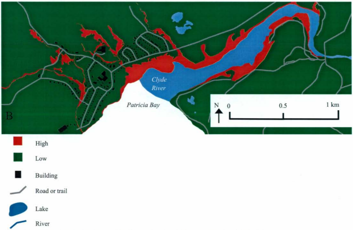


Figure 3.48B Relative risk classification for coastal and fluvial flooding within the community of Clyde River.

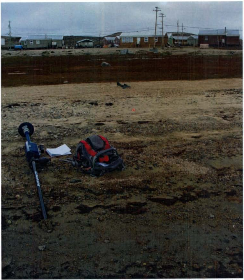
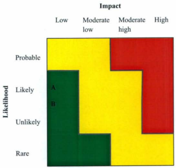


Figure 3.49 The beach area in Clyde River, looking north towards the southeast section of the community. The *Puccinellia* grass seen in the background typically characterizes areas that are periodically inundated by salt water (photo M. Irvine, August 2007).



A Coastal flooding
B Fluvial flooding

Figure 3.50 Overall classification of current risk level of coastal flooding (indicated by letter A) and fluvial flooding (indicated by letter B) to infrastructure in Clyde River.

3.2.5.3 Slope movement

The relative degree of risk form slope instability was mapped in Clyde River (3.51). The effects of thaw settlement are excluded from this analysis as this risk is incorporated in hazards relating to ground subsidence. Although factors such as vegetation affect slope movement, the principal determinants used in this assessment were slope gradient and sediment texture (Table 3.9). In the assessment terrain with flat to minor slope (0-3°) was assigned a low risk, areas of moderate slope (3.1-15°) with fine or coarse sediment were assigned a moderate risk and steep areas a high risk. These decisions are based on the type of potential slope movement as outlined in Table 3.9.

Slope movement is unlikely to occur on flat to minor slopes and does not pose a risk to infrastructure development. In moderately sloped terrain, solifluction and accelerated creep may occur. These very slow processes cause minor risk compared to the life span of infrastructure. The magnitude of landscape disturbance is also very small. As such, areas of moderate slope were assigned as a moderate risk. Landslides, mudflows and debris flows pose a greater threat to infrastructure development. These forms of slope movement are relatively rapid processes and can severely damage infrastructure. Terrain on which these processes have the potential to occur is assigned a high risk.

Few areas have high risk for slope failure in the townsite area of Clyde River. This is primarily due to the fact that most of the existing community is not built on steep to moderate-sloping ground (Fig. 3.21). The south-east section of the community has a low-risk ranking for slope instability because the terrain is generally flat. The southwest portion of the community is also built on low risk terrain due to the minor slope gradient. Areas zoned for new development have a moderate potential for slope instability. In these areas, the slope is moderate and slope processes such as gelifluction are occurring. There is an area classified as high risk for slope instability along the shoreline in Clyde River. Additional areas of high risk are in the northern section of the townsite, along the slopes of moraines and west of the tank farm along the slopes facing Patricia Bay where evidence of past slumping was observed.

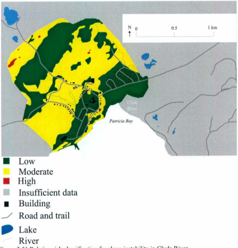


Figure 3.51 Relative risk classification for slope instability in Clyde River.

Table 3.9 Slope movement potential based on sediment type and slope class (Modified from Harris et al., 2001)

Slope class (°)	Sediment	
	Fine-grained (silt)	Coarse grained (sand, gravel or larger)
>15	Landslide/mudflow, debris flow	Debris flow
3.1-15	Solifluction	Accelerated permafrost creep
0-3	Very minor risk	Very minor risk

Overall, slope movement is assigned a low risk ranking because of the low potential impact and the variable likelihood of occurrence (Fig. 3.52, Table 3.8). Based on field observations and air photo interpretation slope movement are not contributing to any significant landscape hazards. Gelifluction is the main type of slope movement on the terrain. There is little evidence of other forms of slope movement, with the exception of one active layer detachment visible to the south-east of the community. In discussions with the community, concerns regarding slope movements were not voiced.

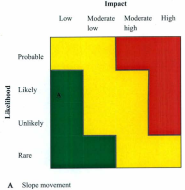


Figure 3.52 Overall classification of current risk level (indicated by A) of slope movement to infrastructure in Clyde River.

3.2.5.4 Erosion

Coastal erosion is limited in Clyde River (Fig. 3.53). During the winter months, sea ice forms in Patricia Bay, protecting the shoreline from wave activity (Fig. 3.54). During the ice-free months, the coastline is at risk from erosion. Erosion is occurring in one small area, and in this area the sediment is ice-rich sand and silt and the slope is moderate (Fig. 3.21, 3.31-3.33, 3.55). Based on discussions with community members, it was learnt that a shed in front of the elders' home has been moved back in recent years due to the receding coastline. There are no other signs of coastal erosion.

Thermal erosion of ice-rich material is occurring along the creek that runs through the centre of town and the foundation and porch of a house in the area is being compromised (Fig 3.57). A core from this area (core 2) shows that the ice content of the permafrost is high, up to 100% at certain depths, and the permafrost contains many layers of interstitial ice (Appendix A). This area of thermal erosion is visible in both the recent set of air photos for the community (1998), and the Quickbird satellite image (2005). Unless preventative measures are taken, thermal erosion will continue to affect the river banks, causing more damage to the house.

Erosion also occurs along the edge of perennial snow banks, resulting in the formation of nivation hollows. These snowbanks also result in the perpetual saturation of downslope sediments, contributing to greater seasonal ground ice formation and heave. Nivation hollows are common along the east-facing slopes of lateral moraines backing Clyde River. Discussions with community members suggest that perennial snow patches are decreasing in size.

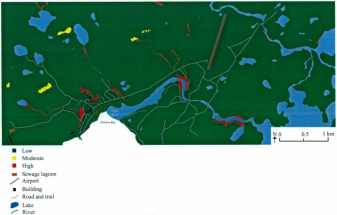


Figure 3.53A Relative risk classification for erosion across the region.

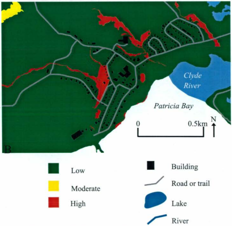


Figure 3.53B Relative risk classification for erosion within the community of Clyde River.

Figure 3.54 View looking north over Patricia Bay towards Clyde River. When the bay is frozen, the shoreline is protected from coastal processes (photo M. Irvine, March 2010).

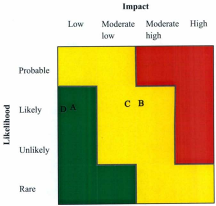
Figure 3.55 View looking east along the shoreline. Coastal erosion is occurring along this portion of Patricia Bay. Boulders were placed to armour the slope against wave erosion, however sediment loss is still occurring (photo T. Bell, July 2007).

Figure 3.56 View looking west at one end of the arena (grey building). Erosion and slumping are occurring along the stream bordering the foundation pad of the Clyde River arena and sports complex. The sediment in this area, which is similar to that underlying much of Clyde River, consists of easily erodible marine sand and silt (photo M. Irvine, July 2007).

Figure 3.57 Thermal erosion and resultant settling of ice-rich permafrost is causing damage to the porch of a house in the centre of Clyde River (photo M. Irvine, July 2007).

For example, elders reported that year-round snow patches used to exist east of the community, between the edge of the townsite and the airport. These snow patches no longer remain throughout the year. By looking at older airphotos (1958 and 1969) of the community, there is evidence of snow patches at the base of moraines and other areas of topographic relief, which no longer appear to form to the same extent. As such, the rate of nival erosion is decreasing.

Overall, coastal erosion was assigned a low risk ranking (Fig. 3.58, Table 3.8). Patricia Bay is a relatively protected coastal area, and coastal erosion is only occurring in a very limited portion of the coastline. Fluvial erosion is occurring along the sides of creeks in the community and is a concern for the arena and houses in the centre of town. Other areas in the community however are not being affected thereby making the overall risk ranking moderate. Overall hazard risk from thermal erosion is moderate. Thermal erosion is occurring under current conditions in the community, although its impact is limited to one portion of the community where it is resulting in damage. The risk from nivation erosion is low. Nivation erosion does occur in Clyde River, but the impact is very low and does not threaten community development.



A Coastal
B Fluvial
C Thermal
D Nivation

Figure 3.58 Overall classification of current risk level of coastal erosion (indicated by the letter A), fluvial erosion (indicated by the letter B), thermal erosion (indicated by the letter C) and nivation erosion (indicated by the letter D) to infrastructure in Clyde River.

3.2.6 Composite landscape hazard map

A composite landscape hazard map was created using the risk classification maps for the four hazard types identified for Clyde River (ground subsidence, flooding, erosion and slope movement). In green areas of the composite map the risk level is low. The terrain is considered relatively stable and suitable for landscape development. The yellow area demarcates a moderate composite risk level in which precautions are required, but successful infrastructure development can occur if appropriate adaptations are employed. Areas outlined in red indicate high risk. Infrastructure development should either be restricted in these areas or planning must take into consideration the high risks.

In constructing the composite landscape hazard map certain precautionary principles are employed (Table 3.10). First and foremost, those areas classified with a high relative risk for flooding, erosion, or slope instability were automatically assigned a high composite hazard risk irrespective of whether they had low exposure risk to other hazards (Table 3.10). The rationale for this automatic classification stems from the fact that these three hazard types are likely to pose unavoidable damage to infrastructure as illustrated by current situations in the community (Fig. 3.60). In contrast, the high risk posed by ground subsidence may be mitigated by appropriate engineering and geotechnical solutions (see above) and there a high risk for this hazard type does not automatically produce a high composite hazard risk. Instead, areas of moderate and high risk for ground subsidence, they are assigned a moderate composite risk ranking. The only other hazard type ranking that contributes to a moderate composite risk for an area is erosion. In this case the erosion is classified as moderate risk and describes the landscape instability associated with nivation processes below and beneath large perennial snow banks to the north of the community. No areas of moderate risk for flooding exist in the Clyde River area. In addition, there are no areas with moderate relative risk towards more than one hazard.

Table 3.10 Individual landscape hazard risk used to rank the composite landscape hazard risk

Relative risk of landscape hazard	Composite classification
High relative risk for flooding High relative risk for erosion High relative risk for slope movement	High
High relative risk for ground subsidence Moderate relative risk for ground subsidence Moderate relative risk for erosion	Moderate
Moderate relative risk for slope movement Low relative risk for all landscape hazards	Low

Figure 3.59 displays the composite landscape hazard map of Clyde River, with specific examples of high, moderate and low hazards illustrated in Figure 3.60. An area classified as a high composite landscape risk includes houses built along the creek running in the western section of the community. Thermal-erosion is occurring along the periphery of the creek during flood events, and the ice-rich, silty sediment is eroding and subsiding. The coastal area in front of the community is also designated as a high physical landscape constraint due to coastal inundation, however, no permanent structures exist in this area and development is not planned for this section of the community. Another high hazard area is the terrain north of the arena. Marine sediments are exposed in this area, and sediment is being washed downslope by meltwater and rain.

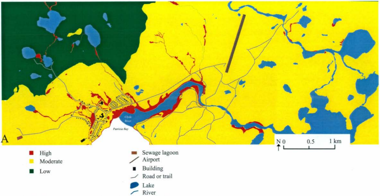


Figure 3.59A Composite landscape hazard map of Clyde River across the region.

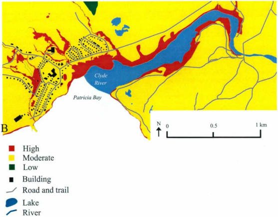


Figure 3.59B Composite landscape hazard map of Clyde River within the community of Clyde River.

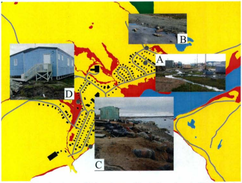


Figure 3.60 Examples of areas of high, moderate and low landscape hazards. The letters refer to examples of physical landscape constraint designations based on different data sources (photos M. Irvine, July and August 2007).
A) Interpretation of air photos that pre-date development indicated that this area that is situated below marine limit contains large ice-wedge polygons. Shallow permafrost coring and analysis suggest high ice and salinity content. If ground conditions warm, the ice will melt, causing uneven ground subsidence.
B) Assessment of the size and condition of culverts suggest that some of those in the south-eastern portion of the community are of insufficient size to handle large water flows, which are being diverted from areas upslope.
C) Informal discussions with community members suggest that this area of the coastline is rapidly eroding, requiring structures to be moved landward.
D) Air photos and ground observations were used to determine where thermal erosion is occurring. The porch on this house is being damaged by thermal erosion.

Portions of the runway are in areas classified as moderate composite landscape hazard. Ice-wedge polygons underlie the southern section of the runway and in the terrain east of the airport. Uneven ground subsidence and ground cracking will occur under the runway and airport building if ground ice melts if still present. Another area of concern is the residential units in the south-east section of the community. Ice-wedge polygons also underlie this area, and uneven ground subsidence will occur in this area if ground ice melts. Much of the eastern section of the community is in areas ranked as a moderate physical landscape constraint. This area is at risk to landscape hazards (in particular ground subsidence related to thermokarst) but the risk level is moderate. Much of the area of future development is projected for areas classified as moderate composite landscape hazard. Development in this area needs to take into consideration the risk of slope failure and ground subsidence. Hydrological infrastructure, such as culverts and trenches, should be properly planned and maintained to avoid or limit areas of water pooling, a problem that is occurring in the southeast section of the community.

Terrain classified with a low composite hazard is for the most part relatively stable with no active hazard identified except for gelifluction, which in areas where it occurs is labeled a moderate hazards risk. Because gelifluction is slow and has a low impact potential, it is deemed to be a low risk to infrastructure assuming appropriate land use designation. Terrain north of the townsite is generally stable and ranked as a low composite landscape hazard. Key reasons for this ranking is that the area has relatively low salinity and ice content levels, is not in close proximity to water sources like Patricia Bay or Clyde River and is above marine limit. Precautions should still be employed when building in these areas, as permafrost conditions underlie the area. This area is upslope of the current townsite, and development in these areas has implications for downslope development, in particular urban hydrology. In addition, the sediment is silt and fine sand, and if the overlying vegetation cover, or washed/coarse lag is removed, it will be at risk of erosion.

3.2.7 Composite physical landscape constraint map

The composite physical landscape constraint map created for Clyde River (Fig. 3.59) illustrates the suitability of the landscape for development based on landscape hazards and landuse limitations. In addition to these constraints, certain terrain is excluded from future development as these regions lie within setbacks from former dumpsites or the airport (Fig. 3.61). There are development setbacks around two former dump sites, with the size of the setback (450 m) based on guidelines set by the Territorial Government (Fig. 3.11). Portions of these setbacks are at low risk from landscape hazards and could be stable areas of infrastructure development (Fig. 3.62). The detail of the risk of these former setbacks was excluded from analysis in this thesis. The type and level of risk could be explored to determine the appropriateness of the size of these setbacks and if these development restrictions should be amended in the context of Clyde River. If there is contamination in the soil, the risk level of these containments will increase if the permafrost thaws due to a warming climate.

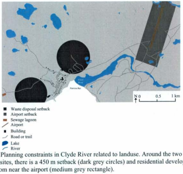


Figure 3.61 Planning constraints in Clyde River related to landuse. Around the two former waste dumpsites, there is a 450 m setback (dark grey circles) and residential development is restricted from near the airport (medium grey rectangle).

Figure 3.62 Previous landuse precludes certain areas from development in Clyde River. As these development exclusions are based on territorial regulations, the validity of the size of the setbacks in the Clyde River context should be examined. Much of the terrain in the development setbacks is of low risk from a landscape hazard perspective (photo M. Irvine, Aug. 2007).

By overlaying zoned landuse limitations on constraints imposed by the physical environment, a composite physical landscape constraint map is created (Fig. 3.63). Regardless of the designation of the terrain, site assessment precautions should always be employed when building on arctic landscapes. These environments are dynamic and sensitive, and constantly changing. One critical factor is that permafrost conditions underlie these areas, and as permafrost is a thermal condition, it may thaw and become unstable with changes in the environment. The sensitivity of the permafrost to change will not be uniform, and will vary based on local conditions. Thus, ongoing and potential future landscape changes must be considered and accounted for in all community planning and decision-making (see section below on climate change).

3.2.8 Additional physical landscape constraints in Clyde River

Research in Clyde River identified additional physical landscape constraints. Gravel is essential for infrastructure developments in Clyde River. Building pads and roads should be constructed with gravel to prevent erosion by surface water (Fig. 3.64 - 3.65). Lack of suitable coarse granular aggregate is a significant problem for Clyde River. Coarser material, however, is present near the townsite. Cobble gravel is found along the sides of the Clyde River and bedrock outcrops are found across Patricia Bay (Fig. 3.24 and 3.27). Unfortunately, there is no equipment in the community to perform test pitting or to crush rock into gravel. This study did not look at the feasibility of bringing equipment into the community, but it is predicted that this endeavour would be very costly. Demand has outstripped supply, with no feasible resolution in sight.

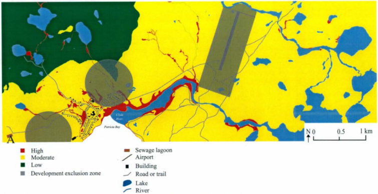


Figure 3.63A Composite physical landscape constraint map of Clyde River across the region.

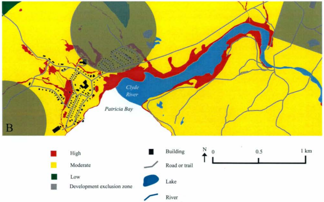


Figure 3.63B Composite physical landscape constraint map of Clyde River within the community of Clyde River.

Figure 3.64 Most infrastructure in Clyde River is built on pads constructed using sand and silt. Sand is not a suitable material for construction as it is very easily eroded (photo M. Irvine, July 2007).

Figure 3.65 Houses in Clyde River are built on silty-sand pads. After rain events, sediment is washed downslope, and expensive remediation efforts are required. The black and white rolls in the foreground of the photo are geofabric and plastic grid that are used to stabilize the sediment on the slope and under the houses (photo M. Irvine, July 2007).

3.2.9 Implication of climate change on landscape hazards

This thesis focuses on assessing current conditions, but any change in climate variables will have implications for landscape hazards and the associated risk classification for the community. Uncertainty exists with respect to future changes in climate in the region, whether a function of natural variability or the consequences of anthropogenically driven climate change. Table 3.11 summarizes the changes observed by local residents as recorded by Fox (2003) with potential future implications on the landscape. These changes in climate variables will cause changes in the magnitude and frequency of landscape hazards. In general, under climate change projections, it can be expected that landscape processes will be more pronounced leading to great impact potential.

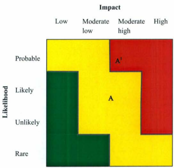
Table 3.11 Locally observed climate-related changes in Clyde River, and the implications on the landscape (Fox 2003).

Observed Changes	Result	Potential Exposure
Weather more variable	Quicker spring melt, greater frequency of storms	Increase in flooding, erosion, and slope instability
Changes in snow distribution	Alterations to thermal balance of permafrost and active layer depth	Increase in permafrost thaw and ground subsidence
Glaciers receding	Increase in river flow	Increase in erosion
Change in wind speed and direction	Changes in snow distribution and active layer depth	Increase in permafrost thaw and ground subsidence
Melting of snow patches	Increase in surface water flow	Increase flooding, erosion and permafrost thaw
Longer summers and shorter winters	More precipitation falling as rain compared to snow, more surface ponding of water, alterations to surface hydrology	Increase in permafrost thaw, probability of slides and erosion
Formation and timing of sea ice	Decrease in duration of sea ice	Increase in shoreline erosion

The potential implications of climate change on landscape processes and consequent hazards were examined. The altered risk level of landscape hazards in Clyde River due to climate was estimated and compared to the current risk level. The implications of climate change of the location of coastal flooding was explored and mapped. For other landscape hazards in the area a lack of data and an understanding of how the climate and environment will change prevented an accurate ability to map the distribution of hazards under climate change. This comparison is explored below.

Thermokarst related ground subsidence

Under climate change projections, air temperatures in the Arctic will increase (ACIA, 2004). Local residents in Clyde River have already observed that the winters are shorter and summers longer (Fox, 2003). These projections and observations suggest warmer ground temperatures in the future. This will translate into an increase in the depth of the active layer and increased probability of permafrost thaw and subsidence in areas of moderate to high ground ice content. Because the ground ice content is considered to be higher in areas of current development, the impact of high ground temperatures is likely to have a greater significance in these areas than in areas zoned for future development. Thus, general consideration of thermokarst related ground subsidence in Clyde River will be greater, with both the likelihood and level of impact increasing (Fig. 3.66, Table 3.12).



A Thermokarst-related ground subsidence

Figure 3.66 Current risk level (indicated by letter A) and risk level under projected climate changes (indicated by letter A^1) for thermokarst-related ground subsidence to infrastructure in Clyde River.

Table 3.12 Overall classification of future risk level of physical landscape constraints to infrastructure

Parameter	Risk classification	Rationale
Thermokarst ground subsidence	High	Warming temperatures and changing environmental conditions will increase sensitivity of ground thaw
Coastal flooding	High	Changing conditions will increase the flood area and increase likelihood of risk
Fluvial flooding	Moderate	Changing climate conditions will increase the area at risk and likelihood of flooding
Coastal erosion	Moderate	Changing conditions will increase the rate of erosion
Fluvial erosion	High	Changing conditions will result in the likelihood of risk and area of impact to increase
Thermal erosion	High	Changing conditions will result in the likelihood of erosion and area of impact to increase
Nivational erosion	Low	Changing conditions will not change risk level of erosion
Slope movement	Low	Changing conditions will increase likelihood of slope movement but area of impact will still be restricted

Flooding

Under projected climate change scenarios coastal flooding will become problematic for Clyde River due to sea level rise and/or a higher frequency and magnitude of storm surges. Uncertainty exists regarding the present rate of relative sea level change at Clyde River. Most of Nunavut is experiencing glacio-isostatic rebound, with the exception of easternmost Baffin and Devon Islands that are subsiding (James et al., 2009). Sea level change will be geographically variable due to factors such as proximity to the large Greenland Ice Sheet and vertical land movement. Based on current observations of the nearshore environment, sea level in Clyde River is thought to be rising, but at a slow rate (D. Forbes, pers. comm. 2010). In addition to rising sea levels, there are projected to be more coastal storms, higher winds and a longer period of ice-free conditions.

These factors cause the south-east section of the community to be at higher risk to coastal inundation (Fig. 3.67). There are culverts that drain from the southeast part of the community under the road to the beach area (Fig. 3.37 and 3.68). If water levels rise, the sea could back up through the culverts and flow into the flat southeast section of the community, flooding the area. Low-lying portions of the terrain south of the road leading to the airport will also be at risk. Due to the projected increases in areas susceptible to flooding and the increased probability of flooding events, the overall risk level for coastal flooding in Clyde River will increase (Fig. 3.69, Table 3.12).

Under projected climate changes there will be more heavy rain events and more rapid snow melt, translating into larger spring freshets and higher river flows. The extent of the increased river flows will be dependent on numerous factors such as snow accumulation, water flow and precipitation patterns. The risk of fluvial flooding will likely increase in the future with an increase in both the level of impact and the likelihood of occurrence. Thus, the risk level associated with fluvial flooding in Clyde River will increase (Fig. 3.69, Table 3.12).

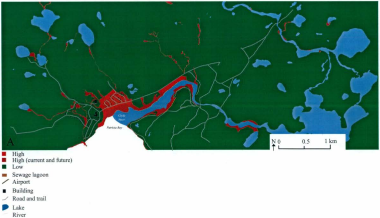
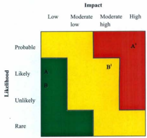


Figure 3.67A Relative risk classification for coastal and fluvial flooding under projected climate changes in Clyde River.

Figure 3.67B Relative risk classification for coastal and fluvial flooding under projected climate changes with the community of Clyde River.

Figure 3.68 View looking south towards Patricia Bay. This culvert currently drains water from the southeast part of town into the beach area. If sea levels rise, during storm events or storm surges, sea water could flow back through this culvert, and others under the road, causing flooding in the lower portions of the community (photo M. Irvine, July 2009).



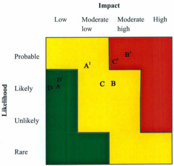
A Coastal flooding
B Fluvial flooding

Figure 3.69 Current risk level for coastal flooding (indicated by letter A) and fluvial flooding (indicated by letter B) and risk level under projected climate changes for coastal flooding (indicated by letter A[1]) and fluvial flooding (indicated by letter B[1]) to infrastructure in Clyde River.

Erosion

In Clyde River under projected climate changes there will be more storm activity, rising sea levels and a decrease in sea ice. It is projected that there will be a larger number and greater magnitude of coastal storms, increasing the likelihood of coastal erosion (ACIA, 2004). As explained in the previous section, sea level in Clyde River is most likely rising. Although the rate of sea level rise will probably be small, rising sea levels, combined with more storm activity, will cause more of the shoreline to be exposed to coastal erosion. In the future, there will be a decrease in the extent and duration of sea ice, and this change is already being observed in Clyde River, causing an increase in the ice free period of the shoreline. These changes will increase the risk level for coastal erosion (Fig. 3.70, Table 3.12).

More frequent heavy rain fall events and stronger spring freshets will increase stream flow rates in the community, increasing the frequency of erosion as well as the rate of erosion. Fluvial and thermal erosion will thus become more of a concern under projected climate changes (Fig 3.70). The extent and duration of snow banks may decrease due to warmer air temperatures, reducing the risk of nival erosion (Fig. 3.70). However, the increases in temperature may be offset by increases in the amount of snowfall, thereby increasing the size and depth of snow banks.

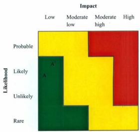


A Coastal
B Fluvial
C Thermal
D Nivation

Figure 3.70 Current risk level for coastal erosion (indicated by letter A), fluvial erosion (indicated by letter B), thermal erosion (indicated by letter C) and nivation erosion (indicated by letter D) to infrastructure in Clyde River. Risk level under projected climate changes for coastal erosion (indicated by letter A^1), fluvial erosion (indicated by letter B^1), thermal erosion (indicated by letter C^1) and nivation erosion (indicated by letter D^1) to infrastructure in Clyde River.

Slope movement

The occurrence of climate-related events that initiate slope movements will become more frequent in the future. For example, it is projected that there will be more periods of heavy rainfall that will saturate sediment, add additional weight, and result in greater depths of thaw penetration, leading to more incidences of slope movements, such as active layer detachments or mudflows (ACIA, 2004). The impacts of increased likelihood and impact of slope movement due to projected climate changes is likely lower than other landscape hazards in Clyde River. Regardless of changes in the climate, in many areas of Clyde River the slope gradient is not steep enough to allow for rapid slope movements such as active layer detachments. Under projected climate change scenarios, the risk level for slope movement will only slightly increase (Fig 3.71, Table 3.12).



A Slope movement

Figure 3.71 Current risk level (indicated by letter A) and risk level under projected climate changes (indicated by letter A') for slope movement to infrastructure in Clyde River.

Chapter 4 Assessment of Research Framework

Chapter 4 presents a critique of the research framework. It examines the accuracy of the research, notably how well the framework assessed landscape constraints; the 2 and implementation of the research in Clyde River; and the transferability and applicability of the research framework to other communities in Nunavut.

4.1 Accuracy of the research

An important component of the assessment of this research framework is to determine how effective it is in identifying and mapping physical landscape constraints in Clyde River. Hazard and risk assessments are inherently subjective and any products are influenced by the perception, experience, knowledge and judgment of the researchers and stakeholders involved. As few studies of a similar nature exist, there is limited opportunity for comparison or reference. Although decisions are based on the best possible science, project outcomes are subjective. Future monitoring of infrastructure issues and maintenance may provide one opportunity to test the accuracy of the framework approach. The overall aim of the framework is to reduce the impact of landscape hazards on community infrastructure and several aspects of the proposed framework that increase the accuracy of the research are discussed below.

Iterative approach

This framework has an iterative approach, which allows project findings and conclusions to be reassessed and modified as necessary. The steps in the framework are revisited, allowing for additions and improvements at each stage in the research. For instance, after the initial field season in Clyde River, ground subsidence related to thermokarst was identified as a key physical landscape constraint in the community. Researchers returned the next summer to conduct permafrost coring in order to improve their understanding of this landscape hazard.

Different types of knowledge

Knowledge of the land and scientific knowledge are utilized and combined in this framework. The two types of knowledge are generally gathered in very different manners and are complementary (Mackinson and Nottestad, 1998). Knowledge of the land commonly has a historical context, passed on through generations and held by people that have a vested interest in the area that they live and depend on. Scientific knowledge is also important, and outside researchers provide a different perspective, skill set, experience and expertise than those of community members. Scientific knowledge can also provide a technical explanation to phenomena and processes that may be recognized by community members, though not necessarily understood. Similarly, scientific knowledge can be collected and analyzed through more quantifiable and testable techniques.

In this project, knowledge of the land, such as the details of historic weather-related events and previous landscape conditions, was critical and could only be obtained through discussions with the people living in the community who have a historical knowledge of the area. Scientific knowledge provided an explanation for the glacial and sea level history and characteristics of landscape conditions. Although both forms of knowledge are valued in this project, time restraints prevented a greater exploration and use of knowledge of the land, and there was a higher use of scientific knowledge. By integrating knowledge of the land with the expertise and skills of researchers, we obtained more comprehensive and applicable results.

4.2 Community acceptance

The overall success of this project is dependent on the community's acceptance of the project and how effective project findings are in guiding decisions regarding infrastructure development and planning. This requires a strong science-policy integration to enable successful dissemination of information and linkage between landscape science, community planning, regional policy, good building practices, and engineering assessments. For risk and adaptation research to benefit communities, researchers need to inform communities of the environmental conditions and issues that are identified by their research. Policy-makers and decision-makers in turn need to integrate these findings and recommendations into community planning and regional policy. Community planners need to ensure that such recommendations are incorporated into on-the-ground planning (Kelly and Adger, 2000; Perotto-Baldiviezo et al., 2004; Ford, 2008).

In order for landscape hazard research to be accepted and implemented into planning decisions, communities need to have both the desire and the capacity for the research. In the Clyde River project, the community expressed strong interest in the research and asked for the project to be conducted. The researchers were welcomed into the community and the community accepted the researchers from the start. Community members showed an interest in project methods and findings and understood the importance and significance of the research.

An important consideration in the success of the research process was that Clyde River had the institutional capacity and human resources to support the research. Ittaq Heritage and Research Centre, a local initiative based in Clyde River, coordinated research in the community. Ittaq acted as a liaison between researchers and the community and facilitated a series of interactions. Ittaq assisted in arranging community presentations, a community feast which included posters and informal discussions of research, meetings with the Elders and Hunters and Trappers Association, as well as the hiring of local field assistants and guides. This partnership allowed researchers to collaborate with the appropriate residents. Having a contact such as Ittaq was critical to the success of this northern research project, especially in light of cultural, social, economic and language differences. With the increasing quantity of climate change research in many northern communities, and the feeling of research/consultation fatigue felt by some communities, it is critical that communities both want and can cope with the research.

A focus on community interactions also increases the potential acceptance of the results and the probability that the research will be utilized, as local stakeholders feel they have contributed to the project (Cronin et al., 2004). The framework developed in this study stresses the importance of community interactions at all project stages, not just at project commencement and termination. Local stakeholder input is recognized as critical in determining project scope and direction. Results are relayed back to the community at multiple points during the project, both to inform the community of the findings and to receive community input and suggestions. Multiple community interactions increase the appropriateness and applicability of the research and allow project findings to be more easily incorporated into community planning and infrastructure development decision-making.

Measuring the impact of this framework and its results can be assessed through examination of how regional and local planners integrate the findings into their community plans for Clyde River. Community plans are updated every 5 years in Nunavut and this represents an opportunity to assess the level of adoption of planning constraints imposed by landscape hazards into the next planning exercise. An important part of the planning update is community consultations. At these meetings community members voice their opinions of various aspects of the draft revised plan. Considering public awareness in the project, it would be useful to gauge how community members perceived planning constraints associated with landscape hazards in relation to other land use exclusions and factors discussed in the context of land rezoning and priority areas for development.

4.3 Transferability and applicability of framework

A goal of this thesis is to assess the transferability and applicability of this research framework to other communities in Nunavut, and arctic communities in general. The physical and social geography of Nunavut communities highlights the need for risk, adaptation and hazard assessment projects. Previously, much of this style of research has focused on non-arctic environments (Petley, 1998; Cabuk, 2001). This work contributes to bridging this gap by assessing the risk and hazard fields in an Arctic community context

In Clyde River, slope movements related to gravity are not a significant concern. However, in other communities this landscape hazard is more dominant. For instance, the community of Arctic Bay, Nunavut, is surrounded by and built right up to the base of steep slopes on three sides with a beach on the other. The hills behind the community show evidence of slope instability, such as active layer detachments, slides and rock falls. Increases in snowmelt rate and rainfall are projected for the area, which will increase the risk of slope failures. In addition, future development is planned for areas of higher relief, exposing them to higher risks of slope failures (Ford et al., 2007). Thus, for Arctic Bay, the landscape hazard assessment would need to be modified to have a greater emphasis on slope related hazards, including field and laboratory activities that would assess the sensitivity of slope failure in detail. One example would be to use geophysics and GIS modeling to assess the subsurface properties of sediments and rock to determine which areas might be more prone to slope failures such as debris flows or active layer detachments (Kneisel and Rothenbuhler, 2007).

Sea level rise is currently not a major concern in Clyde River. However, in other communities such as Cambridge Bay and Kugluktuk sea level may rise as much as 50 cm by 2100 (James et al., 2009). In these communities, the research framework must be modified beyond simple sea level modeling to have a larger focus on assessing coastal sensitivity. Field activities could include an assessment of fall storms, fetch, sea ice conditions and extent, shoreline usage, tidal patterns and vertical land motion monitoring.

Other challenges to this framework (explained below) do not prevent the application of this framework to other communities, but should be considered before it is implemented.

Time requirement

Time is required to properly conduct the research and to ascertain accurate findings. As this type of assessment has consequences for people living in the communities, a quick process that does not take into account contextual conditions, including socio-economic factors, is not likely to be accepted and will thus not be successful or beneficial. As learnt in this Clyde River case study, a positive working relationship with the community is necessary for project success, which takes time and energy to develop. Interactions with the community should occur on multiple occasions to ensure the input of the community is properly understood and incorporated, and that the project results are appropriately transmitted back to the community. As previously stated, openness of community is key to this project.

Resources

The scientific expertise and equipment resources required for application of this framework generally do not exist in communities and must be brought in. To properly execute this framework, certain knowledge, such as an understanding of the glacial and sea level history, and skills such as surficial mapping are required. This is typically developed through formal training and years of experience. Fieldwork requires tools not available in the communities and may require experience to use. For instance, permafrost coring was demonstrated to be a vital component of the Clyde River project. The drill used to extract permafrost cores is highly specialized and built for permafrost conditions. Currently no such drill exists in Nunavut and must be flown in. The analyses of the permafrost cores also require specific technology such as CT-scanning, which cannot be conducted in any facility in Nunavut. Successful project completion is therefore dependent on outside expertise and support.

Chapter 5 Conclusions

This chapter summarizes the project results. The chapter begins by describing the key research findings. The potential future research initiatives are explored, and there are suggestions as to how this project could be improved and taken to the next step. The chapter concludes with ways this thesis contributes to other projects and to the broader fields of risk and adaptation assessment in the Arctic.

5.1 Summary of key findings and conclusions

The main research objectives of this thesis were to:

(1) Devise a research framework that assesses the nature and spatial extent of landscape hazards on infrastructure planning and development in Nunavut communities as they exist today, and under projected climate change scenarios.

(2) Test the developed framework in a Nunavut community to gauge its effectiveness, level of community acceptance, accuracy in delineating landscape risks, and potential application to other arctic communities.

A multi-hazard research framework was developed to assess planning constraints imposed by the physical environment and tested in Clyde River. This process allowed for the key research questions to be addressed.

– *What types of landscape hazards impact infrastructure development in the Arctic?*

This thesis found that flooding, erosion, slope instability and permafrost dynamics (ground heave and subsidence) are the key hazards active in Clyde River, and that these hazards are likely to occur but may not be the dominant ones in other Arctic communities. The spatial distribution of these hazards is variable and is a function of the physical environment and human modifications to the landscape. Permafrost conditions underlie most communities in Nunavut and its dynamic nature of results in a specific set of landscape hazards. These include slope movements such as gelifluction and active layer detachments, and the growth of buried ice lenses, and ground subsidence related to thermokarst.

- *How will landscape hazards change under projected climate changes?*

Under climate change projections the risk of current landscape hazards will largely be magnified. Based on recently observed environmental changes in Clyde River and projections for the future, there will likely continue to be changes in the timing, type and intensity of precipitation, ocean temperatures, storm activity, sea ice conditions, air temperature and wind speed and direction. These environmental changes will translate into an overall increase in the likelihood and severity of current landscape risks.

- *What infrastructure adaptations and maladaptations are used in arctic communities, and what are the implications for landscape and community development?*

Both adaptations, which diminish a landscape risk, and maladaptations which enhance the risk, exist in Nunavut communities. Adaptations in Clyde River include buildings foundations modified for permafrost terrain, such as houses built on adjustable foundation types and the use of thermosiphons. Maladaptations also exist: an example includes building pads constructed from of fine-grained material (silty sand) which is easily washed away by precipitation events and snowmelt-generated runoff. Another example of a maladapation is poorly maintained culverts. Silt, sand, and garbage had infilled many culverts, and heavy machinery has crushed others, causing water pooling and ground subsidence. The different methods of slope stabilization techniques in Clyde River have ranging levels of effectiveness. On a sandy slope in the center of town along the coast, crushed oil drums were installed to prevent erosion. However, surface water flow is still causing erosion, and the oil drums are having little or no positive affect. Gabions filled with cobbles are stabilizing a slope in the central section of Clyde River, and sediment is not being removed.

Research in Clyde River highlights the importance of considering the impacts of infrastructure development on different parts of the community. This is exemplified in the Clyde River case study where new infrastructure developments are directing water into older portions of the community that lack adequate drainage infrastructure to handle increased flows. This is causing physical and thermal erosion, resulting in water pooling and ground subsidence.

- *What modifications to landscape hazard assessments must be employed to ensure they are applicable and appropriate for arctic communities?*

Standard landscape hazard frameworks must be modified to match the unique conditions and characteristics of arctic communities. To ensure that the range of landscape hazards occurring in specific environment is included, the framework needs to remain flexible. This allows the appropriate field and laboratory activities to be conducted and to capture and place emphasis on the appropriate landscape hazards within specific planning contexts. For instance, in the Clyde River research, after initial field research in the community, it was determined that permafrost coring would be required to have a proper understanding of the ground conditions and the susceptibility to ground thaw. In addition, standard methods of communication were not suitable to inform residents of research findings, and both the style and the method of presenting information were modified to match the needs of residents.

– *How can the risk level for specific landscape hazards be mapped and ranked?*
Environment variables that allow for the formulation of landscape risks were identified, assessed and mapped. For example, slope and sediment grain size were measured in order to understand and map the risk level for slope movement and erodability. For each hazard studied in this research, key variables that contribute to the hazard were identified and delineated. This allowed for the creation of risk maps for individual landscape hazards.

For this framework, a risk matrix was used to rate the general risk level associated with specific landscape hazards. This matrix assesses the likelihood of occurrence and the severity of impact to determine a risk level for a specific hazard. The risk level was assigned as low, moderate or high. The risk matrix had positives and negatives. Compared to other risk matrices that have more categories, this matrix had the advantage of only three risk level categories, which made the matrix easy to understand. However, having only three risk levels prevented the ability to distinguish between more than three risk levels, leading to the potential to over-simplify the results. Another benefit of this matrix is that the language did not install fear, compared to other matrices that use words such as "extreme" or "catastrophic" in reference to high risk. Using such terms can give the impression that for a risk to be classified as "high" it needs to be, or cause, a catastrophic event such as a large landslide.

There were advantages with using a matrix to describe risk level compared to other methods. The risk level, and how the risk level may change, was clearly shown, and it does not take experience or any special expertise to interpret the result. However, one main disadvantage is that it does not allow of the level of uncertainty to be shown, which can readily be shown in other methods such as statistics.

- *How can hazard mapping be presented and communicated in a manner appropriate for people with different cultural and educational backgrounds?*

The presentation of the hazard map is critical to ensuring that it is understood and utilized by its intended users. For this thesis and the framework it employs, the hazard map needs to be understood by local residents, community planners, social scientists and physical scientists, all of whom have different educational, social and cultural backgrounds. The hazard map was presented in a non-technical manner, using a simple three colour scheme of red, yellow and green to represent areas of high, medium and low cumulative risk.

In order to ensure the communication was appropriate for Clyde River, written and oral information was presented in Inuktitut and English, and there was a strong reliance on visuals in posters and presentations. In addition, the delivery method of the research varied, and included community presentations and small group meetings where there was the opportunity for questions, comments and discussions. Research findings were also presented at a community feast to which most residents attended. During this feast, posters in English and Inuktitut were displayed, and members of the research team served food to community members. This allowed for informal discussions and questions.

5.2 Next steps

Expanding individual sections of the framework in order to provide a more in-depth landscape hazard assessment could augment this research. These are outlined below.

Multiyear monitoring

This research would have benefited from a greater period of field study and monitoring. While this thesis focuses on assessing current conditions, the environment in Nunavut is constantly changing; a process that may become magnified in the future due to anthropogenic climate change (ACIA, 2004). Community monitoring of key parameters at a multi-year scale would allow for an understanding of how and at what pace the local environment is changing, and engage the community which may increase the likelihood of considering this research in community planning and decision making. Potential environmental parameters to be measured include: annual ground temperature changes within and below the active layer, snow drifting patterns, relative sea level change, wind direction and speed, impact of storms and rates of ground heave and thaw. The monitoring of infrastructure changes, such as the seasonal movement of building foundations, the effectiveness of culverts during periods of high water flow, and the level of required infrastructure maintenance would also have been beneficial (Nelson et al., 2001; Couture et al., 2003). Monitoring would allow the research to go beyond assessing current conditions to provide a more accurate understanding of the potential impact of changes in climate dependent parameters.

Data uncertainties

The mapping techniques in this research did not take into account the uncertainties, errors or transitions between the boundaries of mapped units. In geological and risk mapping, error regarding the delineation of units can stem from a range of sources, including the level of detail that was mapped, accuracy of digitization and unit definition (Kennelly, 2002). For example, delineating the exact boundary between areas of high or low ground ice is impossible as ice content is regarded as spatially heterogeneous. One method to deal with this uncertainty is to create a buffer or transition zone around the boundaries of units (Kennelly, 2002). The width of the transition zone should vary based on the error associated with defining the unit, and may be abrupt or gradual (Greve and Greve, 2004). For example, along the mapped boundaries of the extent of fluvial flooding, a buffer of a set amount of metres would allow for a transition zone between areas of high and low flooding risk.

Community values

A theme not included in this research is the importance and role of community values. Indigenous peoples living in the Arctic typically have a close connection to the land, with their way of life strongly linked to the environment. Interaction with the environment is often based on an array of factors, including spiritual and cultural values (Huntington and Fox, 2005). A community's cultural values may not agree with the suitability of the landscape for development based on landscape hazards, but this factor may trump other considerations. As such, this research could have benefitted from the addition of a community value layer, which shows how cultural and social concerns may constrain development, or weights particular areas more favourably over others. For example, in Clyde River residents do not want to live out of sight of the rest of the community, or too far from the town center which houses key infrastructure such as the school and grocery store. Thus, while extensive areas of low development risk occur some distance north of the present community, it is unlikely that these will be settled owing to cultural and access considerations. Similarly, cultural values may push development into areas deemed less desirable in the landscape hazard model, necessitating greater mitigation and engineering adaptation in order to ensure sustainability.

Data coverage

Multiple tools were used to collect different datasets in this project. The density and spatial extent of data gathered from different field methods were dissimilar, with certain methods covering a larger area, or having a higher resolution. For example, in

Clyde River time constraints confined topographic surveying to the area directly around current development. Instrumental limitations precluded permafrost coring from terrain conditions that had large particle sizes (e.g., cobbles or boulders) or high surface moisture (e.g., the wet sedge meadow blanketing the terrace east of the town and north of the road). As such, data coverage for these field investigations was not as extensive as other datasets, such as surficial mapping. Additional fieldwork activities would aid in resolving this issue, as explained below.

Additional data

The accuracy of data interpretation would be increased with a higher resolution of data points and additional data sources. For example, in this project permafrost coring provided good point data on ground conditions. From these cores, variables such as salinity, ground ice, chemical composition and sediment texture were assessed. However, there is uncertainty regarding the interpolation of ground conditions beyond the permafrost core sites. Geophysical techniques such as ground penetrating radar or capacitively-coupled resistivity could be used to provide sub-surface images and to delineate changes in ice, sediment and other variables (Hauck and Kneisel, 2006; De Pascale et al., 2008; Wu et al., 2009; LeBlanc et al., 2010). These techniques would augment the interpolation and decrease the uncertainty of the terrain conditions between permafrost coring sites. In addition, because of their operability, these techniques could be used to provide a much more extensive and inclusive survey of permafrost conditions, including areas in which permafrost coring was not feasible.

5.3 Contributions

5.3.1 Enhancing Resilience in a Changing Climate Program

The research for this thesis was not conducted in isolation. This thesis was undertaken as part of an NRCan project in the "*Enhancing Resilience in a Changing Climate Program.*" The project included research initiatives in Clyde River that aimed to augment the community's capacity to live in a changing environment and provide guidance to decision making. Research focused on assessing the community's drinking water supply, sea level change, coastal and nearshore processes, vegetation characteristics and landscape hazards. Project results in the form of maps, posters and reports in English and Inuktitut are in the process of being summarized and reported back to the community. In addition, Geological Survey of Canada (GSC) publications will be written for each sub-project, focusing on methodology and results. Together, this research provides scientific information on current conditions and the implications of future changes in the Clyde River environment, with a particular focus on those associated with climate change.

This thesis principally addresses the overall project goals through the creation of a composite landscape hazard map. This map shows which areas, based on the physical environment, are suitable for community development, which areas pose moderate constraints, and which areas pose high constraints. How these landscape constraints may change under projected climate change scenarios is also explored. This information provides the community, planners and other decision makers with a practical tool that can provide guidance to planning of future development and the maintenance of current infrastructure.

During this project, a partnership was formed with the Collaborative for Advanced Landscape Planning (CALP), which is based at the University of British Columbia. A focus of CALP is to tie together science and planning at the community level, and to use visualization in order to plan for a changing climate. CALP is in year two of a three year GEOIDE (GEOmatics for Informed DEcisions Network) project in Clyde River. This project will create maps and other visualization materials for the community that shows what the community could look like in the future under different development scenarios (CALP, 2010). The research presented in this thesis is providing information on landscape conditions and risks that will feed into CALP's project, which will increase the accuracy of the visualizations.

5.3.2 CAVIAR

This project also contributes to the International Polar Year project CAVIAR (Community Adaptation and Vulnerability in the Arctic Regions) project. An aim of CAVIAR is to gain a better understanding of how people living in the Arctic are affected by environmental changes, and to provide guidance to adaptation strategies and polices (cf., Ford and Smit, 2004). Although this research project focuses on hazard and risk assessment for planning and development, it contributes to an understanding of overall community health and human security, and links risks associated with a changing landscape to other aspects of vulnerability.

This project contributes to the goals of CAVIAR by contributing a vulnerability assessment on community development and infrastructure. Compared to other CAVIAR projects, this is the only case study providing an in-depth assessment of the interactions between the physical environment and hard infrastructure. This project shows that infrastructure vulnerability is a function of processes occurring in the physical environment and the characteristics of the infrastructure and community development. For instance, permafrost melt will lead to ground subsidence, with melt dependent on parameters such as ground salinity and ice content. The implications of this ground subsidence for infrastructure will depend on infrastructure adaptations, such as the use of adjustable building foundations.

5.3.3 Community contributions

This research provides practical and useful information on physical landscape constraints that can be used by decision makers in Clyde River to direct landuse planning and community development. Currently, there is limited incorporation of the physical environment in the decision making process with respect to infrastructure in the community. The research also provides an indication of how the landscape will change in Clyde River due to climate change, and what this will mean for landscape risks in the community. This thesis provides a contribution to Nunavut communities in general if this research framework is applied elsewhere. This would allow for an understanding of physical landscape constraints, and the implications on infrastructure in other communities, which could be compared and contrasted to findings of this study. This research also adds to the risk and vulnerability literature in light of climate change in the Arctic.

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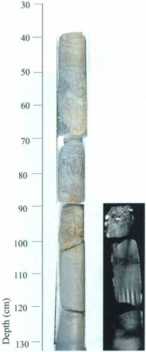
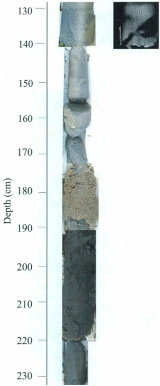
Appendix A: Permafrost core logs





Depth (cm)
130
140
150
160
170
180
190
200
210
220
230

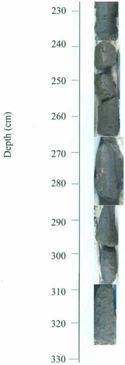


Figure A.1a Photography (left) and CT-scan (right) of core 1.

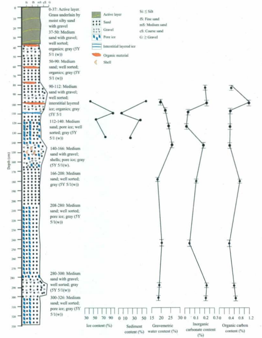
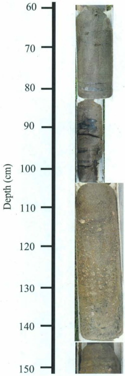


Figure A.1b Composite stratigraphic log with structural and sediment properties of core 1. The ⊼ symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.


Depth (cm)
60
70
80
90
100
110
120
130
140
150

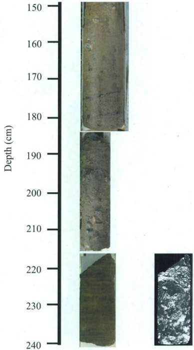
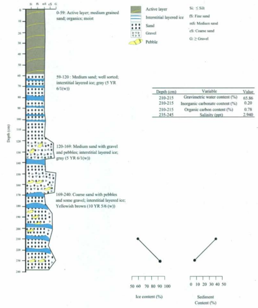


Figure A.2a Photography (left) and CT-scan (right) of core 2.



Depth (cm)	Variable	Value
210-215	Gravimetric water content (%)	65.86
210-215	Inorganic carbonate content (%)	0.20
210-215	Organic carbon content (%)	0.78
235-245	Salinity (ppt)	2.940

Figure A.2b Composite stratigraphic log with structural and sediment properties of core 2.

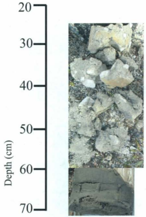


Figure A.3a Photography of core 3.

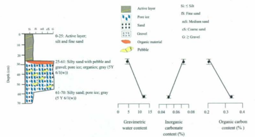
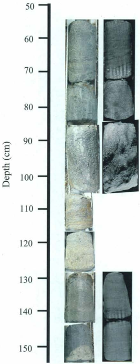


Figure A.3b Composite stratigraphic log with structural and sediment properties of core 3. The ⧗ symbol represents the stratigraphic depth over which the sample was collected.


50
60
70
80
90
100
110
120
130
140
150
Depth (cm)

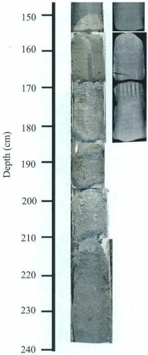


Figure A.4a Photography (left) and CT-scan (right) of core 4.

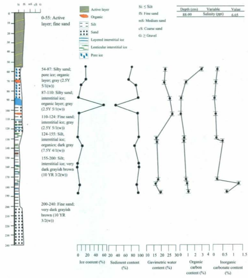


Figure A.4b Composite stratigraphic log with structural and sediment properties of core 4. The symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.

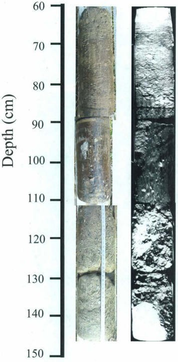


Figure A.5a Photography (left) and CT-scan (right) of core 5.

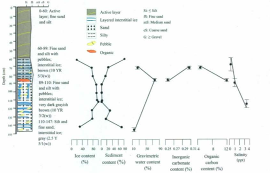


Figure A.5b Composite stratigraphic log with structural and sediment properties of core 5. The ⧗ symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.

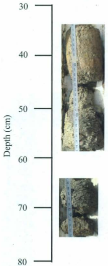


Figure A.6a Photography of core 7.

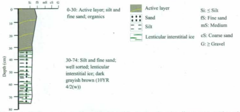


Figure A.6b Composite stratigraphic log with structural and sediment properties of core 7.

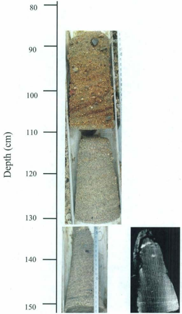


Figure A.7a Photography (left) and CT-scan (right) of core 9. During core drilling, certain segments were eroded by circulating fluids, resulting in a triangular shape.

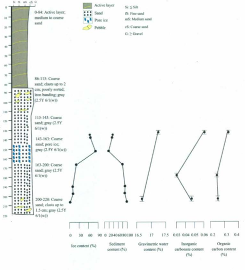


Figure A.7b Composite stratigraphic log with structural and sediment properties of core 9. The ⌶ symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.

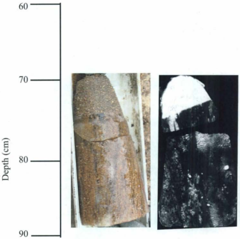


Figure A8a Photograph (left) and CT-scan (right) of core 10.

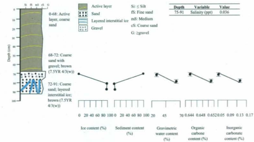


Figure A.8b Composite stratigraphic log with structural and sediment properties of core 10. The ⫪ symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.

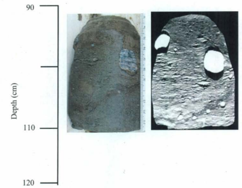


Figure A.9A Photography (left) and CT-scan (right) of core 11.

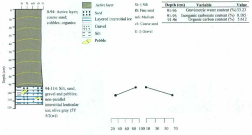


Figure A.9b Composite stratigraphic log with structural and sediment properties of core 11.

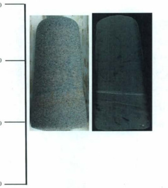


Figure A.10a Photograph (left) and CT-scan (right) of core 12.

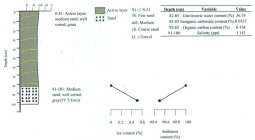
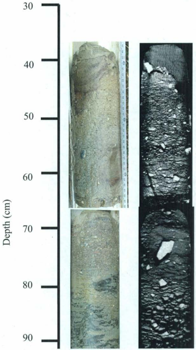
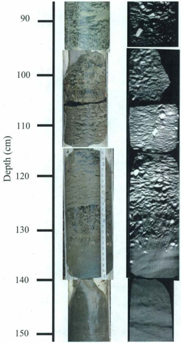


Figure A.10b Composite stratigraphic log with structural and sediment properties of core 12.


30
40
50
60
70
80
90
Depth (cm)



90
100
110
120
130
140
150
Depth (cm)

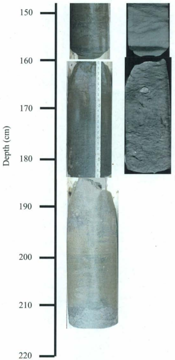


Figure A.11a Photography (left) and CT-scan (right) of core 13.

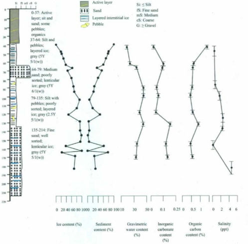
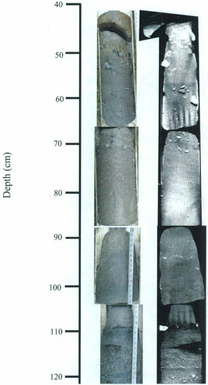


Figure A.11b Composite stratigraphic log with structural and sediment properties of core 13. The ⌶ symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.


Depth (cm)
40
50
60
70
80
90
100
110
120

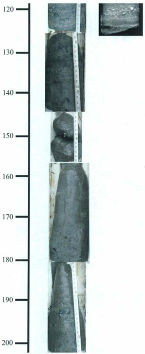


Figure A.12a Photography (left) and CT-scan (right) of core 14.

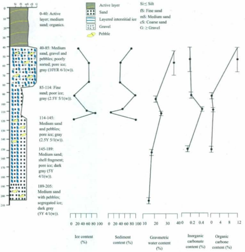


Figure A.12b Composite stratigraphic log with structural and sediment properties of core 14. The ⫫ symbol represents the stratigraphic depth over which the sample was collected. Sediment and ice content samples were point data.

Appendix B: Permafrost core sample data

Table B.1 Structural characteristics of sediment cores

Core #	Depth (cm)	Sediment content (%)	Ice content (%)	Air content (%)
1	93.00	56.00	43.00	1.00
1	105.00	4.00	96.00	0.00
1	112.00	44.00	56.00	0.00
1	130.00	23.00	78.00	0.00
4	55.00	80.50	19.50	0.00
4	68.00	71.80	20.20	8.00
4	74.00	91.15	8.85	0.00
4	87.00	97.35	2.65	0.00
4	95.00	37.60	62.40	0.00
4	103.00	96.05	3.95	0.00
4	128.00	99.00	1.00	0.00
4	137.00	88.00	12.00	0.00
4	155.00	99.00	1.00	0.00
4	159.00	100.00	0.00	0.00
4	177.00	94.00	6.00	0.00
4	186.00	98.00	2.00	0.00
5	60.00	79.00	19.00	1.43
5	70.00	23.00	75.00	1.11
5	80.00	13.00	79.00	5.00
5	90.00	0.00	92.00	7.00
5	100.00	0.00	93.00	6.00
5	109.00	1.00	95.00	3.00
5	111.00	0.00	100.00	0.00
5	121.00	28.70	76.10	0.00
5	131.00	14.70	77.36	8.50
5	141.00	69.44	30.56	0.00
9	134.50	36.00	63.90	0.00
9	138.00	33.00	66.00	1.00
9	152.00	18.00	82.00	0.00
9	167.00	79.00	21.00	0.00
9	190.00	90.00	10.00	0.00
9	198.00	89.00	11.00	0.00
9	207.00	98.00	2.00	0.00
10	71.00	99.00	1.00	0.00
10	81.00	1.00	98.00	1.00
10	87.00	3.00	97.00	0.00
11	95.00	10.00	90.00	0.00
11	104.00	67.00	33.00	0.00
12	97.00	99.50	0.50	0.00
13	40.00	100.00	0.00	0.00
13	48.00	80.00	19.00	1.00
13	50.00	78.00	22.00	0.00

13	92.00	23.00	71.00	5.00
13	99.00	7.00	91.50	1.40
13	108.00	19.50	80.50	0.00
13	116.00	47.19	48.31	4.49
13	124.00	4.26	92.55	3.19
13	129.00	6.45	93.55	0.00
13	142.50	1.30	98.70	0.00
13	150.00	5.62	94.40	0.00
13	155.00	61.70	38.00	0.00
13	160.00	0.00	100.00	0.00
13	162.00	77.50	22.50	0.00
13	167.00	26.00	74.00	0.00
13	182.00	30.00	70.00	0.00
14	45.00	78.00	22.00	0.00
14	60.00	37.50	62.00	0.00
14	80.00	35.90	63.00	1.00
14	94.00	92.30	8.00	0.00
14	109.00	45.65	54.35	0.00
14	112.00	3.00	87.00	10.00
14	119.00	93.40	6.60	0.00

Table B.2 Gravimetric water content and sedimentary characteristics of permafrost cores.

Site #	Depth range (cm)	Gravimetric water content (%)	Inorganic content (%)	Organic content (%)	Pebble or coarse (%)	Granule (%)	V. coarse sand (%)	Coarse sand (%)	Med. sand (%)	Fine sand (%)	V. fine sand (%)	Silt or finer (%)
1	71-76	-	0.188	0.396	0.00	0.00	0.28	0.42	10.06	21.67	55.10	12.46
1	90-94	19.86	0.256	1.136	10.04	2.92	4.20	8.76	13.14	13.32	1.09	46.53
1	100-104	22.48	0.032	0.332	0.00	1.72	0.16	1.09	2.34	25.42	57.24	12.03
1	116-120	23.59	0.015	0.348	0.00	0.00	0.19	1.54	2.70	26.40	60.69	8.48
1	135-140	26.90	0.195	0.340	0.00	0.00	0.00	0.38	1.69	10.15	61.28	26.50
1	175 - 178	18.13	0.118	0.745	3.70	2.28	1.42	3.99	5.70	8.55	28.49	45.87
1	241 - 248	20.60	0.049	0.301	0.00	0.00	0.18	0.53	1.05	11.75	64.21	22.28
1	289 - 293	19.18	0.235	0.510	0.00	0.45	0.22	0.22	1.12	9.15	45.09	43.75
1	306 - 309	18.92	0.198	0.544	0.00	0.34	0.86	1.20	1.72	12.05	46.64	37.18
2	210-215	65.86	0.191	0.557	-	-	-	-	-	-	-	-
3	25-30	4.56	0.073	0.221	55.67	1.56	2.56	5.22	6.56	6.33	5.11	17.00
3	62-65	12.02	0.054	0.316	4.55	1.82	1.82	5.45	10.91	15.45	12.73	47.27
4	102-105	26.27	0.159	0.557	0.00	0.00	0.19	2.08	10.00	14.34	23.96	49.43
4	127-130	14.85	0.191	0.982	0.00	0.00	0.21	0.21	0.84	0.84	2.74	95.15
4	145-149	15.26	0.505	0.916	0.00	0.00	0.12	0.48	1.45	4.11	13.06	80.77
4	168-172	16.21	0.210	1.150	0.00	0.00	0.12	0.58	1.64	2.57	12.51	82.57
4	173-176	14.38	1.347	1.279	0.00	0.00	0.12	1.05	2.81	3.63	12.40	80.00
4	184-186	17.60	0.686	1.377	0.00	0.00	0.14	0.57	2.27	3.55	19.01	74.47
4	54-58	21.23	0.195	3.145	19.88	0.58	1.32	4.53	11.40	19.01	35.53	7.75
4	69-72	20.40	0.123	1.095	0.00	0.00	0.26	2.11	9.51	25.89	27.08	35.14
4	85-89	24.44	0.071	0.572	1.05	0.42	1.47	4.63	11.79	22.32	46.53	11.79
5	70-73	28.19	0.306	5.067	6.84	4.10	11.13	11.13	15.43	19.73	10.74	20.90

5	85-89	74.48	0.256	11.580	0.00	5.71	5.71	11.43	14.29	18.57	12.86	31.43
5	110-115	-	-	-	21.46	3.43	4.29	8.15	14.16	15.45	10.30	22.75
5	145-148	16.72	-	-	2.99	2.24	5.22	8.96	17.16	17.91	13.43	32.09
9	130-134	17.21	0.058	0.315	7.46	2.99	6.97	23.13	36.07	19.90	1.99	1.49
9	175-180	-	0.030	0.247	7.65	8.31	15.47	30.13	23.78	10.59	1.47	2.61
9	200-205	16.72	0.047	0.254	11.36	12.55	22.62	38.31	12.55	2.16	0.22	0.22
10	91-96	33.23	0.185	5.612	-	-	-	-	-	-	-	-
11	69-73	33.22	0.052	0.646	-	-	-	-	-	-	-	-
11	81-86	58.3	0.142	0.653	24.41	0.79	0.79	2.36	5.12	11.02	18.11	37.40
12	82-85	36.75	0.154	0.054	0.00	0.61	0.61	5.79	47.56	33.54	5.49	6.40
13	100-105	45.58	0.098	0.439	0.00	0.00	0.74	2.07	4.73	14.20	24.26	53.99
13	120-125	39.44	0.071	0.572	3.16	2.46	3.51	7.02	11.93	14.04	20.00	37.89
13	135-140	45.98	0.215	0.901	6.25	0.00	0.00	0.63	2.50	5.63	36.25	48.75
13	160-163	35.43	0.171	0.447	0.00	0.49	0.24	0.24	0.73	9.73	64.72	23.84
13	175-179	33.79	0.181	0.526	0.00	0.00	0.00	0.23	1.36	7.27	50.91	40.23
13	40-44	19.35	0.056	1.389	0.00	0.17	0.34	0.50	0.84	9.92	54.45	33.78
13	61-64	24.53	0.141	0.663	9.44	3.86	6.01	9.23	12.66	10.94	11.37	36.48
13	64-67	34.12	0.148	0.591	1.31	7.09	10.50	17.59	20.21	12.60	9.45	21.26
13	91-95	45.37	0.077	0.542	5.35	6.42	5.35	9.36	13.64	13.37	12.30	34.22
14	40-47	37.53	0.188	11.790	31.03	2.46	3.94	7.88	10.84	11.82	15.27	16.75
14	90-94	21.65	0.204	0.016	0.00	0.87	2.03	3.78	5.52	22.38	47.09	18.31
14	105-110	25.38	0.522	1.006	2.87	3.89	8.45	15.03	19.43	15.03	12.33	22.97
14	148-152	17.48	0.156	0.467	2.47	1.14	2.66	10.82	17.08	19.54	23.34	22.96

Table B.3: Pore water salinity values poor water extracted from permafrost cores

Site	Depth range (cm)	Salinity EC (mS)	Salinity (ppt)
2	235-245	4.200	2.940
4	88-99	9.500	6.650
5	60-73	0.538	0.377
5	85-95	1.470	1.029
7	110-120	4.567	3.197
9	175-7	0.670	0.469
9	210-218	3.590	2.513
10	75-91	0.051	0.036
13	81-100	1.630	1.141
13	43-52	0.628	0.440
13	94-105	2.535	1.775
13	82-91	0.907	0.635
13	120-130	3.490	2.443
13	135-140	3.470	2.429
13	151-162	0.145	0.102
13	175-190	6.350	4.445

Table B.4: Anion values of sub-samples taken from sediment cores

Site #	Depth range (cm)	F (ppm)	Cl (ppm)	SO_4 (ppm)	Br (ppm)	NO_3 (ppm)
2	235-245	< 0.1	854	148.1	2.9	< 0.2
2	235-245	< 0.1	1185	193.8	4.2	0.2
2	235-245	< 0.1	1195	184.5	4.3	0.2
4	88-99	0.7	2510	475.0	8.9	< 0.2
5	85-95	< 0.1	418	16.8	3.1	< 0.2
7	110-120	0.1	893	17.6	10.3	< 0.2
7	110-120	< 0.1	872	16.1	11.5	< 0.2
7	110-120	0.2	1946	138.8	9.9	< 0.2
10	75-91	0.02	5.55	1.35	0.14	0.07
10	75-91	0.02	4.99	1.31	0.16	0.26
10	75-91	0.02	19.06	3.54	0.22	0.16
13	94-105	< 0.1	772	9.8	4.2	< 0.2
13	82-91	0.06	225	11.44	2.53	0.30
13	120-130	< 0.1	979	30.8	4.1	< 0.2
13	135-140	< 0.1	881	123.4	3.4	< 0.2
13	175-190	0.8	1567	298.9	5.7	< 0.2

Table B.5: Carbonate content values from poor water extracted from permafrost cores

Site #	Depth range (cm)	$CaCO_3$ (ppm)
2	235-245	9
4	88-99	41
7	110-120	32
10	75-91	< 1

Table B.6: Cation compositions of poor water extracted from permafrost cores

Site #	Depth range (cm)	Ca (ppm)	Cl (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	Mn (ppm)	Na (ppm)	P (ppm)	S (ppm)	Si (ppm)
2	235-245	38.6	872	< 0.05	20.7	77.90	0.42	434.3	< 0.5	48.1	2.7
2	235-245	58.7	1184	< 0.05	23.4	111.66	0.58	556.4	< 0.5	61.3	2.9
2	235-245	61.3	1188	< 0.05	21.8	112.54	0.52	558.8	< 0.5	58.9	2.1
4	88-99	78.0	2468	< 0.05	97.4	190.21	0.34	1402.8	< 0.5	152.8	5.9
5	60-73	8.05	115.8	1.351	5.45	7.778	0.036	45.14	0.06	6.08	8.67
5	85-95	24.70	415.7	28.508	11.47	41.142	0.138	151.17	0.19	8.47	4.10
7	110-120	43.5	933	8.25	20.7	92.99	0.23	323.1	< 0.5	9.3	2.8
7	110-120	45.5	903	7.98	21.4	97.35	0.27	336.9	< 0.5	9.0	3.7
9	175-187	29.07	124.6	0.039	7.81	10.825	0.085	58.72	< 0.05	13.09	3.63
9	210-218	5.99	24.1	0.153	3.12	2.084	0.029	13.60	< 0.05	4.94	2.44
10	75-91	0.85	5.7	0.011	0.53	0.378	0.027	2.65	< 0.05	0.29	0.17
10	75-91	0.67	5.0	0.029	0.47	0.271	0.017	2.48	< 0.05	0.31	0.24
10	75-91	1.77	19.6	0.017	0.99	1.188	0.100	9.71	< 0.05	1.05	0.32
13	81-100	46.45	288.5	114.562	14.79	20.693	1.166	24.27	0.05	60.04	11.08
13	43-52	24.40	140.3	0.168	13.83	15.234	0.425	31.99	< 0.05	5.39	10.21
13	94-105	133.1	763	< 0.05	10.8	133.54	2.66	73.7	< 0.5	3.6	2.0
13	94-105	109.3	629	0.09	10.9	106.22	1.99	67.1	< 0.5	4.3	2.7
13	82-91	40.13	227.2	0.856	12.24	31.682	0.646	36.24	0.12	4.57	5.77
13	120-130	100.1	962	< 0.05	18.2	117.00	1.86	282.8	< 0.5	9.8	3.9
13	135-140	48.8	903	0.06	22.5	69.64	0.26	434.7	< 0.5	39.7	5.8
13	151-162	71.1	778	< 0.05	30.8	65.49	0.39	465.9	< 0.5	132.4	3.6
13	175-190	66.9	1572	< 0.05	58.7	98.84	0.08	934.6	< 0.5	98.2	2.7