A Method for Assessing Coastal Vulnerabilities to Climate Change within an Arctic Community: The Example of Tuktoyaktuk, Northwest Territories

By

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Submitted in partial fulfillment of the requirements for the degree
of
Master of Marine Management

at

Dalhousie University
Halifax, Nova Scotia

August 2013

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List of Abbreviations

ACIA	Arctic Climate Impact Assessment
CIS	Coastal Information System
CVI	Coastal Vulnerability Index
DB	Dissemination Block
DEW	Distance Early Warning
GIS	Geographic Information Systems
GSC	Geological Survey of Canada
GSC-A	Geological Survey of Canada – Atlantic
ICZM	Integrated Coastal Zone Management
IFA	Inuvialuit Final Agreement
NTCL	Northern Transportation Company Limited
NWT	Northwest Territories
PEI	Percent Excess Ice
PIV	Percent Ice Volume
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples

Abstract

Beveridge, L., 2013. A method for assessing coastal vulnerabilities to climate change within an Arctic community: The example of Tuktoyaktuk, Northwest Territories [graduate project]. Halifax, NS: Dalhousie University.

Climate change is posing problems to people throughout the world, but due to the biophysical and socioeconomic characteristics of indigenous Arctic communities, they are some of the most vulnerable in the world. Vulnerability assessments have been conducted on the Arctic region as a whole, as well as for specific communities, providing information for international, national, and territorial managers. Missing, though, is an assessment of the geospatial distribution of coastal vulnerabilities within a community, which would guide decision-making at the local level. This study aimed to create a method that would combine multiple forms, sources, and types of data and information following the principles of integrated coastal zone management and under the guidance of the Arctic Climate Impact Assessment. A coastal vulnerability index was based on 27 indicators of socioeconomic and biophysical exposure, sensitivity, and adaptive capacity. Through a case study of Tuktoyaktuk, NWT, a community of 900 Inuvialuit, 10 indicators of exposure-sensitivity were operationalized, demonstrating the ability for qualitative information and quantitative data to be integrated to produce a more holistic, detailed, and localized assessment of climate change vulnerability. Using GIS, the distribution of vulnerabilities can be mapped to provide an easily understood product for the general public.

Keywords: climate change; coastal vulnerability; vulnerability assessment; community-based decision-making; adaptation planning; Tuktoyaktuk; Arctic

Acknowledgements

First, I would like to thank Dr. Don Forbes, my academic supervisor. He has shown an immense amount of support for the idea behind this project since day one. Without his guidance, my cultural and scientific perspective would not have been broadened to the extent necessary to holistically develop the project.

I would like to thank Gavin Manson for the opportunity to be an intern with the Atlantic Division of the Geological Survey of Canada for the summer of 2013, as well as members of the Division, particularly Nicole Couture, Paul Fraser, and Dustin Whalen. The GSC-A team not only helped immensely to develop my GIS skills, analyze the data, and create the methodology, but they were extremely welcoming and made my internship an incredible experience and a summer.

I must also acknowledge the timely cooperation of Statistics Canada in providing data.

Finally, I would like to thank the Marine Affairs Program; the staff for their wealth of knowledge; the students from the past for their advice; and my classmates, for the team support. I would like to specifically thank Andrea Flynn, my classmate, roommate, and friend, that was always there to edit a paper, listen to a rant, or relax with an episode of Grey's; I would not have made it without her.

In addition, a very large thank you is due to my family for their continuing support for all my endeavours, academic and otherwise. Without them, I never would have made it to the Marine Affairs Program, let alone to the other side.

Chapter 1: Introduction

1.1 Climate Change in the Arctic

"When climate change affects a locality, it will not make the distinction between the individual elements. It will affect the resources that define the place, the interactions between these resources, and the actions of the human population."

(Standing Senate Committee on Agriculture and Forestry, 2003).

1.1.1 Changes and impacts

Climate change is a problem that will affect people throughout the world, but the changes and impacts will differ between regions. Globally, average annual temperatures have been rising at a rate of 0.74 ± 0.18 °C per year from 1906-2005 (Trenberth et al., 2007). In the Arctic, though, the rate of temperature change has been two-fold (Anisimov et al., 2007; Pearce et al., 2011). Although this is an annual average, the majority of the warming has been documented in the winter and spring (Anisimov et al., 2007). These changes in temperature are expected to alter the biophysical environment in many ways, resulting in widespread social and economic impacts.

A highly publicized change that is occurring as a result of global warming is sea-level rise. On average, global mean sea level was rising approximately 1.8 ± 0.5 mm per year for the period 1961-2003 (Bindoff et al., 2007). This rise has not occurred in a linear fashion, though, and appears to have accelerated in the past two decades; from 1993 to 2003 the rate averaged 3.1 ± 0.7 mm per year. As sea levels become higher, waves will reach further onshore, especially during storms (Shaw et al., 1998). Some areas may flood periodically, while others may become permanently submerged. To add to the issues, there is the threat that salt water will infiltrate freshwater resources, potentially contaminating sources of drinking water (Anisimov et al., 2007).

Melting sea ice is also a major concern in the Arctic (Couture et al., 2002; ACIA, 2005; Anisimov et al., 2007; Forbes, 2011; Pearce et al., 2011). Due to warming air temperatures, the ice has been declining both in extent, with a decadal decrease of -7.4% from 1979-2005, as well as in thickness and seasonal duration (ACIA, 2005; Lemke et al., 2007; Forbes, 2011; Pearce et al., 2011). This melting trend is not expected to plateau or decline any time soon; it has been projected that by the end of the 21st century, Arctic sea ice will be reduced by 22-33% of its annual average from 2007 (Anisimov et al., 2007).

A decreased extent of sea ice means there is a greater area of open water, and a reduced duration means the open water season lasts longer. Consequently, waves will have a greater distance and period of time to develop (Manson et al., 2005; Vermaire et al., 2013). If the waves become more developed, they will reach the shoreline with greater force, causing greater damage. The presence of sea ice is also important to the Arctic peoples for transportation, not only between communities, but also to and from traditional hunting grounds (Anisimov et al., 2007; NWT Environment and Natural Resources, 2008; Ford et al., 2010). Thus, if the ice is thinner, travel will be more dangerous, and if the ice has melted entirely and has disappeared, the ways in which hunting grounds and other communities will be access will have to be modified.

It is not just the melting of sea ice that raises concern, but also the melting of ground ice. Permafrost is ground that has a temperature less than 0 °C for at least two consecutive years, although the ground may not necessarily be completely frozen the entire time (Mackay, 1998). In almost all Arctic locations where measurements have been taken, permafrost has been warming (Anisimov et al., 2007; Lemke et al., 2007). In the Canadian Arctic specifically, it is expected that thawing will occur earlier in the spring and persist later in the fall, deepening the seasonal thaw (active) layer (Mackay, 1998; Couture et al., 2002; ACIA, 2005). As the depth of thawing increases, the ground becomes more and more unstable, which can lead to land subsidence and weakening of the surface upon which infrastructure and the foundations of many buildings depend (Couture et al., 2002; Lemke et al., 2007; NWT Environment and Natural Resources, 2008; Ford et al., 2010; Parewick, 2012).

The combination of all the above changes – rising sea levels, a larger open-water season that lasts longer, and destabilized permafrost layer – lead to another major problem that Arctic communities have had to deal with in the past, and will have to prepare for in the future: coastal erosion. Higher sea levels bring water further onto the land; longer and larger expanses of open-water cause waves to hit the shoreline with greater force; and a deepening active layer makes the ground more susceptible to being eroded (Couture et al., 2002; Anisimov et al., 2007; Ford et al., 2010). With many Arctic communities situated along the coast, there is a great risk that they will be damaged in some areas, or possibly lost altogether. Not only is there the potential to lose infrastructure, but important cultural resources, such as archaeological sites, may also be eroded away, which could cause irreversible social losses (NWT Environment and Natural Resources, 2008; Ford et al., 2010).

The above physical changes that are expected to take place will unarguably influence changes in the living environment. It is anticipated that the many species of flora and fauna will not be able to adapt to climate change at the rate at which it is occurring. Many will migrate, moving northward to remain within the climate for which they have evolved to inhabit (ACIA, 2005; Anisimov et al., 2007). These movements will cause changes in the species composition, abundance, and distribution within an area, and will likely result in shifting migration routes of animals (ACIA, 2005; Andrachuk, 2008; NWT Environment and Natural Resources, 2008). While this may be ecologically stressful on the plants and animals, it will also have serious economic, social, and cultural implications. The indigenous Arctic people and their cultures are highly dependent on the natural environment as a food source and way of life. Therefore, any major changes in the availability of their traditional resources will impact the peoples' traditions, food security, and overall health (ACIA, 2005; Andrachuk, 2008; Ford et al., 2010; Pearce et al., 2011).

1.1.2 Adaptability and responses

The people of the Arctic have inhabited northern lands for centuries, adjusting and adapting socially, economically, and culturally in response to the natural climatic and environmental changes that have taken place (ACIA, 2005; Forbes, 2011). For example, they have shifted their hunting grounds to follow migration patterns, they have adjusted their diet depending on species availability, and they have altered their transportation routes depending on the environmental conditions (Ford et al., 2010; Ford & Pearce, 2010). As populations have settled into communities, the people have become more flexible in terms of their food sources, as they can supplement their diet with store-bought foods when country foods are unavailable or unattainable (Andrachuk, 2008; Ford & Pearce, 2010). Changes in diet and dependence on store food instead of country foods has had health implications for many Arctic communities and the need to import food has raised issues of food security.

A number of factors facilitate the adaptability that has become embedded in indigenous ways of life in the Arctic, such as diversity of livelihoods and extensive social networks (Anisimov et al., 2007; Ford & Pearce, 2010). Community members support each other through these practices, allowing risk to be spread and shared rather than falling on the shoulders of a single family or individual. Another feature that enables the ability to cope within a difficult and dynamic environmental setting is the traditional and local knowledge of the harsh northern context, the inherent risks in day-to-day life, and the behaviours that can keep people out of harm's way.

Although the adaptive capacity of the indigenous Arctic peoples has served them well in the past, they are now being faced with new challenges that are limiting, or in some cases inhibiting their ability be resilient; their ability to mobilize their traditional coping strategies. For one, the changes in climate that are currently taking place and that are expected to occur in the future are happening at a much faster pace than in the past (Forbes, 2011). Therefore, they do not have the same time to adapt, but rather they must respond quickly. Many of the indigenous groups have also lost some or all of their traditional nomadic way of life; instead of relocating to follow their food, they have been settled into permanent communities (ACIA, 2005). The fact that they are now tied to one specific location reduces their flexibility to respond. Even if groups of people continued to live a nomadic lifestyle and followed the migration patterns of their traditional food sources, federal regulations on hunting, fishing, and trapping limit the quantity that can be harvested. Thus people's ability to rely on country foods for subsistence, and therefore their flexibility in diet has been reduced (Ford et al., 2010).

The loss of some traditional coping strategies comes the need to build the capacity of communities in other ways. Institutional, technical, and financial resources or capacities to plan, design, and implement necessary adaptations for climate change are the areas most in need of support, but underlying these limitations are social difficulties that stem back to the colonization (Ford & Pearce, 2010; Governments of NWT, Nunavut, Yukon, 2011; Forbes, 2011). Particularly in Canada, the traditional skills, language, and knowledge, and the cultural values and practices that have supported the flexible and adaptive ways of life that have kept indigenous Arctic peoples resilient are being lost (Ford & Pearce, 2010).

1.2 Coastal Management and Climate Change

The physical, social, economic, and cultural characteristics of many Arctic communities and the people's lifestyles renders them some of the most vulnerable in the world to climate change (Anisimov et al., 2007). There is a strong belief, particularly by indigenous Arctic peoples that all aspects of life are interconnected, and thus trying to divide them apart for research and management is ineffective (Governments of NWT, Nunavut, Yukon, 2011). It is important that management efforts acknowledge and respect the linkages between the different systems – biophysical and socioeconomic – and consider them both throughout the decision-making processes (GESAMP, 2001a; Dawson, 2003; Nicholls & Klein, 2005).

Coastal management could be implemented in a top-down manner, placed upon lower levels of government and communities by the national government. This may not be the most appropriate approach, though, as it is important that local people, especially indigenous people, become empowered to make changes concerning their own communities (ACIA, 2005; United Nations, 2005). The right of indigenous peoples to be equally involved in decision-making processes has been officially recognized at the international level through the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) in 2008, and within Canada, specifically for the Inuvialuit people, through the Inuvialuit Final Agreement (IFA) in 1984. Management of resources wherein communities are given an equal or greater voice than higher levels of government is referred to as community-based co-management. The necessity for this type of approach has been directly called for in the context of climate change in the United Nations Hyogo Framework for Action (2005). Specifically, it requests the decentralization and devolution of responsibilities and resources for coping with climate change and associated risks.

Community-based approaches to coastal management have the potential to be more successful than top-down management initiatives by the central government. It is assumed that communities have a greater connection to the land and resources that are to be managed, and thus they have a greater desire to conserve the natural environment (Armitage, 2005). At the same time, it is their lives and livelihoods that depend on the land and its resources, and so they will also have an interest in developing and using the area. Therefore, the communities are the most likely to have sustainable goals, balancing their aspiration to conserve and use the natural resources. It is also important that the interests of all stakeholders are taken into account when developing management plans (Kearney et al., 2007). Not only is it essential to include multiple parties in order to respect different views and opinions, but co-management also allows for the incorporation of different knowledge systems. Integrating traditional, local, and scientific knowledge from varying disciplines and sectors will result in a more comprehensive understanding of the way in which the complex coastal zone functions (ACIA, 2005; United Nations, 2005). By basing management within the community, rather than from a centralized location, it is more likely that these factors will be part of the management regime (Kearney et al., 2007).

Regardless of how much knowledge is integrated in an attempt to understand and plan for climate change, a high level of uncertainty will remain embedded within projections of changes, their rates of occurrence, and their impacts on biophysical and socioeconomic systems (Lemmen & Warren, 2004; ACIA, 2005; Patt et al., 2005). This seriously inhibits coastal managers, because although they are trying to develop projects to be implemented in the short-term, their goals must be for the long-term sustainability of all the components of the coastal zone, and this requires long-term predictions of the future state of the biophysical and socioeconomic systems (Thumerer et al., 2000; United Nations, 2005). Many of the uncertainties that exist within climate change estimates are a result of data gaps and the natural complex interactions between systems and their components, which only become more pronounced as the scope of interest becomes narrowed and more localized (Lemmen & Warren, 2004). It cannot be expected that

Arctic systems and processes will ever be completely understood, but our understanding is improving with each new study. Thus, in order to keep management practices up-to-date with the current state of knowledge, it is necessary that the management planning process be flexible and adaptable so as to continuously incorporate new information (ACIA, 2005).

Internationally it has been recognized that the most appropriate approach to achieving all these management goals (integration of knowledge, community involvement, flexibility) is to implement integrated coastal zone management (ICZM) (GESAMP, 2001b; Nicholls et al., 2007). ICZM is a cyclical process that involves continuous monitoring and evaluation to ensure the management plan is achieving its goals (Figure 1). It is also adaptive; if it is determined that alterations are necessary through the monitoring and evaluation, they can be made without restarting the entire plan development procedure. The ICZM framework also incorporates input from many stakeholders from differing cultures, backgrounds, disciplines, sectors, and levels of government when identifying and assessing issues, and planning and preparing the management program. Through ICZM, all those with an interest in the coastal zone can be united to accomplish the long-term sustainability of the coastal zone (GESAMP, 2001b; Nicholls & Klein, 2005; Nicholls et al., 2007).

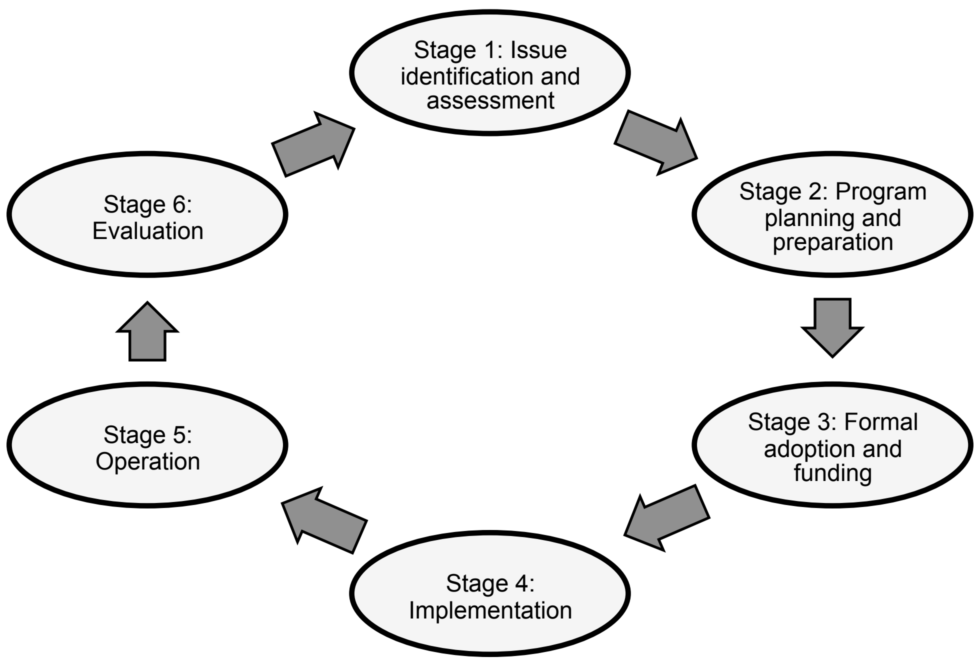


***Figure 1*. The six stages of an integrated coastal management process (Cicin-Sain, Knecht, Jang, & Fisk, 1998).**

1.3 Purpose and Objectives

The Territorial Governments of the Yukon, Northwest Territories, and Nunavut have voiced their need for action towards adapting to climate change. Together, the three governments collaborated to develop a Pan-Territorial Adaptation Strategy that was published in 2011. In this document, they "commit to work closely with partners at all levels – local, national, international – as well as with Aboriginal governments and organizations by sharing climate change adaptation knowledge and developing collaborative activities" (Government of the NWT, Nunavut, Yukon, 2011, p. 7). Six key strategies for adapting were identified, which included providing support for communities by supplying information, training, and tools, and by supporting efforts towards community-based assessments of vulnerability and risk, as well as adaptation planning.

This project aims to develop a tool for Arctic communities to use for assessing coastal vulnerabilities to climate change, so as to facilitate community-based or co-management of the coastal zone in preparation for the climatic changes to come. The purpose of the assessment is to evaluate coastal areas within a community's domain, and determine which are the most vulnerable to being affected by climate change and which are the most likely to result in an impact on the community if damaged. This is important for a community to know because it will allow them to identify the areas that are most in need of proactive adaptation efforts and help in making decisions about resource allocation (Duerden, 2002). The approach to designing this assessment is based on the ICZM process and the rights of indigenous peoples as described by UNDRIP, the IFA, and the Hyogo Framework for Action. The goal is to create a methodology that includes the physical, social, economic, and cultural characteristics of a community, and to develop ways in which traditional and local knowledge, as well as scientific data from a variety of disciplines can be integrated. In addition, recognizing the limitations outlined by the Territorial Governments in the Pan-Territorial Adaptation Strategy, methods that are costly or that require large human capacity are avoided.

Chapter 2: Approach

2.1 Vulnerability

Vulnerability cannot be measured quantitatively; rather, vulnerability is a qualitative concept that can be moulded to suit the needs of different studies (Hinkel, 2011). With different perspectives come different interpretations of the attribute, and thus it is important to begin by defining the term and its components at the outset of a study of vulnerability. If a social study is being conducted, vulnerability often focuses on the political and socioeconomic characteristics, also known as the human system (Kelly & Adger, 2000; Ford & Smit, 2004). In particular, it looks at the adaptive capacities, or the ability for components of the human system to cope with changes. Füssel (2007) describes this as a political economic approach to studying vulnerability. On the contrary, one could take a biophysical perspective, emphasizing the nature of the hazardous events, the frequency at which the event occurs, and the physical systems and built infrastructure that are exposed and sensitive to the impacts of the hazard (Kelly & Adger, 2000; Ford & Smit, 2004; Füssel, 2007). This type of study would take a risk-hazard approach to vulnerability (Füssel, 2007). Both the political economic and the biophysical approaches are sectoral, as the focus is either on the social or the biophysical system.

An alternative approach is to meld the two perspectives into an integrated, multi-disciplinary vision of vulnerability (Füssel, 2007; Torresan et al., 2008). It is acknowledged in this approach that the social and biophysical systems interact with one another, and that the focus of the study is actually a combination of the two: the human-environment system. Rather than considering the adaptive capacity of the human portion, and the exposure-sensitivities of the environment, a resilience approach to vulnerability would study the adaptive capacities and the exposure-sensitivities of the human-environment system as a whole (Füssel; 2007). This is the approach that will be taken in this study because it is the most comprehensive and integrated. Therefore, the working definition of vulnerability is: the exposure of a human-environment system to stresses; the sensitivity or susceptibility of the system to being impacted in the case that a risk becomes reality; and the ability of the system to cope or adapt to the impacts and changes that take place (Klein & Nicholls, 1999; Berkes, 2007; Füssel, 2007; Andrachuk, 2008; Andrahuck & Smit, 2012; Cardona et al., 2012).

Exposure and sensitivity, although two separate components of vulnerability, are sometimes grouped and considered as one: exposure-sensitivity. Exposure is "the degree to which a system is in contact with a stress" and sensitivity is "the degree to which a system is affected" (ACIA, 2005, p. 947). The two are inherently connected and it can often be difficult to determine whether a factor is contributing to vulnerability as an exposure or sensitivity; so, in many studies, they are combined and referred to as 'exposure-sensitivity'. In this project the two will be distinguished from one another, although they will often be discussed as one because they influence vulnerability in the same way: as the exposure or sensitivity increases, so too does the vulnerability.

The adaptive capacity of a system is its "ability to adjust, to moderate possible harm, to realize opportunities, or to cope with consequences" (ACIA, 2005, p. 947), and it inversely influences vulnerability; vulnerability decreases as adaptive capacity increases. Resilience is often used synonymously with adaptive capacity, but the two are not the same; resilience is the ability to mobilize adaptive capacities and respond to a change in a positive manner. This does not mean that a system is able to resist change or remain static over time (Berkes, 2007; Parewick, 2012). Particularly in the Arctic where the impacts of climate change are already affecting the socioeconomic and biophysical systems, it is unlikely that the human-environment system will be able to return to one of its previous states (Berkes, 2007; NWT Environment and Natural Resources, 2008; Parewick, 2012). It is much more probable that new equilibriums will arise as systems absorb changes and acclimate to their newly altered environment.

2.1.1 Conceptual frameworks

The purpose of using a conceptual framework at the outset of this study is to better visualize and comprehend the drivers of vulnerability and the connections among its components. As with the definitions of vulnerability, there are multiple forms of such a framework. For example, Klein and Nicholls (1999) and Ford, Smit, and Wandel (2006) used framework that studied current vulnerability to climate change, whereas Füssel (2007) and Ford and Smit (2004) look to forecast future vulnerabilities. In the Ford and Smit model, future exposure is predicted through probabilities of future climate scenarios, and future adaptive capacity is anticipated through future social probabilities. Füssel (2007) defined this even further, stating that future vulnerability is a function of the future hazard level, current sensitivity, and both the current and future adaptive capacities of a system, as well as some regional exposure factor.

This project will study the vulnerability of the entire human-environment system to climate change, which can be done by looking at the socioeconomic and biophysical systems together as one, or by evaluating them separately and then combining the products in the end. The Frameworks of Ford and Smit (2004) and Füssel (2007) do not differentiate between the two systems, whereas within the models by Klein and Nicholls (1999) and Ford et al. (2006) the socioeconomic and biophysical systems are divided.

Klein and Nicholls portray the two as separate and identify where the linkages exist between them, while Ford et al. consider the larger socioeconomic (social, economic, and in this case also political) and biophysical systems, as well as additional external conditions that influence the ‘system of interest’.

This study takes a three-tiered approach to conceptualizing the overall vulnerability of a human-environment system. Here, the focus is on the current vulnerabilities as well as indicators of future vulnerability, although projections of future situations are not made. The framework could be employed under different climate change scenarios, though as part of a larger risk analysis of the impacts of climate change. It has been stated that the socioeconomic and biophysical systems in the coastal zone are intricately connected, although they also function separately. Therefore, they are considered first as two separate but interactive systems that have exposures, sensitivities, and adaptive capacities that combine to produce an overall vulnerability of the coastal human-environment system (Figure 2).

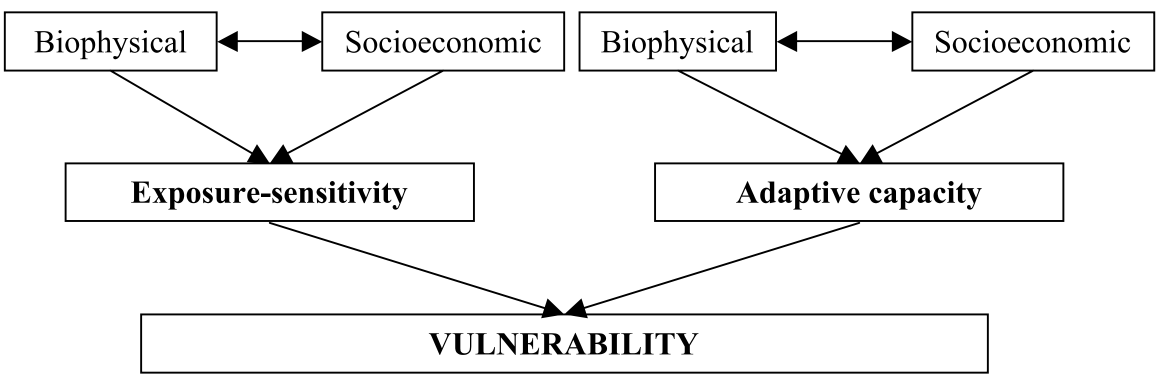


***Figure 2*. The conceptual framework of the vulnerability of a coastal human-environment system that will be used in this study. The biophysical and socioeconomic systems interact with one another to yield exposure-sensitivities and adaptive capacities, which together produce the overall vulnerability of the system.**

2.2 Vulnerability Assessments

The Arctic Climate Impact Assessment (ACIA) published in 2005, and the more recent review of hazard mapping vulnerability assessments for infrastructure in Canada's North (Champalle et al., 2013) both outline five key components that should be present in any assessment of a Canadian Arctic community's vulnerability to climate change. First, the assessment should be developed for a specific community, rather than for the Arctic region as a whole. In other words, the focus should be downscaled and the spatial resolution needs be enhanced. Second, a prospective and historical perspective should be taken, looking both to the future and the past for insights and trends. Third, the approach should be collaborative, interdisciplinary, and comprehensive; it should unite multiple forms of quantitative and qualitative information from numerous disciplines, sectors, and sources, both scientific and traditional. It must also look beyond the scope of climate change to include multiple stresses on, drivers to, and interactions within a human-environment system. Fourth, any framework should be innovative and novel, synthesizing knowledge and tools, in particular hazard mapping. However, in any approach, uncertainties in data and models must be acknowledged, so as not to provide a false sense of understanding. The final component of any vulnerability assessment in Canada's North is that the information must not only be made widely available, but it must be directly distributed in a form that the general public can comprehend; the methodology must be documented in detail and the results and implications must be shared. Other authors that also share these views are described in Table 1.

***Table 1*. Other authors that support the characteristics of vulnerability assessments outlined in the ACIA (2005) and by Champalle et al. (2013).**

Assessment characteristic	Supporting authors
Local level focus	Andrachuk, 2008
	Nicholls et al., 2008
	Ionescu et al., 2009
	Ford & Pearce, 2010
	Ford et al., 2010
	Pearce et al., 2011
	Andrachuk & Smit, 2012
	Appelquist, 2013
Interdisciplinary approach	Klein & Nicholls, 1999
	Lemmen & Warren, 2004
	Ford et al., 2006
	Szlafsztein & Sterr, 2007
	Andrachuk, 2008
	Nicholls et al., 2008
	Torresan et al., 2008
	Ford & Pearce, 2010
	Pearce et al., 2011
Clearly explained and user-friendly product	Thumerer et al., 2000
	Holman et al., 2005
	Barnett et al., 2008
	Ionescu et al., 2009
	McLaughlin & Cooper, 2010
	Hinkel, 2011

As mentioned, one cannot simply measure vulnerability because it is not a quantitative attribute of a human-environment system. Instead, measurable indicators are often used as proxies for the vulnerability of a system. Taking such an approach to studying vulnerability is useful because it provides a method of simplifying and communicating the complexities of the real-world. The final product is a scale that reflects the relative vulnerability of an area, which is known as a vulnerability index, and in the context of the coastal zone, a coastal vulnerability index (CVI) (Barnett et al., 2008; Cutter, 2010; McLaughlin & Cooper, 2010; Hinkel, 2011; Balica et al., 2012). Although the final results may be simple to interpret, the process of arriving at that value can be extremely difficult, especially if there is a lack of data, or limited financial or technical resources or human capacity for obtaining and analyzing the information, as is often the case when studying in the Arctic (Füssel, 2009; Appelquist, 2013).

2.2.1 Indicators

The most basic approach to creating a CVI is to focus solely on the biophysical vulnerabilities within the coastal zone (Balica et al., 2012). However, according to the principles of integrated coastal zone management (ICZM) and as stated above in the discussion, it is not sufficient to study only one aspect of the human-environment system; vulnerability assessments must be interdisciplinary and comprehensive. Researchers must take warning, though, that as the variety of types and sources of data and information increases, the assessment becomes more and more complex, particularly when one tries to integrate socioeconomic and biophysical components (Balica et al., 2012).

This study aims to use indicators of both the biophysical and socioeconomic vulnerabilities within a coastal area to climate change. For this study, the coastal zone is defined as a strip of land adjacent to marine waters with some defined width. Through a literature review of vulnerabilities studies and indices from around the world and at varying geographic scales, 27 indicators were chosen and categorized as contributing to biophysical exposure, sensitivity, or adaptive capacity, or socioeconomic exposure, sensitivity, or adaptive capacity (Table 2). Indicators were selected based on the support for the indicator in the literature and whether or not the attribute would vary from one coastal segment to the next within an Arctic community. For example, sea-level rise and changes in storminess were not included because, in the small area of a single community, the amount that sea level would rise and the number and intensity of storms will not vary from one part of the coastline to the next. The effects of these changes will differ, though, and it is the factors that contribute to these differences in impacts that were chosen; in the case of sea-level rise, such indicators include elevation and geomorphology.

Table 2. Indicators of coastal vulnerability to climate change within an Arctic community.

Component	Indicator	Score 1-5	Description	References
Socioeconomic exposure-sensitivity	**Land-use**	Protected park or natural to residential or industrial	A community is more *sensitive* to impacts on certain land-use types; e.g., the consequence of having critical infrastructure damaged compared to open land	McLaughlin & Cooper, 2010 Özyurt & Ergin, 2010 Santos et al., 2013
	Population density	Small to large	A larger population within a segment of coastline means a greater portion of the community is *exposed* to being impacted if one area were to be damaged	Torresan et al., 2008 Ford et al., 2010 McLaughlin & Cooper, 2010 Balica et al., 2012 Santos et al., 2013
	Infrastructure density	Low to high	The more infrastructure along a segment of coastline, the more *sensitive* the community is to having that area impacted	Cutter et al., 2003
	Distance of buildings to the shore	Absent to near	Infrastructure that is located further from the shoreline is less *exposed*	Özyurt & Ergin, 2010

Socioeconomic exposure-sensitivity (continued)	**Distance of roads to the shore**	Absent to near	The closer the roads are to the shoreline, the more *exposed* they are to being damaged; the greater the number of exposed roads within an area, the more *sensitive* the community becomes to damages in that area	Couture et al., 2002 McLaughlin & Cooper, 2010 Andrachuk & Smit, 2012
	Age of infrastructure	Old to new	The older the infrastructure, the more *sensitive* it is to being impacted	Cutter et al., 2003
	Population growth	Small to large	The more a population is growing, the greater the future population density, thus the greater the *future exposure*	Balica et al., 2012
	Health status	Best to worst	People who are in poor health are more *sensitive* to climatic changes than those in better health	Anisimov et al., 2007 Ford et al., 2010 Balica et al., 2012
	Presence of cultural heritage resources	Absent to present and very important	If very important cultural heritage resources are present, the *sensitivity* of the community to having that area impacted is greater	Ford et al., 2010 McLaughlin & Cooper, 2010 Pearce et al., 2011 Balica et al., 2012

Biophysical exposure-sensitivity	**Landform**	Highly resistant cliffs to cobble beaches to sandy beaches and estuaries	The landform of the coastline is a major factor affecting the *sensitivity* to being eroded	Torresan et al., 2008 McLaughlin & Cooper, 2010 Özyurt & Ergin, 2010 Pendleton et al., 2010 Andrachuk & Smit, 2012
	Elevation	High to low	The lower the elevation, the greater the *exposure* to being flooded during storm surges and inundated due to sea-level rise	McLaughlin & Cooper, 2010 Andrachuk & Smit, 2012
	Exposure to storm waves	Low to high	The greater the *exposure* to storm waves, the greater the *sensitivity* to storms	Couture et al., 2002 Özyurt & Ergin, 2010 Pendleton et al., 2010 Appelquist, 2013 Santos et al., 2013
	Ground ice volume	Low to high	The greater the ground ice volume, the more *sensitive* it may be to erosion or differential settlement with warming temperatures	Couture et al., 2002 Balica et al., 2012

Biophysical exposure-sensitivity (continued)	**Coastal change**	High accretion rate to high erosion rate	Climate change is expected to increase erosion, therefore areas that are currently eroding at a high rate are more *sensitive* to *future* impacts	Özyurt & Ergin, 2010 Pendleton et al., 2010 Andrachuk & Smit, 2012 Appelquist, 2013 Santos et al., 2013
	Duration of sea ice	Long to short	The shorter the annual duration of sea ice, the greater the open-water season, and the larger the waves, therefore the greater the *exposure*	Andrachuk & Smit, 2012
	Rivers	Absent to present with large discharge	Greater discharge increases the *exposure* to being flooded	Torresan et al., 2008 McLaughlin & Cooper, 2010 Özyurt & Ergin, 2010 Balica et al., 2012

Socioeconomic adaptive capacity	**Access to services**	Best to worst	The better the access to services, particularly medical, the better able a person is to respond in the case that they require assistance	Ford et al., 2010 Mustafa et al., 2011 Balica et al., 2012
	Population age	Middle age to highest/lowest age	The oldest and the youngest are expected to be the least able to absorb and respond to changes	Cutter et al., 2003 ACIA, 2005 Anisimov et al., 2007 Ford & Pearce, 2010 Orencio & Fujii, 2013
	Education level	High to low	Less education (formal and informal) usually means less knowledge and fewer skills (formal and traditional education systems and resulting knowledge and skills) are known for adapting	ACIA, 2005 Schneider et al., 2007 Ford et al., 2010 Mustafa et al., 2011
	Knowledge of hazards and impacts	Most to least	The more knowledge and experience a person has of hazards and impacts, the more aware they are of the potential consequences, and thus the more likely they are of preparing	Ford & Pearce, 2010 Pearce et al., 2011 Mustafa et al., 2011 Balica et al., 2012 IPCC, 2012 Notenbaert et al., 2013

Socioeconomic adaptive capacity (continued)	**Dependence on country foods**	50:50 country foods:store foods to 0:100 or 100:0	A balanced diversity within the diet represents greater flexibility and ability to adjust in the case that one food-type were impacted	Andrachuk, 2008 Ford & Pearce, 2010 Pearce et al., 2011
	Livelihood diversity	High to low	The greater the livelihood diversity, the greater the flexibility and ability to adjust in the case that one form of livelihood were impacted	ACIA, 2005 Andrachuk, 2008 Ford & Pearce, 2010 Pearce et al., 2011
	Number of earning members per household	Most to least	The more people in a household that are generating an income, the more likely it is that the household will have greater financial resources for adapting	Mustafa et al., 2011
	Financial resources or income	High to low	With more financial resources people are able to pay to improve components of their adaptive capacity and reduce contributors to their exposure-sensitivity	ACIA, 2005 Anisimov et al., 2007 Andrachuk, 2008 Ford & Pearce, 2010 Pearce et al., 2011 Andrachuk & Smit, 2012 Notenbaert et al., 2013 Orencio & Fujii, 2013

Socioeconomic adaptive capacity (continued)	**Technological resources**	Most to least	More technological resources allow for more advanced adaptations	Andrachuk & Smit, 2012
	Social networks	Most to least	Someone with more social networks is more likely to have support in the event that they are impacted	Anisimov et al., 2007 Andrachuk, 2008 Ford & Pearce, 2010 Pearce et al., 2011 Mustafa et al., 2011
Biophysical adaptive capacity	**Ecosystem health**	Flourishing to disturbed to absent	If the natural environment is healthy it is able to withstand greater wave energy and will serve to reduce erosion	ACIA, 2005

2.2.2 Evaluation

A standard way of coping with a plethora of sources and units in data is to use a scale of normative values (Barnett et al., 2008; MacLaughlin & Cooper, 2010; Özyurt & Ergin, 2010; Tiburan et al., 2010; Balica et al., 2012; Santos et al., 2013). Typically these scales have ranges of 1-3 or 1-5; the scale in this assessment will range from 1 to 5, and for all but one indicator (landform), relative scores of exposure, sensitivity, and adaptive capacity will be used.

Once the indicators have been converted to a mathematically normalized scale they must be combined. There are numerous equations that can be used, many of which are quite complicated. Some commonalities do exist among the approaches; in particular, interacting indicators are multiplied, and indicators or sets of indicators that do not interact are summed.

$$CVI = (a_1 \times a_2 \times \ldots a_n) + (b_1 \times b_2 \times \ldots b_m)$$

Where CVI = coastal vulnerability index rating
a = ranking of a single indicator in one set of interacting indicators
b = ranking of a single indicator in another set of interacting indicators
n = number of indicators in set a
m = number of indicators in set b

The purpose of calculating a CVI in this study is to rank segments of a coastline within a small community. Due to the localized scale, the same number of variables should be used for each segment, particularly because the rankings are based on a relative scale. Therefore, it is unnecessary to divide by the number of indicators, as it will be the same for all segments and thus redundant. Also, since it has been acknowledged that a coastal human-environment system is extremely complex, and that its components are all connected in some way, all the indicators should be multiplied. The resulting equation, and the one that will be used in the analysis of this study, is as follows:

$$CVI = (i_1 \times i_2 \times \ldots i_n)$$

Where i = the ranking of each indicator
n = the number of indicators

A CVI value is calculated for each segment of coastline. Ideally, segments are defined based on the landform because it is the only indicator that is not scored on a relative scale. The final CVI products of the segments are then normalized, again, by ranking them; the highest being the most vulnerable and the lowest being the least.

2.2.3 Communication

Although CVI rankings are useful in the context of this research, it may not be the best approach for communicating the results to the public because, by multiplying scores, there is the potential that the CVI scores will be large values. Therefore, instead of publishing the results as scores, the final rankings are mapped. Mapping has been identified and supported by many as an effective way to share the results of vulnerability assessments (Thumerer et al., 2000; ACIA, 2005; Füssel, 2007; Torresan et al., 2008; McLaughlin & Cooper, 2010; Mahendra et al., 2011; Mustafa et al., 2011; Preston et al., 2011; Appelquist, 2013; Champalle et al., 2013; Santos et al., 2013) and has been frequently and successfully used to communicate research to northern communities (D. Whalen, personal communication, June 5, 2013). Geographic Information System (GIS) software can facilitate an interdisciplinary approach to such mapping, allowing the complexities of the system to be incorporated, while still producing a simplified and easily understood output. Therefore, the CVI rankings are translated to a colour scale and mapped using GIS.

2.3 Summary

Vulnerability, as defined for this study, is a combination of the exposure of a human-environment system to stresses, the sensitivity of the system to being impacted in the case that a risk becomes a reality, and the ability of the system to cope or adapt to changes and impacts. The conceptual framework that will be used starts with the biophysical and socioeconomic systems separately; the two interact to produce exposure-sensitivities and adaptive capacities, which, together, result in an overall degree of vulnerability. Twenty-seven factors were selected to evaluate vulnerability, and were categorized as contributing to socioeconomic or biophysical exposure, sensitivity, or adaptive capacity. Ideally these indicators would be evaluated between coastal segments based on landform because it is the only indicator that is not evaluated on a relative scale. A CVI is calculated for each segment, regardless of how the coastline is divided, and the final ranks are mapped using GIS using a colour scale.

The proposed assessment was designed based on the requirements outlined by the ACIA (2005) and Champalle et al. (2013), and as supported by numerous other authors. The key characteristics include:

(1) It is used to assess vulnerabilities within a particular community, rather than at a regional scale;

(2) It is both prospective and historical, incorporating traditional knowledge and indicators of where future impacts will be felt the most;

(3) It is collaborative and interdisciplinary, integrating the socioeconomic and biophysical systems, scientific experts, indigenous peoples and local stakeholders;

(4) It synthesizes previous work while taking a new perspective by trying to remove the need for projections and thus some uncertainty; and

(5) The process by which it was created and the reasoning behind each decision are documented in detail, and the final product is a vulnerability map that can be easily understood by stakeholders.

Chapter 3: Methodology

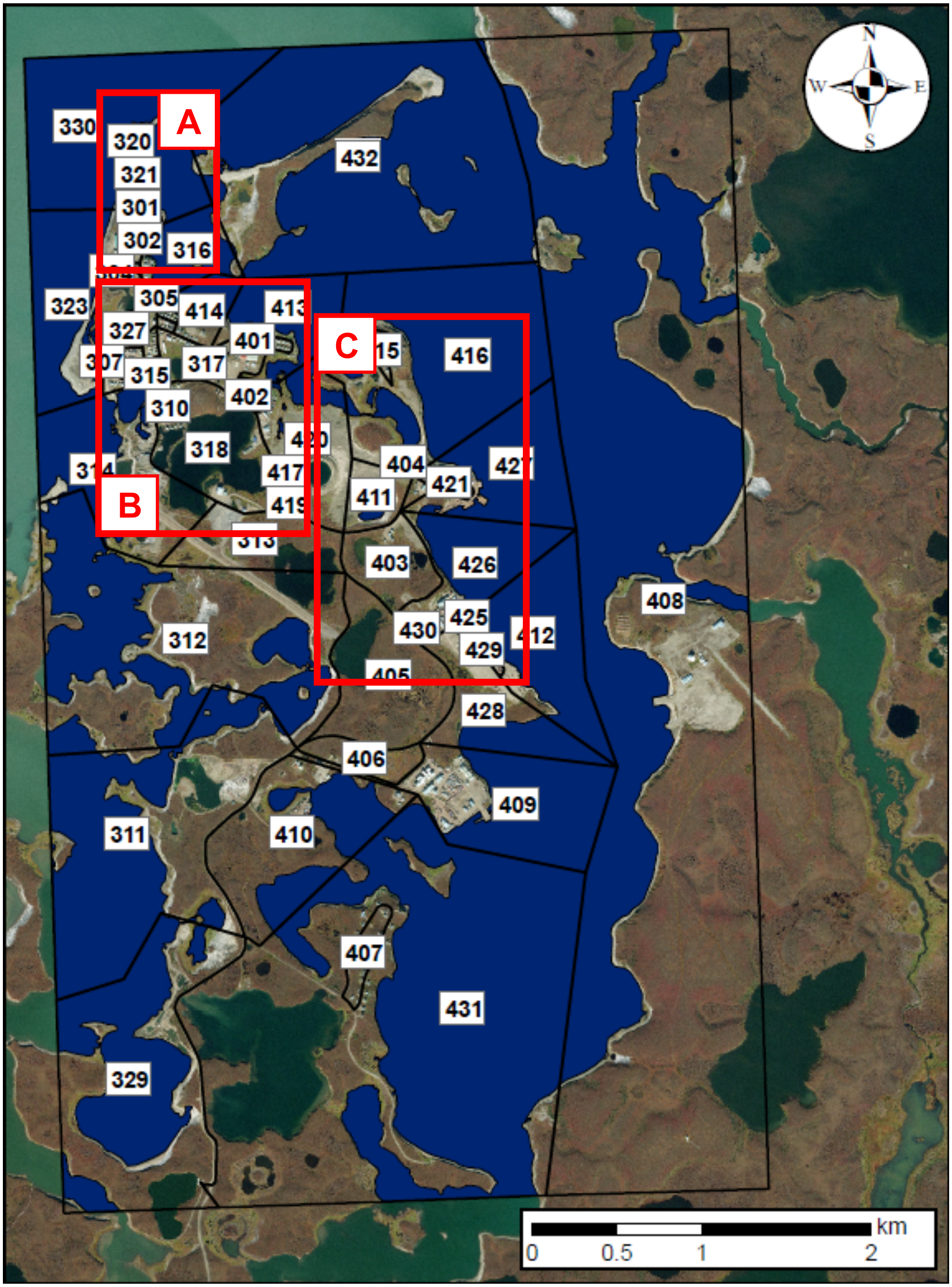
A case study of Tuktoyaktuk (Tuk), Northwest Territories (NWT) tested the suitability of the indicators to be operationalized and the evaluation methods to successfully combine the indicators. Due to time constraints, financial limitations, and the inability to gain access to all necessary data, the focus of the case study was directed towards examining the exposure-sensitivity indicators; even so, not all indicators could be included. To assess many of the socioeconomic indicators (for example the presence of cultural heritage resources), it would be necessary to travel to the community of Tuk and to speak with local residents. Thus, this test is not a complete evaluation of the coastal vulnerability of the community of Tuktoyaktuk to climate change (i.e. a CVI was not calculated), but rather, some components of the CVI were evaluated, providing a preliminary test of the proposed methodology.

3.1 Indicators

Indicators were chosen based on their utility to evaluate the current coastal context and to identify the areas that are the most vulnerable to being impacted by climate change in the future. The indicators were also selected based on whether they would differ between coastal segments within a community, not between communities. Tidal range, for example, does not vary on such a small scale, and thus is not included. The same principle supports omitting projections of sea level rise and changes in storminess.

Data and information for the indicators were gathered from Statistics Canada (2006 and 2011), the Geological Survey of Canada (GSC), and through personal communications with members of the Atlantic Division of the GSC (GSC-A) who have worked in Tuk or are experts in the fields of the indicators, for example ground ice.

Indicators were also evaluated through GIS (ArcMap 9.3), for which a base image of the Hamlet was used; it is a GeoEye image taken September 7, 2010, and was purchased by the GSC-A (www.geoeye.com). A polygon covering all marine waters was created in ArcMap based on the GeoEye image; when this polygon is laid over the GeoEye image, attention is drawn to the land. The smallest scale for which the Statistics Canada data were available was by dissemination block (DB). Therefore, the Hamlet was divided by DB for assessing coastal vulnerabilities. A georeferenced image of the 2011 DBs was obtained from www.statcan.gc.ca (Figure 3).


A
B
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320
321
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316
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323
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414
401
327
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317
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402
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417
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411
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426
408
312
425
430
429
428
406
409
311
410
407
431
329
N
S
E
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km
0
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N
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320
330
432
321
301
325
303
322
326
302
316
323
324
304
km
0 0.05 0.1 0.2
A

316
323
305
414
413
306
327
401
308
328
307
317
309
315
402
310
420
318
314
417
418
419
319
313
km
0
0.1
0.2
0.4
B
N
W
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Figure 3. GeoEye Image (2010) of Tuktoyaktuk and the surrounding area, Statistics Canada labelled dissemination blocks (2011) of the Hamlet, and the marine polygons.

3.1.1 Socioeconomic indicators

Land use

Polygons were drawn over different land uses in each DB based on the GeoEye image. Options for land uses were:

Airport	Drinking water	Dump	Sewage lagoon
Nursing station	NTCL	Fire station	Roads
Seniors complex	Residential	Cemetery	Church
Community centre	Northern Store	School	RCMP
Ice house	Shops	Recreation	Storage
Industrial	Sod huts	Our Lady of Lords (boat)	Camps
Other anthropogenic	Disturbed land	Natural land	Inland water

The area of each polygon was calculated through ArcMap, and the total area of all the polygons within each DB was summed. The area of the 'marine water' polygons was then subtracted to yield the 'land-only' area of each DB. The percent-area of each land-use polygon was calculated by dividing the area of the polygon by the 'land-only' area of the corresponding DB.

Each land use was assigned a score based on the sensitivity of the community to having the particular land use damaged. The score of the land-use polygon was then multiplied by the percent-area, and then the products for all the land-use polygons within a single DB were summed to give a weighted average land-use score.

Population and infrastructure density

Both population and infrastructure density contribute to socioeconomic exposure-sensitivity. Statistics Canada provided data on the number of people and dwellings within each DB; therefore, instead of assessing infrastructure density, dwelling density was evaluated. The ‘land-only’ area calculated for each DB from the land-use indicator was used to calculate the number of people or dwellings per block.

Distance of buildings to the shore

The distance between each visible building in the GeoEye image and the nearest shoreline was measured in ArcMap. The median distance of all the buildings within a single DB was then calculated. The median was calculated so that extreme values would not sway the final outcome.

Distance of roads to the shore

All the roads in the Tuk Hamlet were traced over the GeoEye image in ArcMap. For each road, the shortest distance between it and the shore was measured, representing the most sensitive point in the road to being eroded; the DB where this point on the road was located was recorded. Each DB was scored based on the number of sensitive points within the block and the distance from the coast to each point.

3.1.2 Biophysical indicators

Landform

First, the entire coastline within the Tuk Hamlet had to be characterized. A digital vector file representing the shoreline of Tuk was already available at GSC-A. A second digital vector file also existed in the Coastal Information Systems (CIS) database of the GSC-A for some of the shoreline of Tuk, which had already been labelled for coastal landform. This file was used as a reference guide for categorizing the rest of the shoreline. Using tools in ArcMap, the first vector (the entire coastline of Tuk) was cut at every point where the coastline changed based on the GeoEye image, or at the border of a

DB. Each line segment was then labelled based on the dominant landform (supratidal, beach, cliff, driftwood, rip rap, concrete/anthropogenic, or tidal inlet); other additional features were also noted (detached barrier, attached barrier or spit, or additional driftwood). Each landform and the additional characteristics were assigned a certain number of points based on their contribution to the sensitivity to being eroded; these were summed to yield a total number of points for each line segment.

The length of each line segment was measured in ArcMap, and the lengths of all the segments within a DB were summed to give a total DB shoreline length. Using the same approach as was taken for calculating the percent-area of land for the land-use indicator, the percent-length of each line segment was determined; the length of each line segment was divided by the total length of its block's shoreline. By multiplying the final number of points of each line segment by its percent-length shoreline, and then adding all the adjusted scores for lines within a single DB, a weighted average was calculated.

Elevation

Using the 'marine water' polygons created in the analysis of the land-use indicator, a LiDAR image of the Tuk area from 2004 was clipped by a member of GSC-A to yield elevations for the land only. The mean elevation for each DB was then calculated through ArcMap; these values were then used for ranking the blocks.

Exposure to storm waves

Based on the known northwest direction of storm winds and the expertise of GSC-A staff, the relative wave exposure (high, medium, low) of each block was estimated.

Ground ice volume

A member of GSC-A calculated the percent ice volume and the percent excess ice of each block following the geomorphological method of Pollard and Couture (1999; 2000). The final values were used to rank the blocks.

Rate of coastal change

Rates of coastal change between the years 1950 and 1985 were available for most of the coastline of Tuk from GSC-A. All rates within a DB were combined to yield some measure of the general rate of coastal change within that block. Where data were not available, estimates were made under the guidance of GSC-A members.

3.2 Overall exposure-sensitivity

The biophysical exposure-sensitivity within a block was calculated by multiplying all the scores for the biophysical exposure-sensitivity indicators within one block. For example:

Block	Landform	Elevation	Exposure to storm waves	Ground ice volume	Rate of coastal change	Biophysical score
A	4	3	5	2	1	120

The socioeconomic exposure-sensitivity was calculated in the same way, using the indicators for socioeconomic exposure-sensitivity instead of biophysical. To calculate the overall exposure-sensitivity within a block, the scores for biophysical and socioeconomic exposure-sensitivities were multiplied. These scores were then ranked from highest (most exposed and sensitive) to lowest (least exposed and sensitive).

Chapter 4: Tuktoyaktuk, NWT

Tuktoyaktuk is a small coastal community in the Northwest Territories located on the southern shore of Kugmallit Bay in the Southeast Beaufort Sea, east of the Mackenzie Delta (Figure 4). Approximately 900 people, most of Inuvialuit descent, reside in Tuk (Couture et al., 2002; IRC, 2011; Andrachuk & Smit, 2012; Hamlet of Tuktoyaktuk, n.d.). The name Tuktoyaktuk originates from the Inuvialuktun word *Tuktuujaartuq*, which translates to "looks like a caribou" (Parewick, 2012; Legislative Assembly of the NWT, n.d.). This name stems from a legend of a woman who saw a caribou enter the waters and turn to stone; it is said that the reefs that are visible at low tide resemble this caribou (Hamlet of Tuktoyaktuk, n.d.).

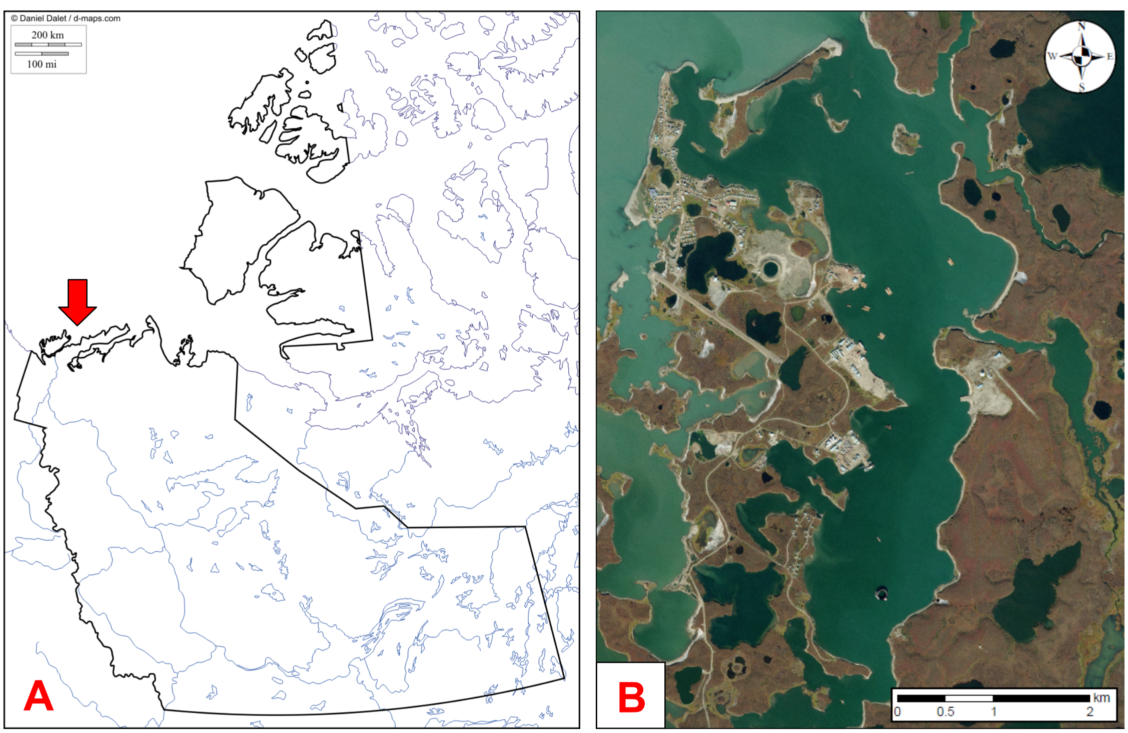

Figure 4. (A) The Northwest Territories, identifying the location of (B) the Hamlet of Tuktoyaktuk. (Image of the Northwest Territories retrieved from http://d-maps.com/carte.php?num_car=23635&lang=en).

4.2 History

The first inhabitants of the area now known as Tuktoyaktuk were the Kagma (Mackenzie) Inuvialuit (Couture et al., 2002). However, the people who now live in the area are not descendants of the original population; in the late 1800s, American whalers came to the region accompanied by new illnesses, which, by 1910, had decimated the entire Inuvialuit population. It was another eighteen years before Inuit returned to the area; in 1928, hunters, trappers, whalers, and reindeer herders from Cape Bathurst and Alaska re-established the indigenous population in Tuk (Couture et al., 2002; Andrachuk, 2008).

Although multiple groups of people had lived within the Tuk region for a number of years, it was not until 1934 that the first permanent building was established: a Hudson's Bay Trading Post (Couture et al., 2002; Andrachuk, 2008; Parewick, 2012). The Post was relocated from Kitigaaryuit to Tuk because the harbour had a greater capacity for larger vessels (Parewick, 2012). Roman Catholic and Anglican churches followed, and the permanent population of Tuk grew from zero to approximately five families by the end of the 1930s (Couture et al., 2002; Andrachuk, 2008; Parewick, 2012).

By the 1950s, Tuktoyaktuk had grown from these original five families to a population of over three hundred (Couture et al., 2002; Parewick, 2012). Infrastructure accompanied the expanding population, and included log and frame houses, a church, school houses, a nursing station, powerhouse, warehouse and store, a Distant Early Warning (DEW) Line site and an airport (Couture et al., 2002; Andrachuk, 2008; Parewick, 2012). The congregation of people and buildings officially became a Hamlet in

1970, which was the same year that oil was discovered approximately 90 km to the northeast (Couture et al., 2002). Nearly forty oil wells were drilled in the Beaufort Sea throughout the 1970s, which was economically beneficial for Tuk as it served as an important harbour for oil companies taking part in the activities (Couture et al., 2002; Andrachuk, 2008). As a result of all the action in the area, the airport was expanded to accommodate larger aircraft and a winter ice-road was established between Tuk and the larger settlement of Inuvik, located 137 km south (Couture et al., 2002; Andrachuk, 2008).

The boom in the oil industry throughout the 1980s saw the construction of larger buildings in the Hamlet and the settlement of the last Inuvialuit families from the land to the community (Couture et al., 2002; Andrachuk, 2008). The Hamlet further developed by creating a 100,000 m^3 freshwater reservoir and be erecting a community centre (Kitti Hall), hockey arena, health centre, and school (Parewick, 2012). Although development in Tuk was progressing, it was brought to a halt when the global demand and cost for oil declined, forcing oil companies to abandon the area (Couture et al., 2002; Parewick 2012). Around the same time, the DEW Line site also closed, and the Hudson’s Bay Trading Post converted to the Northern Store, selling groceries and general merchandise (Parewick, 2012). The activity of oil companies has been on and off ever since this time, but the presence has not been as great as in the 1980s.

4.2 Biophysical Context

The land area of the Hamlet of Tuktoyaktuk is 13.9 km^2 and it is situated on the Arctic Coastal Plain (Rampton, 1988; Hill, Barnes, Héquette, & Ruz, 1994; Statistics Canada, 2012). The majority of the population is established on the northern portion of the hamlet peninsula, which ends in a hook-shaped sand spit. To the west lies the Beaufort Sea (Kugmallit Bay) and to the east is Tuk Harbour. At the mouth of the harbour is a 1.3 km long island that serves as a natural barrier between the inner waters and the Beaufort Sea, decreasing wave exposure and subsequently erosion inside the harbour.

Tuktoyaktuk lies at 69° 27’ North, so the winters are long and cold and the summers are cool and short. The 1971-2000 normal temperatures for the area are -25.9 ± 4.8°C during the coldest month, January, and 10.9 ± 2.1°C when it is the warmest in July (Environment Canada, 2013a). The northern latitude of Tuk also places it within the continuous permafrost zone (Couture et al., 2002). In 2002, the layer of permafrost beneath the Hamlet was approximately 500 m thick, with an active layer (seasonal thaw depth) of roughly 0.5 m (Couture et al., 2002). Consequently, the majority of the sediments are either saturated or have excess quantities of ice, which are present in multiple forms including veins, pores, wedges, and massive ice bodies or lenses (Couture et al., 2002; Johnson, Solomon, Berry, & Graham, 2003; Manson et al., 2005). Ice can also be found within pingos, which are cone-shaped ice-cored mounds (Mackay, 1998).

The Hamlet of Tuk is littered with thermokarst lakes, which are formed by melting of excess ice at depth by formation of a thaw zone (talik) beneath water deep enough that it cannot freeze to the bottom in winter (Murton, 2001). Pingos contrast these depressions, protruding out of the terrain (Mackay, 1998). The Tuk Peninsula has 1,350 pingos, which is the highest concentration in the world (Mackay, 1998; Couture et al., 2002). In acknowledgement of the pingo-phenomenon in Tuk, the federal government designated the Pingo Canadian Landmark 5.5 km southwest of the Hamlet (Parewick, 2012). Other than the pingos, the largest of which stands 50 m high and 300 m in diameter, the Tuk Hamlet can generally be characterized as a low-relief, ice-rich tundra of the Arctic Coastal Plain (Couture et al., 2002; Johnson et al., 2003; Manson et al., 2005; Parewick, 2012).

4.3 Socioeconomic Context

4.3.1 Infrastructure and services

Tuktoyaktuk is the most northerly community accessible by road in Canada, and the largest coastal settlement in the Canada's territory of the western Arctic (Shah, 1982; Johnson et al., 2003; Parewick, 2012). It is also one of the best-equipped in terms of the quantity and variety of infrastructure and services that are available, which is directly linked to the heavy historical presence of the military (DEW Line site) and the oil industry (Couture et al., 2002).

Drinking water for the community is sourced from Kudlak Lake on the eastern side of the harbour (Andrachuk, 2008; GNWT, n.d.). The water is pumped under the harbour to the reservoir in the community, which is the same one that was built in the 1980s; the water treatment facility, though, was upgraded in 2010. The community has established a sewage collection system whereby trucks transport household wastes to a nearby sewage lagoon, which lies seaward of and adjacent to the municipal dump (Couture et al., 2002; Andrachuk, 2008). There is a community health centre, an RCMP detachment, volunteer firefighters, and recreational facilities including playgrounds and a summer swimming pool (Couture et al., 2002; Hamlet of Tuktoyaktuk, n.d.). There is also Mangilaluk School, which has a student population of approximately 200 from Kindergarten to Grade

12 and a teaching staff of 24 (Beaufort Delta Education Council, n.d.). In addition, there are mechanic garages and grocery, hardware, and craft stores (Couture et al.,2002).

Tuk Harbour has been deemed one of the safest harbours for shipping in the Mackenzie Delta region due to its physical characteristics (Couture et al., 2002; Andrachuk, 2008). It serves as an important site for many industries and companies, one of which is the Northern Transportation Company Ltd. (NTCL). The NTCL transports good and store foods, and uses the port in Tuk as a transhipment point for the sealift to other communities in the Inuvialuit Settlement Region.

4.3.2 Social and economic systems

As mentioned, the majority (roughly 80%) of the Tuk population are of Inuvialuit (Inuit) descent. However, only about 22% of the people over the age of 15 speak an Aboriginal language, even though nearly all children ages 5-18 are enrolled in school and thus are taught Inuvialuktun, their native tongue (IRC, 2011; Mangilaluk School, 2013). Even though the traditional language may not be spoken, traditional hunting, trapping, and fishing activities are still an important part of peoples' lives. These practices not only hold a cultural connection, but the bounty is a source of food and some seasonal income for many (Andrachuk, 2008; Couture et al., 2002). In 2008, 63% of households in Tuk relied on country foods for at least half of their meat and fish consumption, although only approximately 6% of the people over the age of 15 participated in catching the foods (IRC, 2011).

In 2011, most homes in Tuk were double (30%) or single (21%) occupancy, though a noteworthy 17% housed more than six people (Statistics Canada, 2012). Many of these residences have adequacy problems and are in need of major repairs (IRC, 2011). Over half the population lives in public housing, for which the Tuktoyaktuk Housing Association, in partnership with the NWT Housing Corporation, is responsible (NWT Housing Corporation, n.d.). Thus, there is still a large portion of people left in charge of paying for and carrying out their own home repairs. Thirty-two percent of families in Tuk earned less than $30,000 in 2008 from the formal economy, and the mean personal income was $32,204, meaning that many are faced with a significant financial limitation to conducting these repairs (IRC, 2011). Regardless of the state of a persons' home, living in a remote Arctic community is accompanied by a high cost of living, particularly with the additional expenses of the necessary equipment for accessing country foods, such as skidoos and boats (Andrachuk & Smit, 2012).

Seventy-four percent of the Tuktoyaktuk population was employed in 2009, but nearly half these people were labelled unskilled or having a low skill set (IRC, 2011). There are not many job opportunities in Tuk, especially that require a higher education. Consequently, many individuals opt out of seeking to further their formal education, as they do not want to leave their family and friends in search of employment (Andrachuk, 2008; Andrahuck & Smit, 2012). The jobs that are available are mostly in oil and gas exploration and petroleum industries, construction companies, and in the transportation industry, primarily through NTCL (Couture et al., 2002; Andrachuk & Smit, 2012; Legislative Assembly of the NWT, n.d.). There are also opportunities for general wage employment, such as working retail, and through tourism and guided sport hunting. In addition, there are some positions available in the local government, health and social services, as well as the school.

4.4 Climate Change

4.4.1 Impacts and projections

One of the first indicators of climate change is a rising trend in temperatures. In January 2013, the average mean temperature was -29.4 °C, which does fall within the 1971-2000 normal range of -25.9 ± 4.8 °C (Environment Canada, 2013b). In July 2012, though, the average mean temperature exceeded the normal range of 10.9 ± 2.1 °C with a temperature of 16.1 °C. This warming is a great concern for many reasons.

The permafrost in Tuk is naturally warmer than other areas, with temperatures ranging from 0 to -2 °C (Couture et al., 2002). Therefore, even a small temperature increase could thaw the ground ice and cause the land to subside. In 2002, the projection was made that by 2050 the active permafrost layer would grow by 20-30 cm (Couture et al., 2002). If the active layer encounters excess ice as it grows deeper, the ground becomes less stable. Many of the foundations of buildings in Tuk rely on the permafrost for structural support, and if the integrity of the underlying ground is lost, then the buildings will likely be damaged (NWT Environment and Natural Resources, 2008).

Warming temperatures also cause sea ice to melt. There has not only been a reduction in the spatial extent of the ice, but also the length of time that it is present (ACIA, 2005; Lemke et al., 2007; Forbes, 2011; Pearce et al., 2011). Less sea ice means there is a greater area and duration of open water, therefore waves are able to develop further offshore and build greater momentum before coming in contact with land (Manson et al., 2005; Vermaire et al., 2013). This increased wave exposure will likely cause problems with flooding and will increase coastal erosion, threatening the people and infrastructure near the coast.

The sea level in the Beaufort Sea as measured by a tide gauge relative to the land surface (the so-called 'relative' sea level) has been rising for millennia (Hill et al., 1985; Hill et al., 1994). From tide-gauge records, the rate of relative sea-level rise over recent decades has been 3.5 ± 1.1 mm/year since 1961 (Manson & Solomon, 2007) and regional subsidence at Tuk is about 2.5 mm/year (James, 2011). This subsidence rate is added to projections of sea-level rise from climate scenarios to obtain projections of local relative level, which range from about 20 cm to just under 1 m for the coming 90 years (2010-2100) (James, 2011).

The frequency and intensity of storms is also increasing in the region (Couture et al., 2002; Vermaire et al., 2013). Typically, the stormiest time of year is late summer and the beginning of autumn, which is usually before the winter sea ice has developed (Couture et al., 2002; Manson et al., 2005). This means that waves have more space to develop, resulting in greater storm surges, leading to flooding and extensive erosion. The two worst storms on record were in 1944 and 1970. The first destroyed the original Hudson's Bay Company Trading Post that was located on the tip of the peninsula, and the second contaminated Kudlak Lake, the community's source of freshwater, and eroded over 13 m in a single area. Many other areas have been impacted by storms and erosion over the years as well, such as the sewage lagoon and dump site, both of which have begun to contaminate nearby shorelines as a result (Couture et al., 2002; Andrachuk, 2008; Parewick, 2012).

Tuktoyaktuk is currently faced with problems of erosion, flooding, and an unstable permafrost layer, and climate change stands to exacerbate the situation. A longer open-water season and more rapid relative sea level rise are likely to increase erosion and flooding, which will be accelerated further by the degradation of permafrost and the subsequent subsidence of land (Couture et al., 2002).

4.4.2 Adaptations

The Hamlet of Tuktoyaktuk was informed early on that the most cost-effective method for coping with the extensive erosion was to abandon the area and rebuild further inland (Andrachuk, 2008). Aklavik, an Inuvialuit and Gwich'in community in the Mackenzie Delta, was relocated by the Federal Government (Johnson, 2001), though many people refused to leave. The new settlement, Inuvik, on the East Channel (eastern edge of the delta) is now one of the largest and most developed Canadian Arctic communities in the Northwest Territories. In Tuk, political leaders have fought to focus their efforts on controlling the erosion and protecting the shoreline. This decision was made because of the financial and technical constraints of relocating, and the fact that community members feel there is nowhere for them to go (Andrachuk, 2008).

Tuktoyaktuk's journey to adapt to the problem of erosion officially began after the 1970 storm that threatened their drinking water supply. Federal Government experts came to Tuk and conducted a study of the mechanisms that underpinned the severe erosion, and considered potential response methods (Couture et al., 2002; Johnson et al., 2003; Andrachuk, 2008). The study concluded that the major issues were subsidence due to warming and degrading permafrost along the coast and exposure to waves (Shah, 1982; Couture et al., 2002; Johnson et al., 2003; Andrachuk, 2008). It was recommended that the best solution for Tuk would be to implement a Longard Tube System, which is a set of sausage-shaped tubes filled with sand to reduce future damage.

The system of tubes was designed and implemented in 1976 along the western shore of the peninsula in front of what is now the seniors' complex; at the time it was the site of the school (Couture et al., 2002). Unfortunately, due to financial limitations, the system was not able to be completed as planned. The tubes were successful in slowing erosion, at least until they were destroyed in the early 1980s by a combination of vandalism and increased storminess (Shah, 1982; Couture et al., 2002; Johnson et al., 2003; Andrachuk, 2008).

In 1986, a beach nourishment program was implemented as an alternative approach to reduce erosion along Tuk's shoreline. Sand was dredged from the harbour to fill sand bags, which were stacked along the same shoreline as the former Longard Tubes (Couture et al., 2002; Johnson et al., 2003; Andrachuk, 2008). This method protected the shore from waves and slowly released sand so as to replenish that which had been eroded (Couture et al., 2002; Johnson et al., 2003). Although the bags likely decreased erosion by protecting the exposed coastal ground ice from waves, the maintenance costs were tremendous; the bags tended to break open during storms, costing the territorial government $100,000 a year for eight years to repair and refill them. In a 1993 storm, half of the entire barrier system was removed, and the following year the project was finally abandoned, and the approach deemed inappropriate for protecting the Tuktoyaktuk coastline (Couture et al., 2002).

The Hamlet was not ready to give in yet, though. Concrete was taken from the old school in 1996 after it had been abandoned, and was added to the surviving sand bags at the northern end of the peninsula (Couture et al., 2002). A number of small storms over the following year partially destroyed the hardening, but with funding from the

Government of the NWT Department of Municipal and Community Affairs, limestone boulders were imported from Inuvik and added to the barrier (Couture et al., 2002; Andrachuk, 2008). Unfortunately, though, the project was not created with the guidance of an expert, and as a result the Hamlet completed the project unaware that the boulders they were bringing in were too small and were placed too far offshore to support the functioning of the pre-existing sand bags (Couture et al., 2002; Andrachuk, 2008).

Continuing with the efforts to protect the end of the peninsula, forty concrete slabs donated by an oil company were lined along a 100 m segment of the shoreline (Couture et al., 2002; Andrachuk, 2008). This time, though, they were positioned according to an engineered design. Between the slabs and the limestone boulders, Tuk has been successful thus far in slowing and in some cases preventing erosion along the northern portion of the peninsula (Couture et al., 2002).

Regardless of the extensive efforts to combat erosion, a number of buildings have either been removed (the original school, the RCMP detachment) or have been damaged and subsequently removed (the original curling rink) (Shaw et al., 1998; Couture et al., 2002; Andrachuk, 2008; Parewick, 2012). Andrachuk (2008) interviewed citizens of Tuk both formally and informally, and reported that there was a sense among community members that relocation will eventually be inevitable. However, until that point, they will continue to try to preserve their physical community.

Chapter 5: Results

5.1 Socioeconomic Indicators

5.1.1 Land use

There were 28 land uses in total. Each was placed into one of 11 categories (Figure 5). These categories were assigned points based on the impact that would be felt by the community if the particular land use were damaged (Table 3).

Table 3. Categories of land uses and the number of points assigned to each for the land-use indicator.

Points	Category	Land use
11	Critical infrastructure	Airport
		Drinking water
		Dump
		Sewage lagoon
		Nursing station
		NTCL
		Fire station
		Roads
10	Seniors complex	Seniors care
9	Residential infrastructure	Residential
8	Community infrastructure	Cemetery
		Church
		Community centre
		Northern store
		School
		RCMP
		Ice house
7	Other infrastructure	Shops
		Recreation
		Storage
6	Industrial infrastructure	Industrial
5	Tourism infrastructure	Sod huts
		Our Lady of Lords (boat)
4	Camps	Camp
3	Anthropogenic land	Other anthropogenic; e.g. abandoned buildings
2	Disturbed land	Disturbed but natural
1	Untouched land and water	Natural and water

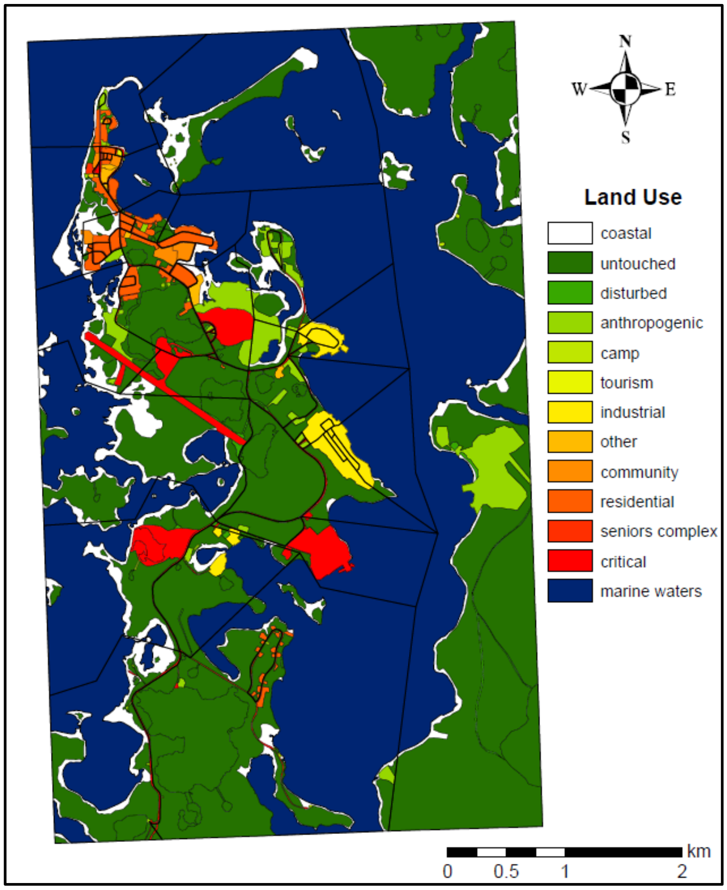

Figure 5. **Geospatial distribution of land-use categories.**

The results of this land-use analysis ranged from 1.02 (block 432) to 11.00 (block 324). It is not possible that a single block could have scored less than 1.00, so the relative rankings were assigned as follows (see Figure 6 for geospatial distributions):

Rank:	**1**	**2**	**3**	**4**	**5**
Land-use weighted average	1-2.99	3-4.99	5-6.99	7-8.99	9-11
No. blocks	13	12	15	6	16

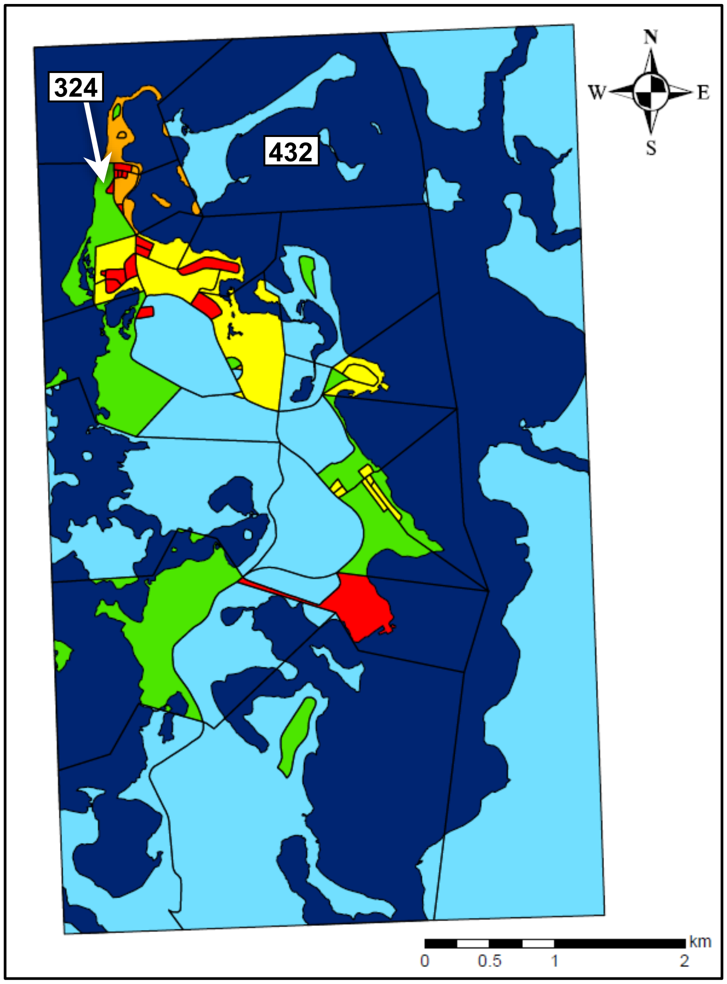

***Figure 6*. Geospatial distribution of the land-use rankings within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue, marine waters. Block 324 is the most sensitive; block 432 is the least sensitive.**

5.1.2 Population density

The population within the DBs ranged from 0 to 151 people (block 401). The smallest block was 418 (0.001207 km^2 land), and the largest was 408 (4.527 km^2 land). The resulting densities ranged from 0 to 5376 people/ km^2 (block 307). To cope with this wide range, the densities were ranked from lowest to highest, which was used to assign the final values (see Figure 7 for geospatial distributions):

Rank:	1	2	3	4	5
Population density	Rank 1 (no people)	Rank 2-7	Rank 8-13	Rank 14-19	Rank 20-25
No. blocks	40	6	6	6	4

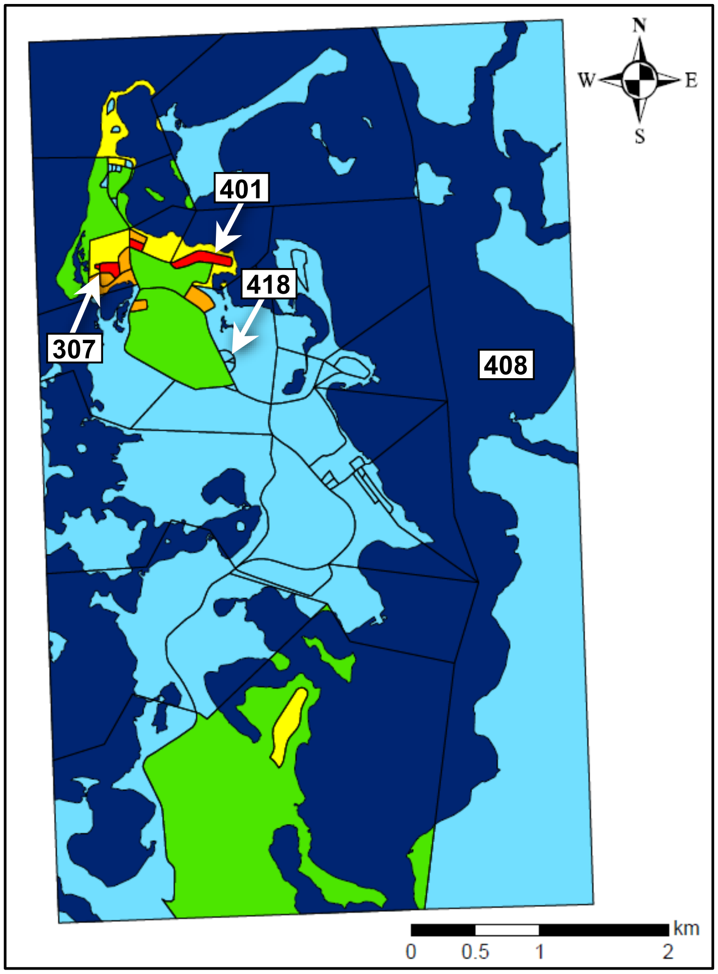

***Figure 7*. Geospatial distribution of the population density rankings within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue, marine waters. Block 401 has the largest population; block 418 is the smallest; block 408 is the largest; block 307 has the greatest population density therefore is the most exposed.**

5.1.3 Dwelling density

The number of dwellings in a single DB ranged from 0 to 41 (block 401), and the densities ranged from 0 to 3175 dwellings km^2 (block 328). As was done for the population density indicator, the densities were ranked and then assigned final values (see Figure 8 for geospatial distribution):

Rank:	**1**	**2**	**3**	**4**	**5**
Dwelling density	Rank 1 (no dwellings)	Rank 2-8	Rank 9-15	Rank 16-22	Rank 23-29
No. blocks	36	7	7	7	5

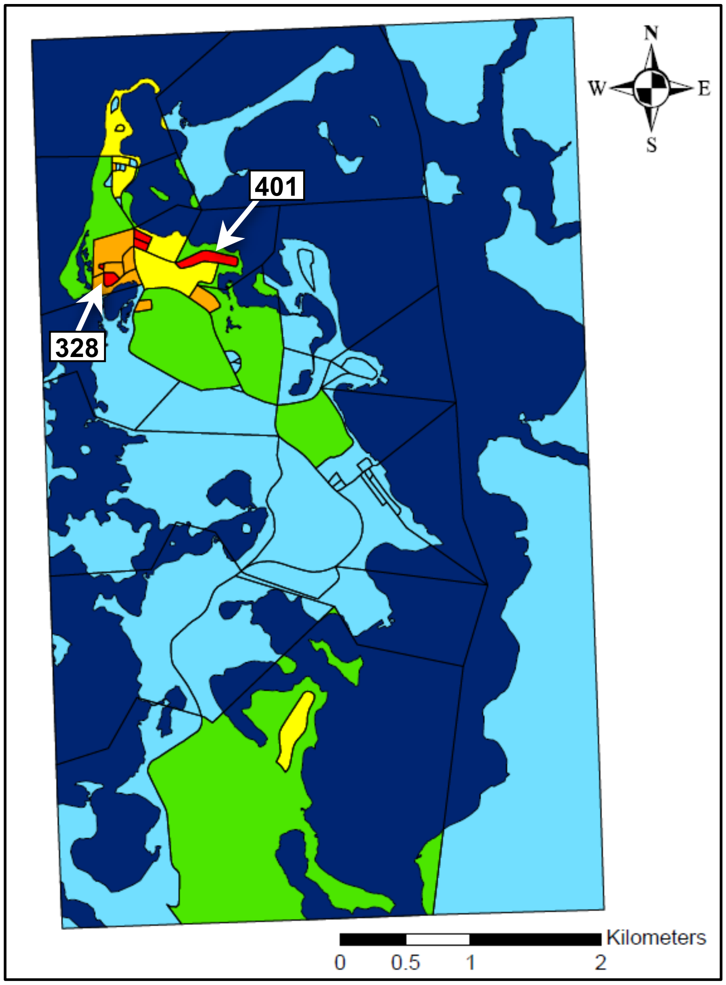

Figure 8. **Geospatial distribution of the dwelling density rankings within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue, marine waters. Block 401 has the most dwellings; block 328 has the greatest dwelling density, therefore is the most exposed.**

5.1.4 Distance of buildings to the shore

The closest buildings were less than 2 m from the shore (block 316) and the furthest were 563 m (block 318). The median distances of buildings to the shore per DB ranged from approximately 19 m (block 432) to roughly 390 m (block 311). These distances were divided evenly into the following ranks (see Figure 9 for geospatial distribution):

Rank:	**1**	**2**	**3**	**4**	**5**
Distance of buildings	No buildings	300-400 m	200-300 m	100-200 m	0-100 m
No. blocks	11	1	2	15	33

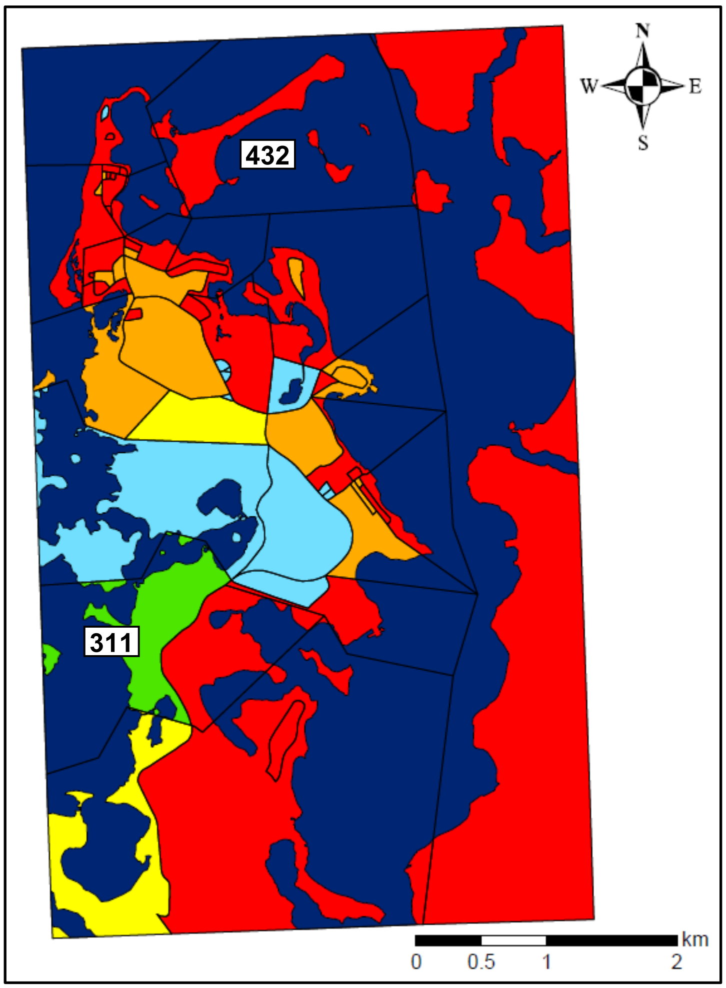

***Figure 9*. Geospatial distribution of the rankings for median distance of buildings to the shore within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue, marine waters. Shortest median distance of buildings to the shore are in block 432; furthest median distance of buildings to the shore are in block 311.**

5.1.5 Distance of roads to the shore

The most sensitive roads had a point less than 2 m from the shoreline (blocks 416, 426, 431), and the least sensitive had a minimum distance of roughly 355 m (block 318). All the recorded distances were ranked from largest to smallest, and then assigned points based on the following system:

Points:	**1**	**2**	**3**	**4**	**5**
Road *i*	No roads	Ranks 1-12	Ranks 13-24	Ranks 25-36	Ranks 37-48

All the points for roads recorded within a single DB were summed; the results ranged from 2 (blocks 313 and 417) to 14 (block 431). These summed points were used to assign the final values (see Figure 10 for geospatial distribution):

Rank:	**1**	**2**	**3**	**4**	**5**
Distance of roads	No roads	1-4 points	5-8 points	9-12 points	13-16 points
No. blocks	27	13	17	3	1

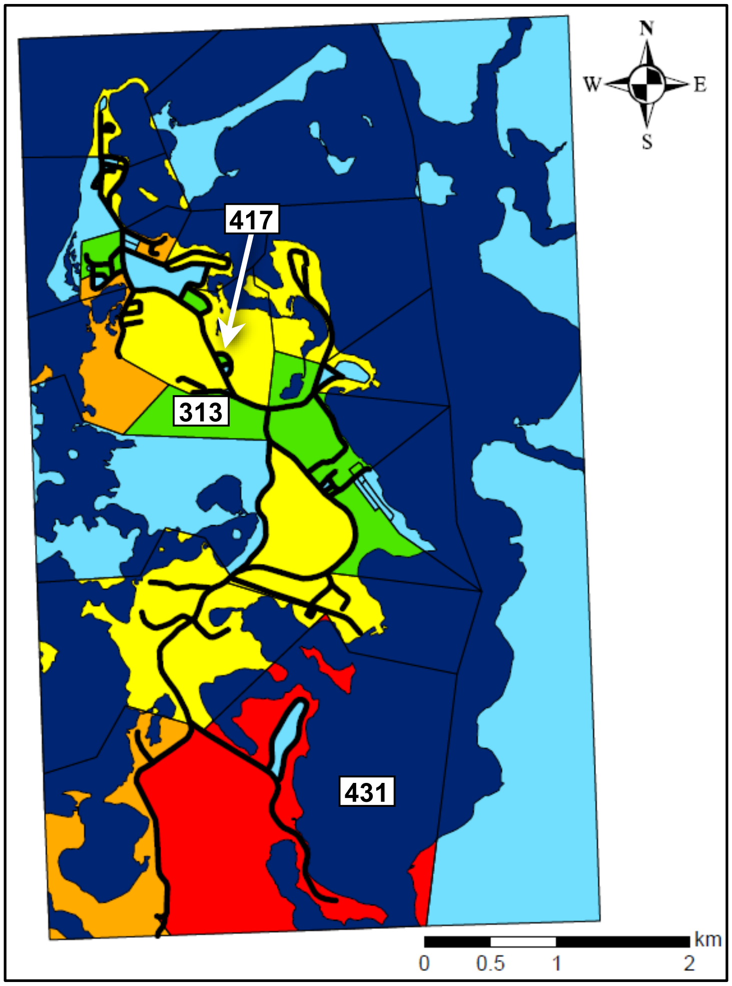

***Figure 10*. Geospatial distribution of the rankings for the distance of roads to the shore within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue, marine waters. Blocks 313 and 417 have the least exposure and sensitive roads; block 431 has the most exposed and sensitive roads.**

5.2 Biophysical Indicators

5.2.1 Landform

Points were assigned to each coastal segment based on the following system (see Figure 11 for geospatial distribution of dominant landforms):

Dominant landform:	Supratidal	6
	Beach	5
	Cliff	4
	Driftwood	3
	Rip rap	2
	Concrete/anthropogenic	1
	Tidal inlet	0
Additional features:	Detached barrier	+2
	Attached barrier or spit	+1
	Driftwood	-1

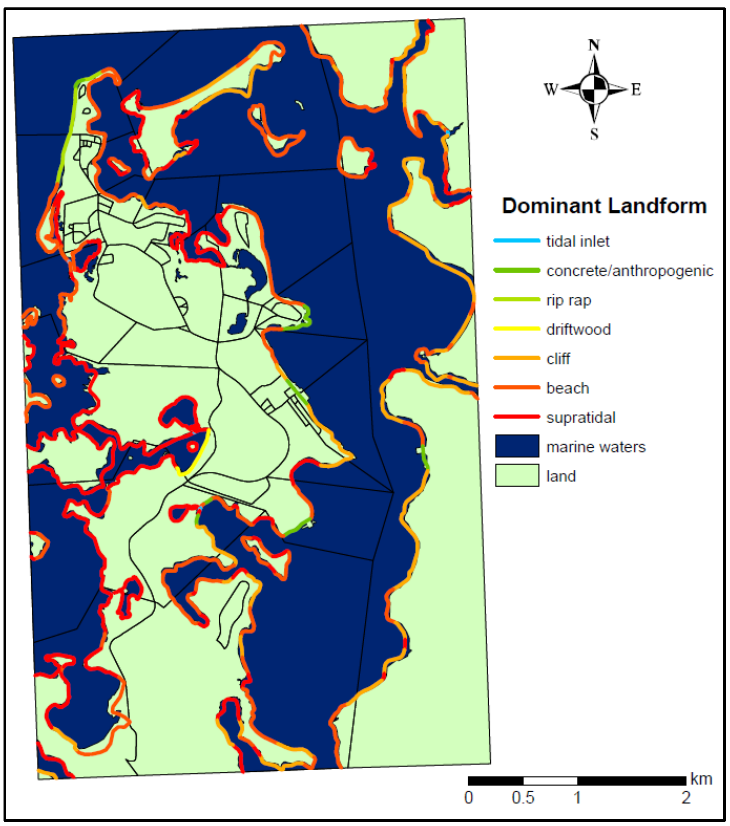

***Figure 11*. Geospatial distribution of dominant landforms.**

Each coastal segment received a number of points based on the dominant landform, and points were added or subtracted from these if additional features were present. The total points of each coastal segment were multiplied by the percent-length of the segment. The products of all the line segments within one DB were then summed, producing a range of 1.04 (block 408) to 6.00 (block 420). No DB had a score between 0 and 1, so the following ranking system was used (see Figure 12 for geospatial distributions):

Rank:	**1**	**2**	**3**	**4**	**5**
Landform score	Inland	1.00-2.25	2.25-3.50	3.50-4.75	4.75-6.00
No. blocks	41	1	2	3	15

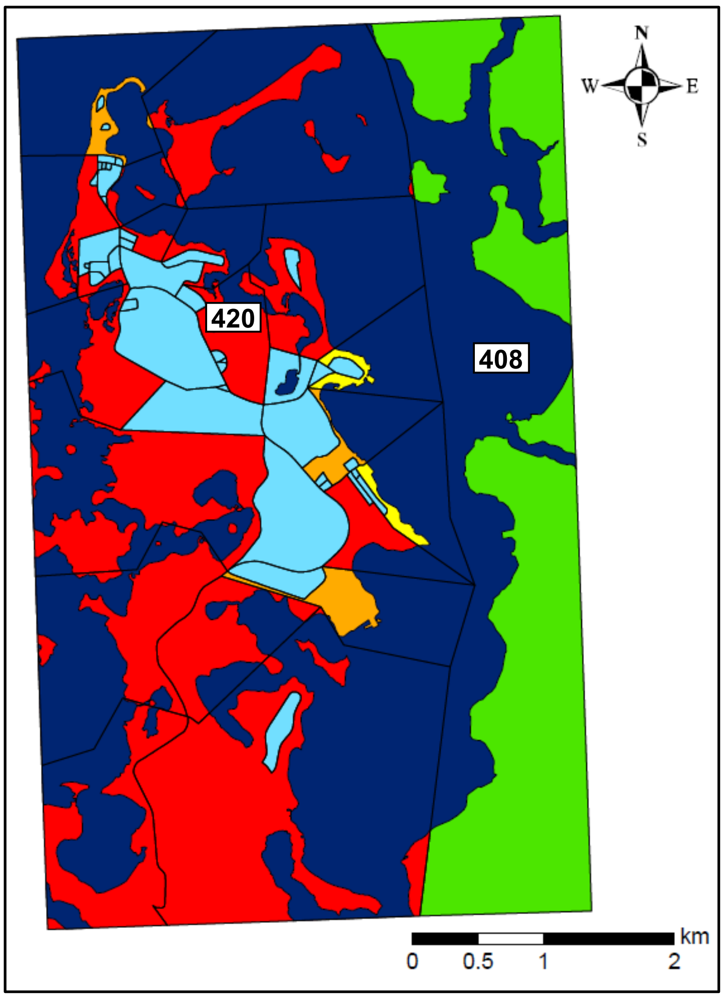

***Figure 12*. Geospatial distribution of the landform rankings within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue is marine waters. Block 408 is the least sensitive of those receiving scores; block 420 is the most sensitive.**

5.2.2 Elevation

Elevations throughout the Hamlet ranged from -0.85 m to 352.3 m. the DB with the lowest mean elevation was 411 (1.14 ± 1.402 m), and the highest was 415 (10.07 ± 2.498 m). This range was divided into the following five ranks (see Figure 13 for geospatial distributions):

Rank:	**1**	**2**	**3**	**4**	**5**
Mean elevation	>9.5 m	7.0-9.5 m	4.5-7.0 m	2.0-4.5 m	<2.0 m
No. blocks	1	4	9	38	10

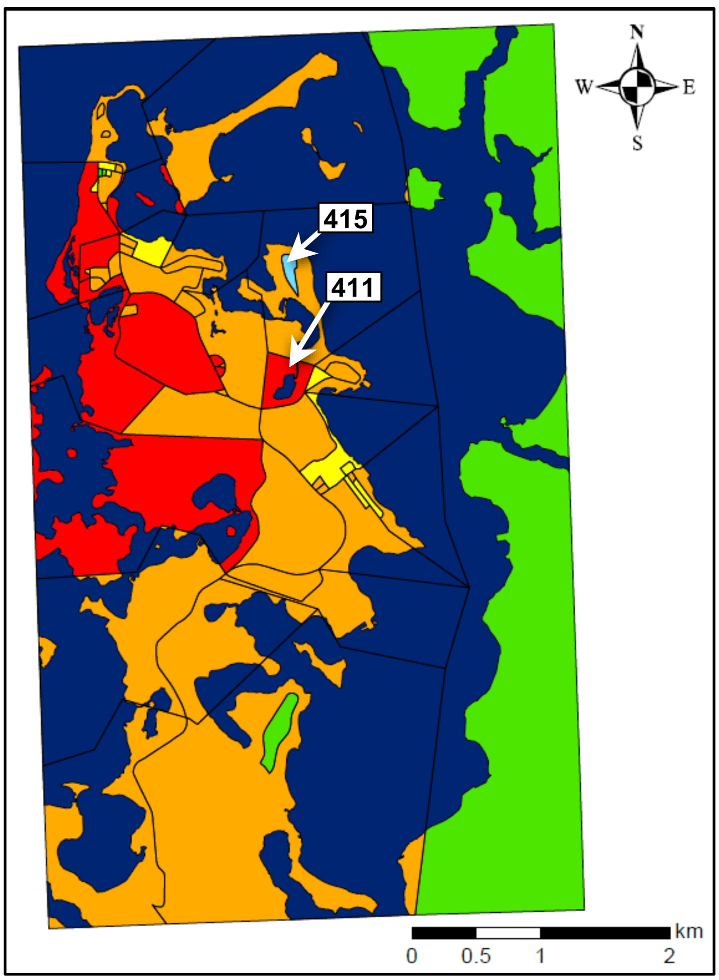

***Figure 13*. Geospatial distribution of the elevation rankings within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue is marine waters. Block 411 is the most sensitive; block 415 is the least sensitive.**

5.2.3 Exposure to storm waves

Exposure to storm waves was not calculated, but rather was estimated based on the knowledge that storm waves typically come from the northwest. Each DB was assigned a rank based on the following values (see Figure 14 for geospatial distributions):

Rank:	**1**	**2**	**3**	**4**	**5**
Degree of exposure	Inland	Low	Medium	High	Very high
No. blocks	41	7	7	3	4

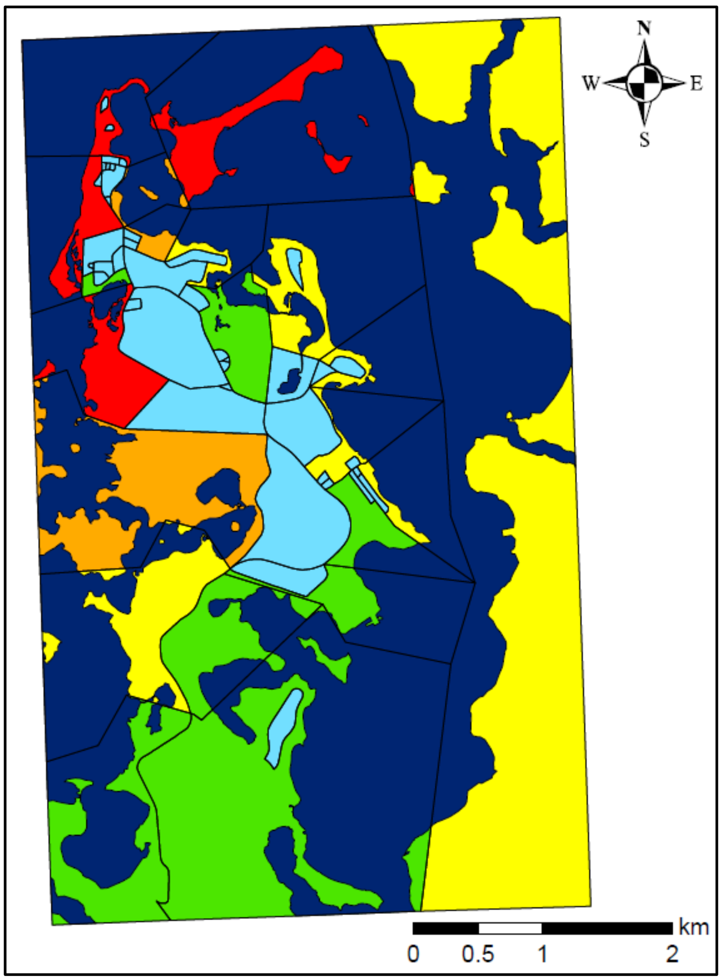

***Figure 14*. Geospatial distribution of the rankings for wave exposure within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue is marine waters.**

5.2.4 Ground ice volume

Most ground ice is present within pores, and so when it melts it remains in the pore as water. It is the excess ice (that which is outside the pores) that, when melted, will cause the land to settle (Couture et al., 2002). Therefore, the decision was made to use the percent excess ice (PEI) rather than the percent ice volume (PIV) for this indicator. For coastal blocks with more than one value, the length of coastline known to be a particular geomorphology was translated into a percent-length of the coastline within a block using the same method that was employed for the landform indicator. This percent-length was then multiplied by its corresponding PEI, and all the products of the lines within a DB were summed to yield a weighted average for that DB. For inland blocks, only one value was calculated.

The average and weighted average PEI values ranged from 0 (blocks 323 and 420) to 88.5 (block 414). The first rank was assigned the values of 0-1% excess ice; the remainder (1-89%) was divided equally into the following ranks (see Figure 15 for geospatial distributions):

Rank:	**1**	**2**	**3**	**4**	**5**
Percent excess ice	0-1 %	1-23%	23-45%	45-67%	67-89%
No. blocks	3	21	23	13	2

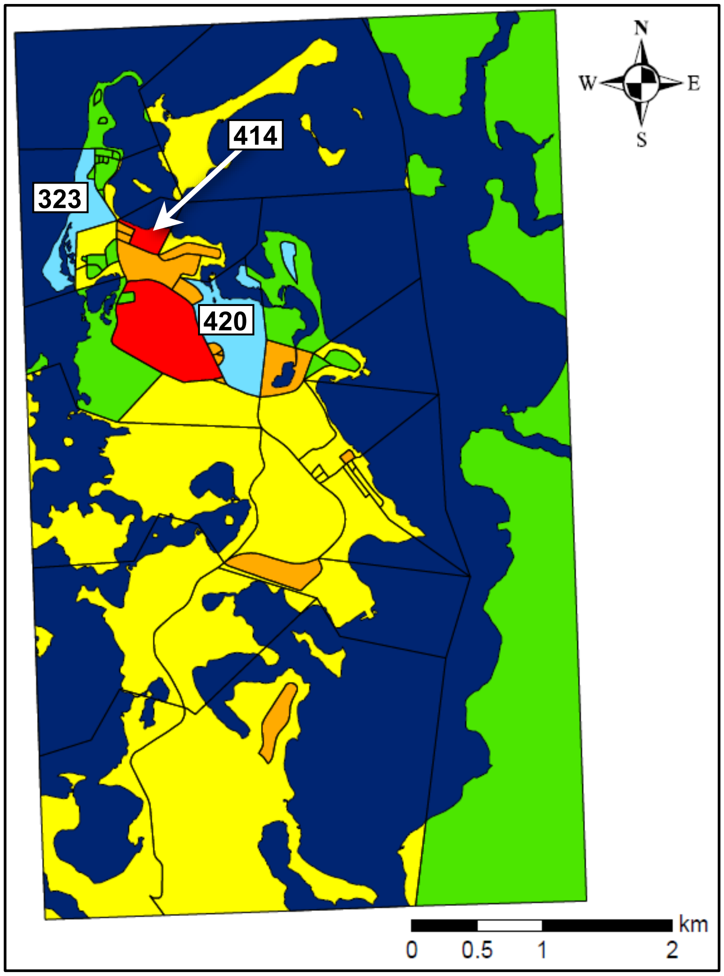

Figure 15. **Geospatial distribution of the rankings for the percent of excess ice within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue is marine waters. Block 323 and 420 are the least sensitive; block 414 is the most sensitive.**

5.2.5 Rate of coastal change

The rates of coastal change throughout the Hamlet ranged from -2.162 m/year (erosion) to 2.870 m/year (accretion) between 1950 and 1985. The median value within each DB was calculated, and the resulting range -0.841 m/year (block 420) to 0.4115 m/year (block 426) . These values were divided into five ranks (see below for ranks and see Figure 16 for geospatial distribution). For blocks that did not have data (311, 312, 329), a ranking of 1-5 was assigned based on the scoring of other blocks with similar wave exposure, elevation, and coastal morphology.

Rank:	**1**	**2**	**3**	**4**	**5**
Rate of coastal change	Inland	0.225 to 0.600 m/yr	-0.150 to 0.225 m/yr	-0.526 to -0.150 m/yr	-0.900 to -0.525 m/yr
No. blocks	41	1	8	6	3

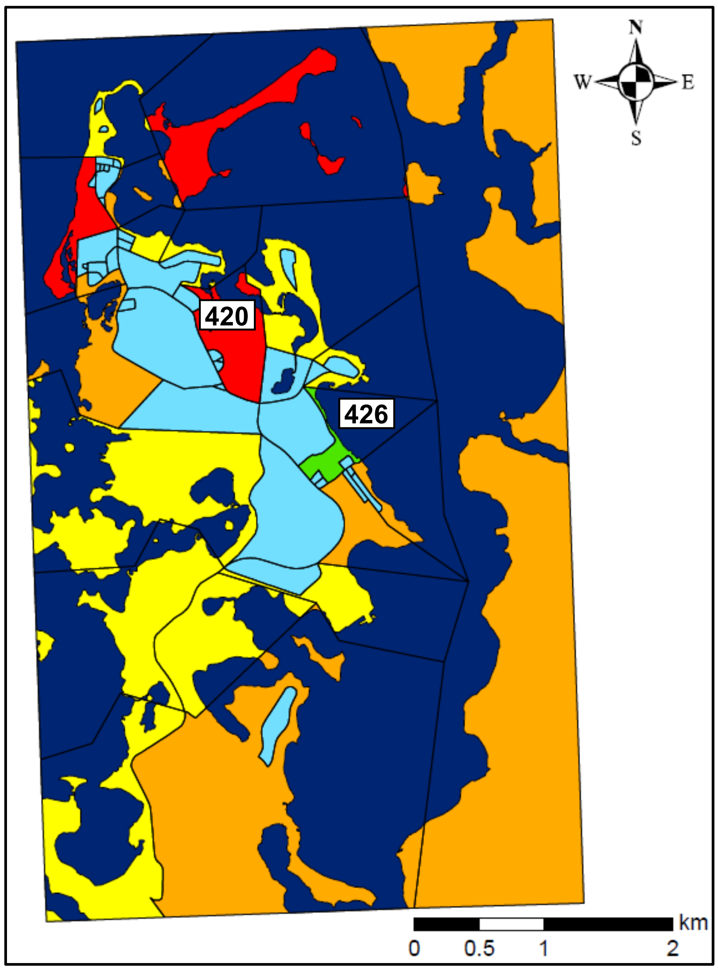

***Figure 16*. Geospatial distribution of the rankings for the rate of coastal change within each dissemination block. Light blue, rank=1; green, rank=2; yellow, rank=3; orange, rank=4; red, rank=5; dark blue is marine waters. Block 420 is the most sensitive; block 426 is the least sensitive of those with coastlines.**

5.3 Overall Results

5.3.1 Socioeconomic exposure-sensitivity

The final scores for socioeconomic exposure-sensitivity ranged from 1 (block 312) to 1,875 (block 401), the least and most exposed and sensitive respectively. All the blocks were then ranked from most to least exposed and sensitive, for which there were 36 ranks (Figure 18). More blocks were in the lesser exposed and sensitive half of the rankings (37 blocks ranked 19-36) than in the more exposed and sensitive half (25 blocks ranked 1-18).

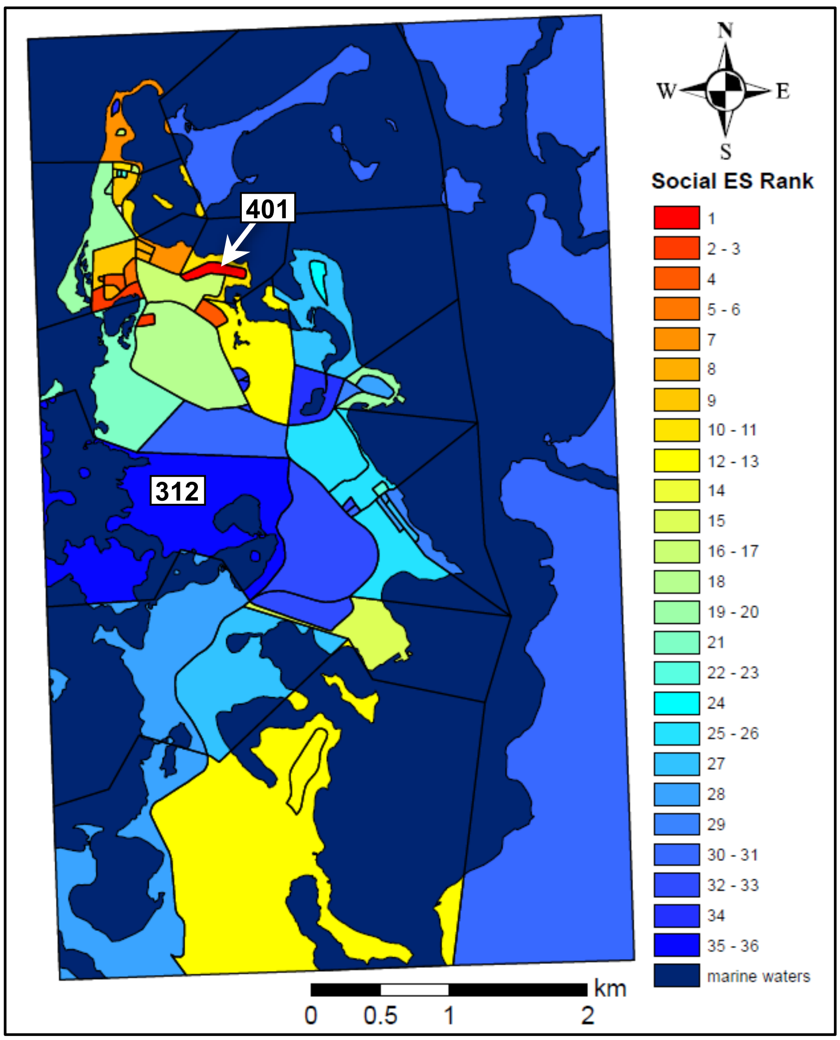

***Figure 17*. Geospatial distribution of socioeconomic exposure-sensitivity rankings. Block 312 has the least socioeconomic exposure-sensitivity and block 401 has the greatest.**

5.3.2 Biophysical exposure-sensitivity

Biophysical exposure-sensitivities ranged from 1 (block 415) to 1,200 (block 432). The blocks were then ranked from most to least exposed and sensitive (Figure 17). There were a total of 25 rankings, and more than half the blocks fell within the lesser exposed rankings (18 blocks ranked 1-13; 44 blocks ranked 14-26).

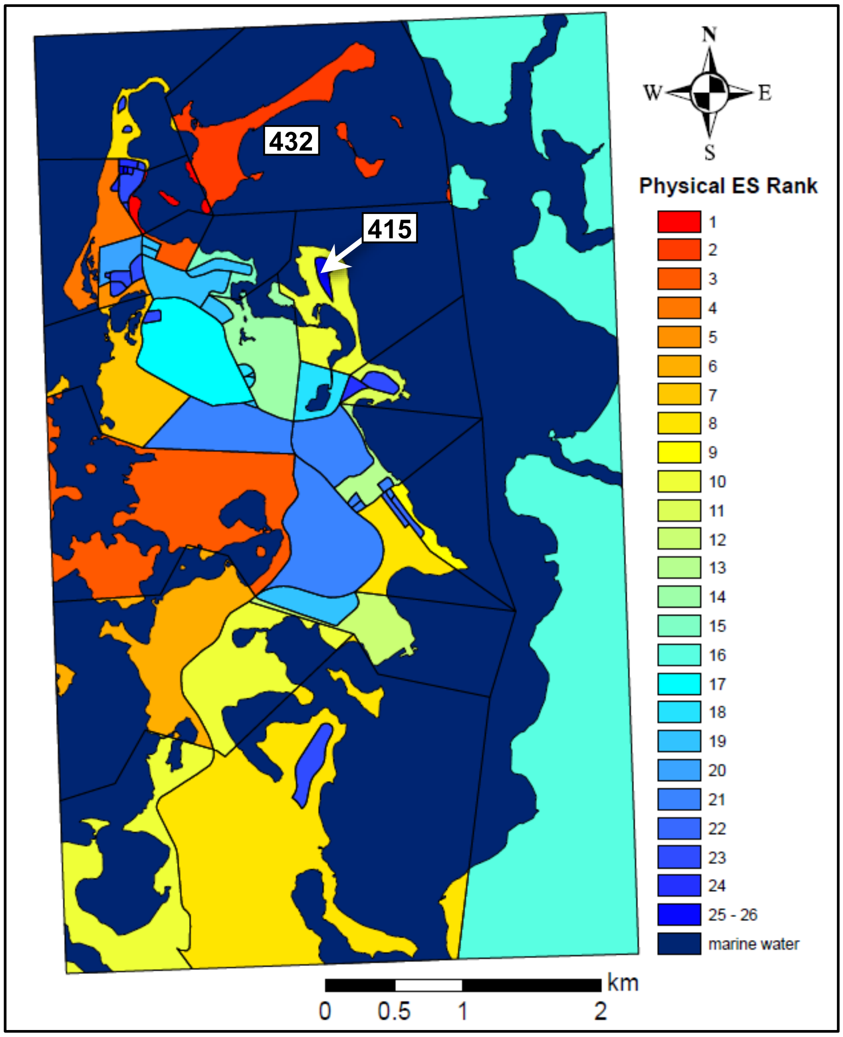

***Figure 18*. Geospatial distribution of biophysical exposure-sensitivity rankings. Block 415 has the least biophysical exposure and sensitivity; block 432 has the greatest biophysical exposure and sensitivity.**

5.3.3 Overall exposure-sensitivity

There was a total of 51 overall exposure-sensitivity ranks, with scores ranging from 16 (block 320) to 576,000 (block 315) (Figure 19). Thirty blocks fell within ranks 1-25, and 21 ranked 26-51; therefore more than half of the blocks were more exposed and sensitive.

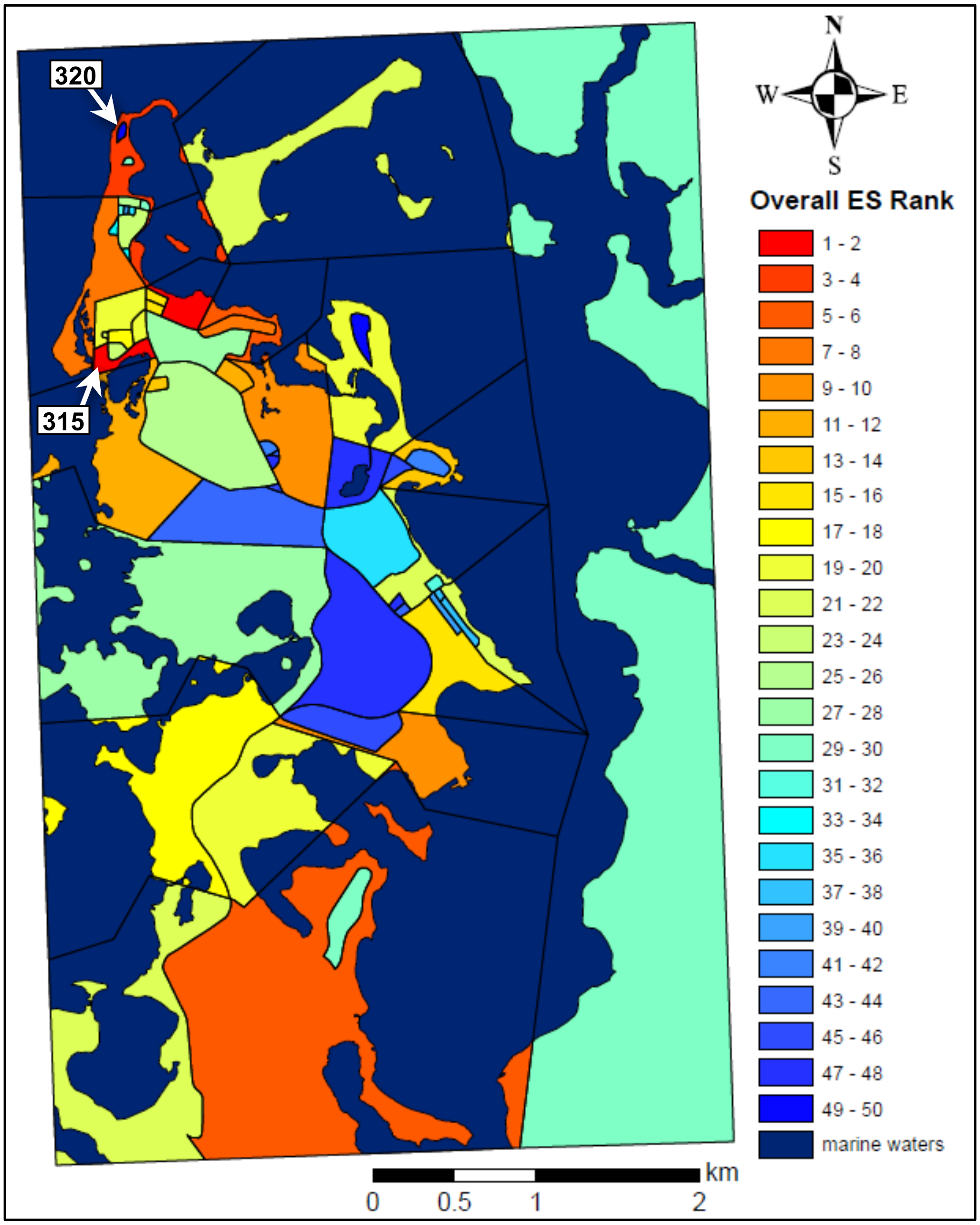

***Figure 19*. Geospatial distribution of overall exposure-sensitivity rankings. Block 320 is the least exposed and sensitive overall; block 315 is the most exposed and sensitive overall.**

Chapter 6: Discussion

6.1 Approach

6.1.1 Vulnerability

The working definition of vulnerability for this study was the same as the definitions used by Klein and Nicholls (1999), Berkes (2007), Füssel (2007), Andrachuk (2008), Andrachuk and Smit (2012), and Cardona et al. (2012): a human-environment systems' exposure to stresses, sensitivity of being impacted, and ability to cope with changes. Füssel (2007) refers to this approach to understanding vulnerability as the resilience approach. Taking this route meant that the project had to integrate the human system and the environment within which it functioned. It was important that such a holistic view was taken to understanding vulnerability because the goal of the project was to create a methodology that assessed the overall vulnerability of a community; therefore, all components needed to be addressed.

6.1.2 Conceptual framework

In designing the conceptual framework, both the biophysical and socioeconomic systems were included. Balica et al. (2012) also included administrative and institutional systems in their flood vulnerability index, which includes legislation, regulation, as well as decision, planning, and management processes. This component was unnecessary for this study within communities because the characteristics of the administrative and institutional systems would not vary within the small area of an Arctic community.

The development of the conceptual framework and the process of teasing apart the socioeconomic and biophysical systems to establish a list of indicators highlighted the complexity of the coastal zone. Breaking down the larger image of the coastal zone into its biophysical and social elements, and defining relationships between exposures, sensitivities, adaptive capacities, and variables of climate change was an intellectual challenge. It was an important process, though, as it yielded a better understanding of Arctic coastal zones and coastal communities, and how the socioeconomic and biophysical systems might be impacted by climate change.

6.1.3 Vulnerability assessments

The Arctic Climate Impact Assessment (ACIA; 2005), Champalle et al. (2013), and numerous other authors (refer to Table 1) noted the importance of collaboratively completing vulnerability assessments, and this was reiterated through the process of developing and analyzing the indicators of this study; one person cannot possibly understand or have access to all the information required for all the indicators. The assessment of Tuktoyaktuk was conducted by one researcher in collaboration with staff of the Geological Survey of Canada-Atlantic with extensive experience in Tuktoyaktuk. For lack of time and resources, the study did not include community consultation or the opportunity to source information from community members and other experts. Therefore, it must be clearly noted that this project did not complete a full assessment of the coastal vulnerability of Tuktoyaktuk to climate change; rather it demonstrated how the methodology and some of indicators could be applied, which is an important step towards developing a successful vulnerability assessment within an Arctic community (Hinkel, 2011).

A relative 1-5 scale was developed for each indicator, as was done by McLaughlin and Cooper (2010), Mustafa et al. (2011), Özyurt and Ergin (2010), and Tiburan et al. (2010). In contrast, Balica et al. (2012) and Schmidtlein et al. (2008) took mathematical approaches, calculating normative values and converting values to z-scores, respectively. The 1-5 scale was chosen over carrying out calculations because it allows qualitative information to be included, such as traditional knowledge, and it does not require extensive expertise in mathematics.

The ranks of exposure-sensitivity of each indicator within a DB were multiplied to yield an overall exposure-sensitivity score. In some studies, such as those by Balica et al. (2012), Özyurt and Ergin (2010), and Szlafsztein and Sterr (2007), the vulnerabilities of different systems were calculated separately and then summed to yield the overall vulnerability. Although no example was found where all indicators were multiplied, there were many assessments that multiplied the values given to the indicators within the physical or the social systems (Szlafsztein & Sterr, 2007; Hamzah & Omar, 2010; Özyurt & Ergin, 2010; Pendleton et al. 2010). It has been documented in numerous publications that the components of the coastal zone are highly interactive and complex (GESAMP, 2001a). Therefore, especially for assessments in the Arctic where the socioeconomic and biophysical systems are so intricately connected through indigenous culture, it seems more appropriate that all the indicators be considered as part of one overarching human-environment system.

It can be demonstrated through the few indicators selected for the assessment of Tuk that the socioeconomic and biophysical systems are connected through numerous interactions, therefore is appropriate to multiply the values of all indicators (Figure 20). Land use is a result of decisions made by people, which are often based on the biophysical characteristics of different sites, such as landform and elevation. The density of people in an area is also related to the land use, and dwelling density is associated with population density and land use. The distance of roads and buildings to the coast influence one another and they are both related to land use. The landform along a coastline is associated with elevation, exposure to storm waves, land use and population density; and excess ground ice was calculated using the geomorphology (which is associated with the landform) and elevation. The last indicator, the rate of coastal change, is influenced by land use, landform, elevation, exposure to storm waves, and the volume of excess ground ice.

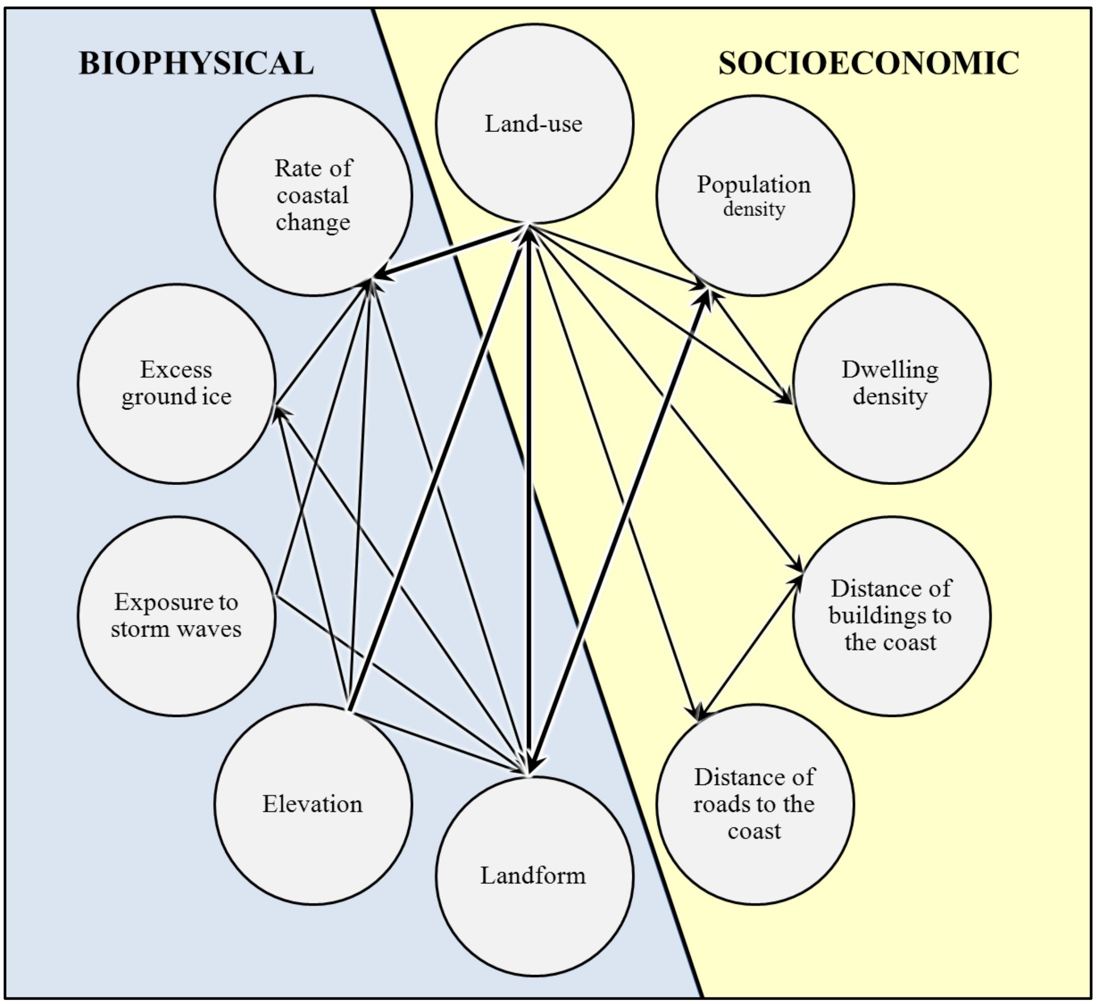

***Figure 20*. Associations between the indicators of biophysical and socioeconomic exposure-sensitivity to climate change that were explored in this study. Darker arrows demonstrate where the boundary is crossed between the biophysical and socioeconomic systems.**

An issue did arise from multiplying the indicator values: the final products were very large and had a wide range. In the assessment of Tuk, the scores for overall exposure-sensitivity ranged from 16 to 576,000, and only 10 indicators were used; the complete assessment of vulnerability proposes 28 indicators, which yields a potential maximum score of 3.73×10^{19}. The range of scores was reduced to a manageable range of 1-51 by ranking each block; it is these numbers that are meant to be the final piece of information used by decision-makers and communicated to the public. In a complete assessment, the maximum range is the number of coastal segments that are evaluated. Therefore, multiplying the indicators is still an appropriate approach as long as it is understood that the products are not indicative of the magnitude of vulnerability, but rather they are to be used to rank coastal segments. Once the coastal segments, or in this case dissemination blocks were ranked, they were transposed to a colour scale and mapped using GIS, a method for which there is significant support in the literature (Mahendra et al., 2011; Mustafa et al., 2011; Preston et al., 2011; Balica et al., 2012). This final map is the final output and key component of this assessment, and is what should be dissemination to the public and used to communicate the results.

6.2 Socioeconomic Indicators

6.2.1 Land use

The 2010 GeoEye image was helpful in developing this indicator, although it was not an entirely accurate approach. It was clear where the natural land areas were, but it was sometime difficult to distinguish between types of infrastructure. Some could be identified through other maps, whereas other infrastructure, such as shops, were labelled based on the guidance of GSC-A staff familiar with the community; some infrastructure was certainly mislabelled, though. There were also difficulties in assigning a level of importance to the different types of land use; the way in which land use was categorized and assigned points in this assessment was an estimate of the views of community members in Tuktoyaktuk. To properly evaluate this indicator, community members must be involved; their input is required to identify the different land uses, and even more so to categorize them and assign a level of relative importance.

It may be useful to extract the evaluation of critical infrastructure from the land-use indicator, so that the exposures of the critical infrastructure could be studied in more detail. If this were done, factors that would need to be incorporated are the different types of critical infrastructure and their distances to the coast. It may also be beneficial to consider roads separate from the land-use indicator as well; weighted scores were calculated based on the area of a land use, and due to the small area that roads cover, the potential importance of the roads could not be fully evaluated.

6.2.2 Population density

Determining population density over an entire dissemination block (DB) was not entirely accurate because the Hamlet is not evenly divided among blocks, particularly in the more populated areas. Ideally, population density should be calculated for an area along the coastline rather than for an entire DB. To optimize the consistency of this type of calculation, the coast should be divided into segments based on a predetermined length.

6.2.3 Dwelling density

Dwelling density is a useful indicator, but the density of buildings would have been much better because it would have reflected the total number of buildings that would be damaged were a particular coastal segment to be impacted, rather than just the number of homes. Assessing only dwellings creates a gap, excluding industrial buildings, shops, and critical infrastructure such as the airport. The dwelling data was sourced from Statistics Canada, but it is unlikely that they have all required data, particularly the locations of hunting camps. It is important that hunting camps be included, particularly in the case of Tuktoyaktuk where community members have voiced their concerns about losing their camps to erosion, because they serve an important role in facilitating traditional hunting activities (D. Whalen, personal communication, July 10, 2013).

6.2.4 Distance of buildings to the shore

Measuring the distance between each building and the coast in ArcMap was very tedious; however, if this were to be done for a defined strip of land along the coast (referred to from now on as the coastal zone), fewer buildings would need to be measured, which would make the method of measuring the distance of each building to the coast less onerous. It would also mean that the range of distances would likely not be as great; therefore, the classes of rankings could be more detailed than 100 m. Using the DBs caused an issue in evaluating this indicator because some of the blocks reached much further inland than other blocks; therefore, some blocks were predisposed to having a median distance of buildings to the shore that was closer than others. There was also a problem because there were different numbers of buildings per block. For example, block

408 only had a few buildings, but they were all nearly adjacent to the coast, therefore the entire block ranked 5.

6.2.5 Distance of roads to the shore

The distance of roads to the shore was a difficult indicator to evaluate because the distance needed to be combined with the number of roads present in a block. If only a coastal zone were being evaluated, it would be much easier because it would be unlikely that more than one road would fall within any one coastal segment; therefore the median, average, or minimum distance of that one road to the coast could be calculated and used for evaluating the ranks. There should also be some measure of the importance of the roads in conjunction with the exposure to the coast, thus supporting the extraction of roads from the land-use indicator. For example, a road that joins the sewage lagoon and dump to the community is likely more important to the community as a whole than a road that leads to a single camp. This could only be assessed through community partnerships.

6.3 Biophysical Indicators

6.3.1 Landform

Although identifying coastal landforms based on the 2010 GeoEye image based on the CIS data was possible, it was still an interpretation with more or less confidence in some areas. Landforms could be evaluated more accurately through ground surveys or with input from people who know the coastline well. A balance would have to be struck, though, between being detailed and accurate, and ensuring that the assessment did not get too complicated to the point that it became impractical. This is a major problem with conducting vulnerability assessments, particularly in the coastal zone where so many interconnected factors need to be taken in consideration. To prevent complications during the assessment, key coastal landform categories could be identified prior to conducting surveys.

As with other indicators, problems arose from using dissemination blocks for dividing the area; there could only be four categories because inland blocks (that do not have a coastal landform) had to be ranked as the least exposed and sensitive (1). Therefore, all the coastal blocks were distributed through thanks 2-5; there was a large number of fives and only a few fours, threes, and twos. The differing sizes and distributions of the blocks also meant that there were vastly different lengths of shoreline for which an average had to be calculated, which may have led to an oversimplification of the sensitivity of the shore in some areas. If this assessment were conducted for the coastline only, the grading system would have all five options and thus the results would be better distributed.

6.3.2 Elevation

The mean elevation was more appropriately indicative of smaller blocks than larger blocks or those with wide ranges in elevation (for example if a pingo were present). This leads back to the issue within using DBs as a means of dividing the Hamlet for this assessment. The use of the DBs also means that the mean elevation is for the entire block, but when the concern is coastal flooding, the focus should be on the elevation along the backshore, i.e. the land that would protect the community from flooding. If this indicator were evaluated only along the coast, for example along the backshore, the result would be a much better indication of the risk of flooding or inundation along particular parts of the coast.

6.3.3 Exposure to storm waves

Exposure to storm waves was evaluated using the most qualitative methods in this study: by using the general northwest direction of storm waves and the orientation of the coastline to determine where waves are likely to contact the shore with the most force. Although this is a unique method in the context of this study, it does demonstrate how quantitative data and qualitative information can be combined within one assessment by converting all the values to a 1-5 scale. What made this method for evaluating an indicator difficult, though, was that one value had to be assigned for the entire coastline of a DB. An excellent example is Tuk Island, which falls entirely into block 432; one side of the island is directly exposed to storm waves from the northwest, where the other side is completely protected. Therefore, the average does not appropriately indicate the exposure of either shore. There was also the issue that only four categories could be used to assess differing exposure to storm waves because the lowest had to be assigned to inland blocks.

6.3.4 Percent excess ice

The decision was made to use excess ice as an indicator for thaw consolidation, and not the total percent ice volume as an indicator for probability of erosion. Excess ice indicates the risk that building foundations will shift, and so it is an important factor to consider. Not all blocks were coastal, though, and so the second component, percent ice volume as an indication of potential increased erosion, was not evaluated. If the ground-ice indicator were to be employed along the coastline only, it would be beneficial two use both indicators, one for the total volume of ice and one for the volume of excess ice.

6.3.5 Rate of coastal change

Calculating or estimating the rate of coastal change in an area would likely be difficult to evaluate through community-based methods, however, it could be evaluated through the application of traditional knowledge of which areas have eroded the most over time. The use of such qualitative methods may be necessary because the data required for determining the rate of coastal change have not been gathered for all Canadian Arctic communities, and even if they had, the expertise may not be available to conduct the necessary analyses. Fortunately for this study the data were available and had been analyzed for the majority of the Hamlet's coastline. The rates of coastal erosion were from 1950-1985 and there were data gaps for some blocks, but because the rankings were relative, the estimates were likely indicative of the current and future erosion and accretion rates in Tuk.

Yet again, the use of DBs for dividing the Hamlet posed operational problems. Not only did the inland blocks require the lowest ranking (1), but it meant that a single degree of coastal change had to be assigned to the coastline of an entire block. The issue of average rates was the greatest in the larger blocks, for example block 408, or in areas where the rates varied drastically, for example on Tuk Island (block 432). If this assessment had been done for just the coastal zone, the rates would not need to be combined over such great distances.

6.4 Overall Exposure-Sensitivity

Biophysically, block 432 was the most exposed and sensitive, which is consistent with the known status of Tuk Island, which falls within the block. The rate of erosion, exposure to storm waves, and the sensitivity of the landform all ranked 5, while the mean elevation ranked 4 and percent excess ground ice ranked 3. If this assessment were to be used for making decisions for adaptation planning in Tuktoyaktuk, block 432 should therefore be the focus for biophysical exposure-sensitivity. Management could not address the exposures and sensitivities related to elevation and ground ice content, but the scores for landform could be reduced through implementing some form of coastal protection, such as concrete slabs or rip rap, if they could be successfully implemented in such an ice-rich setting. Physically protecting the coast would also likely reduce the rate of erosion. Further studies would need to be completed before any action were taken, though, to determine the most effective way to protect Tuk island without negatively impacting other areas.

Block 401 was the most socioeconomically exposed and sensitive, which is reasonable because it is mostly residential (identified through the analysis of the land-use indicator) and it is located near the coast. The indicators that contributed the most to the socioeconomic exposure-sensitivity of this block were the distance of buildings to the shore and the dwelling and population densities (both scored 5). Therefore, if this were the basis for decision making, efforts should address these factors, for example by relocating people and buildings away from the coast or by retrofitting the infrastructure to better withstand the expected future changes such as sea level rise.

Overall, the most exposed and sensitive block was 315. Biophysically, it ranked sixth, with the landform and elevation indicators both receiving a score of 5. The DB was the third most exposed and sensitive socioeconomically, with the distance of buildings to the shore contributing the most. In translation, block 315 is the most exposed and sensitive because there are buildings built next to a sensitive coastal landform that has a low elevation. It is this type of statement that should be used to move forward in coastal management of climate change vulnerabilities. Potential approaches that could be taken to reducing the exposure-sensitivity of block 315 would be to relocate the buildings, prepare them for sea level rise, or implement some form of coastal protection. Absolutely no action should be taken based on this partial assessment of Tuk because it considered only a few indicators of future exposures and sensitivities.

6.5 Unaddressed Indicators

6.5.1 Socioeconomic exposure-sensitivities

Median age of infrastructure

Unfortunately, information was unavailable for the age of infrastructure within Tuk, and so it had to be excluded. Were this assessment conducted from within the community, or with community partnership, the general age of the infrastructure could have been estimated. This is not a difficult indicator to evaluate; for example, infrastructure was not introduced into Tuk until the Hudson's Bay Trading Post in 1934, which means the oldest any building could be is 79. With a range of 80 years, the five ranks could easily be evenly divided. The ages of buildings also could be considered relative to one another instead.

Population growth

Population data were available for Tuk by dissemination block for 2006 and 2011, but between those years, Statistics Canada changed the division of the blocks. Therefore, population growth could not be calculated and had to be excluded.

Health status

Health is very important for indicating where the most vulnerable people are located. It was known from the outset, though, that the necessary information on health would not be available due to confidentiality requirements, especially at the level of the DB. In order to obtain this type of information, community collaboration would be essential, and relationships and trust would need to be built prior to requesting such information. This assessment was designed for community members, though, and so the same confidentiality issues may not be as limiting were this indicator evaluated from within the community.

Presence of cultural heritage resources

The presence of cultural heritage sites was included in the land-use indicator; however it could not sufficiently be addressed for the case study of Tuktoyaktuk. All cultural characteristics and sites could only be identified by community members and, in this case, those who are part of the Inuvialuit culture. Therefore, to evaluate this indicator, community collaboration would be required.

6.5.2 Biophysical exposure-sensitivities

Duration of sea ice

The duration of sea ice is an important indicator to accompany the exposure to storm waves. It was omitted from this assessment of Tuk because complete information on the length of time sea ice is present was not available. The only difference known by GSC-A is between when the ice breaks up inside the harbour versus elsewhere in the Hamlet (the difference is typically no more than one week); when the ice typically forms has not been documented at the required detail. In other Arctic communities there may be a greater difference, and so the duration of sea ice should still be included as a general indicator.

Rivers

No major rivers were identified on the GeoEye image of the Hamlet of Tuktoyaktuk; therefore, this indicator was excluded. Other Arctic communities may be located near to rivers, and so river presence and level of flow should remain as an indicator of the exposure to potential flooding.

6.6 Adaptive Capacity Indicators

6.6.1 Socioeconomic adaptive capacities

Access to services

The only way access to services could be evaluated is through communications with community members. It would be necessary for the critical services to be identified, and the accessibility of those services to be defined from different areas. This indicator is associated with the importance and sensitivity of roads, but other modes of transportation would also need to be considered, such as ATV, skidoo, and boat.

Population age

Information on population ages was not available from Statistics Canada by DB for Tuktoyaktuk; therefore, it can be assumed that it is not likely to be available for other Arctic communities in Canada. Instead, this information could be sourced from the community. Exact ages are not necessary, but rather the general relative age of people within an area would suffice.

Education level

'Education' in the context of this study refers to the formal knowledge gained from schooling, as well as traditional knowledge and skills. Therefore, Statistics Canada could not provide all the information required, and so community participation would be necessary for evaluating this indicator completely. 'Education' could be divided into the median or mean level of formal schooling and the general level of traditional knowledge and skills.

Knowledge and experience of hazards and impacts

The indicator for education covers the general knowledge of people, whereas the indicator for knowledge and experience of hazards and impacts is specific to the context of potential climate changes and impacts. This indicator is more related to traditional knowledge; therefore, it would need to be evaluated by community members. If community consultations were conducted, it would be important to define the hazards and impacts for which a person has knowledge of and experience with prior to the meeting.

Dependence on country foods

Information on the dependence on country foods was available for Tuktoyaktuk through the Inuvialuit Indicators website (www.inuvialuitindicators.com), which sources data from the NWT Bureau of Statistics and Aboriginal Affairs and Northern Development Canada (previously Indian and Northern Affairs); however, it was only given for the Hamlet as a whole. It is important to include this indicator because it reflects the flexibility in diet, but depending on the homogeneity of the peoples' lifestyles within a community, it may not be a necessary indicator for all assessments.

Livelihood diversity

Livelihood diversity refers to the formal and informal economies, as well as subsistence hunting, trapping, and fishing. Information on the former two may be available from Statistics Canada, but the amount of subsistence activities practiced within a community likely are not. Thus, community input would need to be used.

Number of earning members per household

This information was not available from Statistics Canada for Tuk, and it is unlikely to be available for other communities because there needs to be information regarding the participation of household members in the informal trade economy. Instead, community consultations could provide the requirements for evaluating this indicator.

Financial resources or income

Statistics Canada had values for income for the Hamlet of Tuk as a whole, but not at the level of DB. The importance of financial resources as an indicator for assessing vulnerabilities within an Arctic community needs to be studied; because of the importance of sharing systems and social networks among community members, the resources available in one particular area may be less important compared to the importance of having financial resources available to the community as a whole. My hypothesis is that the strength of the relationships between people and the financial resources available to the group of people within that particular network is more influential on vulnerability than simply the financial resources and income within a segment of coastline.

Technological

As with the indicator of financial resources, it may not necessarily be the technological resources of individual people, but rather a combination of the technologies available to people within a social network as a whole. This indicator thus needs to be studied further.

Social networks

The strength of people's social networks is only known by community members, and therefore the indicator of social networks could only be evaluated from within a community. Depending on the strength of the relationships between individuals, this indicator may not be required; if the entire community is one cohesive group, then the degree of social networking would be the same. It is important to include social networks as an indicator in the overall framework, though, because in some cases there may be segregation between community members.

6.6.2 Biophysical adaptive capacities

Ecosystem health

Estimates of ecosystem health could be made from aerial photographs based on the theory that greater human presence is associated with poor ecosystem health, and industrial presence even worse (GESAMP, 2001b). To better evaluate this indicator, though, community-based mapping or field surveys should be conducted.

6.7 Assessment Method

The five key characteristics that went into designing this assessment were that:

(1) It was downscaled to the level of the community;

(2) The past, present, and future were considered;

(3) The approach was collaborative, interdisciplinary, and comprehensive;

(4) The framework synthesized knowledge and tools from multiple approaches; and

(5) The study was documented in detail and widely distributed.

These components were identified explicitly in the Arctic Climate Impact Assessment (ACIA; 2005) and by Champalle et al. (2013), but are also supported by numerous other authors (see Table 1).

The first characteristic, that it be downscaled to the level of a community, was at the core of the assessment. Not only did the assessment focus on one community, but it examined variability within that community. The methodology also satisfied the second criterion by using data from the past and characteristics of the present to try to visualize the future. Although collaboration with all the necessary stakeholders and parties was not possible for the assessment of Tuk, the methodology was designed to require interdisciplinarity, particularly through partnerships with members of the community of interest. Through the design of the assessment, tools and information were drawn from varying geographic locations and disciplines, producing a framework built upon an integration of approaches. And finally, care was taken to document each step in the process of creating the assessment and testing the indicators and methodology.

Prior to commencing this project, it was known that the process would be complex, required data would be lacking, and there would be financial and technical limitations to obtaining and analyzing the information (Füssel, 2009; Appelquist, 2013). All these inhibitors, other than technical difficulties were experienced while trying to complete the assessment of Tuk. In many instances, the data had simply never been collected, such as rates of erosion along the inner western shores of the Hamlet. Time and money were the greatest limitations, though, particularly because community consultation and collaboration were integral to the design, but they were simply not possible within the scope of this project. Therefore, without being able to travel to the community to have their input in the design and the evaluation of the indicators, the proposed methodology could not fully be tested, and thus the output is not complete and should not be used as a basis for adaptation planning in Tuktoyaktuk.

Although the lack of community involvement was a great hindrance for this specific assessment, there is still potential for the approach and framework. The methods were designed for use by Arctic communities; they were made to require minimal capacity and to respect and incorporate indigenous rights and knowledge in as many areas as possible. Therefore, were the assessment conducted in the manner for which it was created, the same limitations would not necessarily exist.

Chapter 7: Conclusions and Recommendations

Significant work has gone into researching vulnerabilities and developing vulnerability assessments throughout the world. Many have taken a regional perspective, which can be useful for national and international managers; some have studied communities, providing information for provincial or territorial managers; but very few have focused within a community, which has prevented local managers from taking action. By narrowing the scope to assess smaller areas, the specific locations with highest priority for adaptation actions can be identified and addressed from within the community.

Recommendation 1: Methods should be designed for assessing vulnerabilities to climate change within a community so as to guide community-based decision-making and adaptation planning.

Where studies have looked within a community, they have mostly studied either the socioeconomic characteristics that make people vulnerable, or the biophysical factors that render the land and ecosystems more vulnerable. It is important, particularly in the coastal zone, that both systems be incorporated into an assessment, especially in an indigenous Arctic community where the connection between the people and the natural environment is so strong. Vulnerability has been defined in this study as the exposure to hazards, the sensitivity to being impacted, and the adaptive capacity to cope with changes. Although it may be important for the methods applied in this study to separate the constituents into socioeconomic and biophysical systems, it is further essential that the final product reunite the pieces into a complete picture.

Recommendation 2: A holistic approach should be taken to designing vulnerability assessments, including the social, economic, cultural, biological, and physical factors that contribute to the overall vulnerability of an area.

This study tested the proposed indicators and evaluation methodology on Tuktoyaktuk, NWT, and it was repeatedly identified that collaboration with experts and partnerships with community members could significantly improve the evaluation of the indicators and therefore the overall assessment. Many of the biophysical indicators, such as ground ice volume and the rate of coastal change, would be difficult to assess without the experience and technical resources of the GSC-A. Similarly, without the input of Tuktoyaktuk residents, many of the social indicators could not be tested.

Recommendation 3: Vulnerability assessments should be based within a community, should incorporate the input of experts from varying disciplines, and should be facilitated by a coastal manager.

Although conducting a study that integrates different knowledge types and sources of data is complex and difficult, the ranking system allowed for all the information to be combined. Multiplying the values for the indicators did result in some staggering products, which yields the potential to misconstrue the magnitude of vulnerability. However, by converting these overall scores to a ranked scale, this issue could be mitigated, and by translating this to a colour scale, the results could be easily visualized and understood.

Recommendation 4: The outcomes of vulnerability assessments should be communicated in the form of a map and in terms of the most and least vulnerable areas within a community so as to aid with prioritization of adaptation efforts.

This study aimed to develop a method that would blend together the different forms, sources, and types of knowledge and information that have been or could be gathered to paint an image of the geospatial distribution of coastal vulnerabilities to climate change throughout an Arctic community. By expanding the conceptual framework to include all the contributing factors that could potentially vary within a community, a more comprehensive analysis could be conducted. By reducing the results back to the concept of vulnerability, a single relative scale could be given. This final product of the relative vulnerabilities between coastal areas within a community can help managers determine where adaptation efforts need to be directed, and the detailed assessment method can help to identify which factors require attention. Although a full test of the proposed assessment method could not be completed for Tuktoyaktuk, this preliminary study demonstrates that such an approach is possible.

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Appendix 1

Assessment form for Tuktoyaktuk, NWT

	EXPOSURE-SENSITIVITY															
	SOCIOECONOMIC							BIOPHYSICAL								
DBUID	Land use	Population density	Dwelling density	Distance of buildings to the shore	Distance of roads to the shore	**Socioeconomic ES score**	**Socioeconomic ES rank**	Landform	Elevation	Exposure to storm waves	Percent excess ground ice	Rate of coastal change	**Biophysical ES score**	**Biophysical ES rank**	**OVERALL EXPOSURE-SENSITIVITY SCORE**	**OVERALL EXPOSURE-SENSITIVITY RANK**
301	5	3	3	5	1	225	12	1	3	1	2	1	6	23	1350	**26**
302	4	2	3	5	3	360	9	1	4	1	2	1	8	22	2880	**25**
303	4	1	1	5	3	60	18	1	4	1	2	1	8	22	480	**31**
304	5	1	1	5	1	25	24	1	4	1	2	1	8	22	200	**35**
305	5	4	5	5	1	500	8	1	4	1	4	1	16	18	8000	**15**
306	5	5	5	4	1	500	8	1	4	1	4	1	16	18	8000	**15**
307	5	5	4	4	2	800	4	1	4	1	2	1	8	22	6400	**19**
308	5	4	4	4	2	640	5	1	4	1	2	1	8	22	5120	**21**
309	5	4	5	5	1	500	8	1	4	1	2	1	8	22	4000	**24**
310	5	4	4	5	3	1200	2	1	4	1	2	1	8	22	9600	**14**
311	2	1	1	2	3	12	29	5	4	3	3	3	540	7	6480	**18**
312	1	1	1	1	1	1	36	5	5	4	3	3	900	4	900	**29**
313	1	1	1	3	2	6	31	1	4	1	3	1	12	20	72	**44**
314	2	1	1	4	4	32	22	5	5	5	2	4	1000	3	32000	**7**
315	3	4	4	5	4	960	3	5	5	2	3	4	600	6	576000	**1**
316	4	2	2	5	3	240	11	5	5	4	3	4	1200	2	288000	**3**
317	3	2	3	4	1	72	17	1	4	1	4	1	16	18	1152	**28**
318	1	2	2	4	3	48	19	1	5	1	5	1	25	16	1200	**27**
319	3	1	1	1	1	3	34	1	4	1	4	1	16	18	48	**47**
320	2	1	1	1	1	2	35	1	4	1	2	1	8	22	16	**51**
321	4	1	3	5	1	60	18	1	4	1	2	1	8	22	480	**31**
322	5	1	4	4	1	80	15	1	2	1	2	1	4	24	320	**33**
323	2	2	2	5	1	40	20	5	5	5	1	5	625	5	25000	**9**
324	5	1	1	4	2	40	20	1	3	1	2	1	6	23	240	**34**
325	5	1	1	5	1	25	24	1	2	1	2	1	4	24	100	**41**
326	5	1	1	5	1	25	24	1	3	1	2	1	6	23	150	**37**
327	3	3	4	5	2	360	9	1	5	1	3	1	15	19	5400	**20**
328	5	5	5	5	1	625	6	1	4	1	2	1	8	22	5000	**22**
329	1	1	1	3	4	12	29	5	4	2	3	3	360	10	4320	**23**

330		4	3	3	5	3	540	7		4	4	5	2	3	480	8		259200	**4**
401		5	5	5	5	3	1875	1		1	4	1	4	1	16	18		30000	**8**
402		5	4	4	5	2	800	4		1	4	1	4	1	16	18		12800	**12**
403		1	1	2	4	2	16	27		1	4	1	3	1	12	20		192	**36**
404		2	1	1	5	1	10	30		1	3	1	2	1	6	23		60	**46**
405		1	1	1	1	3	3	34		1	4	1	3	1	12	20		36	**49**
406		1	1	1	1	3	3	34		1	4	1	4	1	16	18		48	**47**
407		2	3	3	5	1	90	14		1	2	1	4	1	8	22		720	**30**
408		1	1	1	5	1	5	32		2	2	3	2	4	96	15		480	**31**
409		5	1	1	5	3	75	16		4	4	2	3	3	288	12		21600	**10**
410		1	1	1	5	3	15	28		5	4	2	3	3	360	10		5400	**20**
411		1	1	1	1	2	2	35		1	5	1	4	1	20	17		40	**48**
412		2	1	1	5	1	10	30		3	4	3	3	4	432	9		4320	**23**
413		3	3	2	5	3	270	10		5	4	3	3	3	540	7		145800	**5**
414		3	3	3	5	4	540	7		5	3	4	5	3	900	4		486000	**2**
415		2	1	1	4	3	24	25		1	1	1	1	1	1	25		24	**50**
416		1	1	1	5	3	15	28		5	4	3	2	3	360	10		5400	**20**
417		2	1	1	1	2	4	33		1	5	1	4	1	20	17		80	**43**
418		4	1	1	1	1	4	33		1	4	1	4	1	16	18		64	**45**
419		2	1	1	1	1	2	35		1	5	1	4	1	20	17		40	**48**
420		3	1	2	5	3	90	14		5	4	2	1	5	200	14		18000	**11**
421		3	1	1	4	1	12	29		1	4	1	2	1	8	22		96	**42**
422		3	1	1	1	2	6	31		1	4	1	3	1	12	20		72	**44**
423		3	1	1	5	2	30	23		1	3	1	4	1	12	20		360	**32**
424		3	1	1	4	1	12	29		1	4	1	3	1	12	20		144	**38**
425		3	1	1	4	1	12	29		1	3	1	3	1	9	21		108	**40**
426		2	1	1	5	2	20	26		4	3	3	3	2	216	13		4320	**23**
427		3	1	1	4	3	36	21		3	4	3	3	3	324	11		11664	**13**
428		2	1	1	4	2	16	27		5	4	2	3	4	480	8		7680	**16**
429		3	1	1	5	1	15	28		1	3	1	3	1	9	21		135	**39**
430		3	1	1	1	1	3	34		1	4	1	3	1	12	20		36	**49**
431		1	2	2	5	5	100	13		5	4	2	3	4	480	8		48000	**6**
432		1	1	1	5	1	5	32		5	4	5	3	5	1500	1		7500	**17**

Appendix 2

Complete assessment form for any coastal Arctic community

	EXPOSURE-SENSITIVITY INDICATORS																					
	SOCIOECONOMIC											BIOPHYSICAL										
Coastal segment	Land use	Population density	Infrastructure density	Distance of buildings to the shore	Distance of roads to the shore	Age of infrastructure	Population growth	Health status	Presence of cultural heritage resources	**SOCIOECONOMIC ES RANK**	**SOCIOECONOMIC ES SCORE**	Landform	Elevation	Exposure to storm waves	Ground ice volume	Coastal change	Duration of sea ice	Rivers	**BIOPHYSICAL ES RANK**	**BIOPHYSICAL ES SCORE**	**OVERALL ES SCORE (1)**	**OVERALL ES RANK**
A																						
B																						
C																						

Appendix 2 (continued)

Coastal segment	ADAPTIVE CAPACITY INDICATORS																
	SOCIOECONOMIC												BIOPHYSICAL				
	Access to services	Population age	Education level	Knowledge/experience of hazards/impacts	Dependence on country foods	Livelihood diversity	No. earning members/household	Financial resources or income	Technological resources	Social networks	**SOCIOECONOMIC AC SCORE**	**SOCIOECONOMIC AC RANK**	Ecosystem health	**BIOPHYSICAL AC SCORE**	**BIOPHYSICAL AC RANK**	**OVERALL AC SCORE (2)**	**OVERALL AC RANK**
A																	
B																	
C																	

Appendix 2 (continued)

Coastal segment	OVERALL VULNERABILITY			
	Overall exposure-sensitivity score (1)	Overall adaptive capacity score (2)	**OVERALL VULNERABILITY SCORE**	**OVERALL VULNERABILITY RANK**
A				
B				
C				