Hazard Mapping in the North

A review of approaches for key hazard types

Northern Climate ExChange
YUKON RESEARCH CENTRE • Yukon College

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1 INTRODUCTION

This review describes a framework for understanding the process of hazard mapping, and its necessary resources and broad uses, while also presenting more detailed information related to the following four major climate-driven hazard types of high priority to northern communities:

- Permafrost degradation;
- Landslides and ground movement;
- Coastal erosion; and
- Flooding.

Each of these hazards is significantly influenced by atmospheric conditions and climate change. The distribution of these hazards across the northern regions is particularly complex because changes in air temperature, precipitation, and vegetation cover significantly influence environmental conditions and can increase the vulnerability of the land to hazards. However, they are all relevant to Northern Canadian communities.

Following this introductory section, this report is broken down into five major sections, as follows:

- **Section 2 and 3.** Describes a the initial steps that are common elements in all hazard mapping projects.
- **Section 4.** Describes steps and considerations for specific hazard types researched in this project. Specific hazard mapping models, required datasets, and other hazard-specific considerations are presented. Each hazard closes with a summary of key points to consider.
- **Section 5.** Discusses the importance of communication and end-user involvement at all stages of a hazard mapping initiative, and reviews considerations for final production and publication of hazard maps.

This report is intended to provide guidance to non- hazard mapping experts who are charged with the task of reviewing proposed hazard mapping projects, or determining if a hazard mapping project has the necessary steps to be useful to a community or end-user group. The report does provide information regarding details that should be present in a funding proposal or project description for a hazard mapping project. At the end of most sections, there is a highlighted “reviewer check”. These are specific questions that a proposal reviewer should be able to answer about each stage of a proposed hazard mapping project.

1.1 METHODOLOGY

This report is the outcome of a desktop study where two key kinds of literature were reviewed. We reviewed hazard mapping literature that:

1. Developed or critiqued approaches, for example: technical expertise, data types, and methodologies employed in generating the hazard maps; intended uses of the information presented in the hazard maps; spatial scales of the information contained in the hazard maps; uncertainties in the climate hazards data and analyses; and other key characteristics of the hazard maps
2. Assessed the strengths and weaknesses of different hazard mapping approaches and their level of applicability with the hazard information requirements for built environments

This review focused on peer-reviewed literature as well as reports by government, communities, academia, unpublished theses, consultants, etc., and website content published in or after 2008 in English or French. A selection of hazard mapping initiatives and assessments was gathered by using hazards-based search terms (e.g. hazard, vulnerability, method, approach, climate change, flooding, permafrost, snow overload, landslides, infrastructure, built environment, physical impact, etc.).

It should be noted that this review is not an exhaustive appraisal of hazard mapping methods, but rather aims to distill the most important contributions from a range of applicable approaches and contexts relevant to northern communities. Interpretation and professional judgement were required to synthesize information from different sources and determine the applicability for Northern Canadian communities.

1.2 DEFINING KEY TERMS: HAZARD, RISK, VULNERABILITY AND EXPOSURE

Although there are varying definitions of the term “hazard” (Wood 2011), the definition used in this report highlights the fact that the central feature is the occurrence, or presence, of a physical process or event that has the potential to produce harmful effects. In some cases, the term “hazard” is used interchangeably with similar terms, such as “risk” or “vulnerability.” Indeed, the three terms are closely related. As such, it is important to differentiate these concepts and provide a clear set of definitions used throughout the remainder of this report. Given the similarities in techniques and methodologies, both hazard and risk initiatives were examined and evaluated in the context of this desktop study. However, this report is meant to be applied to hazard mapping initiatives.

Natural hazards are physical processes which have the potential to cause loss of life; injury or other health impacts; property and infrastructure damage; negative effects on livelihoods, socio-cultural values and economic wellbeing; disruption to community services and business; or environmental damage (UNISDR 2009; Agard and Schipper 2014). By contrast, the concept of “risk” is perhaps the most directly used within decision-making processes related to natural hazard preparedness, emergency management, and climate change adaptation. A hazard is the physical process that places something of value, at risk. For example, if a landslide occurs in an area where there is no human use, there is no risk to us because we are not exposed to the risk. If a landslide of the same character occurs where there is a road or infrastructure, there is a risk. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur" (Agard and Schipper 2014, 23). Hazard helps determine the "probability of occurrence" side of a risk equation, but is generally not directly linked with the consequence side of the equation. Risk management is often used as a decision-making process for mitigating the impacts of natural hazards, including prioritizing alterative mitigation measures and determining levels of protection that are planned for (CSA 2011).

Within the disciplines of climate change adaptation and disaster risk reduction, risks arising from natural hazard events are typically mapped by understanding the interactions between the hazard, the exposure, and the vulnerability of values at risk. This concept is shown graphically in Figure 1 with respect to climate-driven hazards specifically, however, the Venn diagram model in the center is broadly applicable to all forms of geo-hazards, beyond just climate. The following defines these terms:

1. **The Natural Hazard:** The physical process, phenomena, or event that might cause impacts (e.g., occurrence and extent of flood);
2. **Exposure:** The presence of assets or populations in an area influenced by a natural hazard (e.g., the presence of a community within a floodplain); and
3. **Vulnerability or Sensitivity:** The characteristics, including the resources, abilities, and management systems, of a community that influence its susceptibility to the adverse effects, or impacts, of being exposed to a hazard (e.g., community preparedness for flooding) (Adger 2006; UNISDR 2009; Cutter et al. 2009b; Wood 2011; IPCC et al. 2012). Factors such as poverty, and social connectedness and social support mechanisms, will affect vulnerability of communities overall irrespective of the type of hazard (Adger 2006; Cutter et al. 2009a; Cardona et al. 2012; Field et al. 2014). Hazard-specific factors also contribute to the nature of risk management and adaptation processes (ICSU-LAC 2010a,b)

The direct and indirect impacts of hazards can be long-lasting; potentially altering the character, economy, cultural activities, and many other characteristics of exposed communities. Some hazard events have limited financial impact but very high human costs in terms of loss of life and numbers of people affected. Others have very high financial but relatively limited human costs (Field et al. 2014). Risk management is often used as a decision-making process for mitigating the impacts of natural hazards, including prioritizing measures to reduce vulnerability or exposure to a hazard.

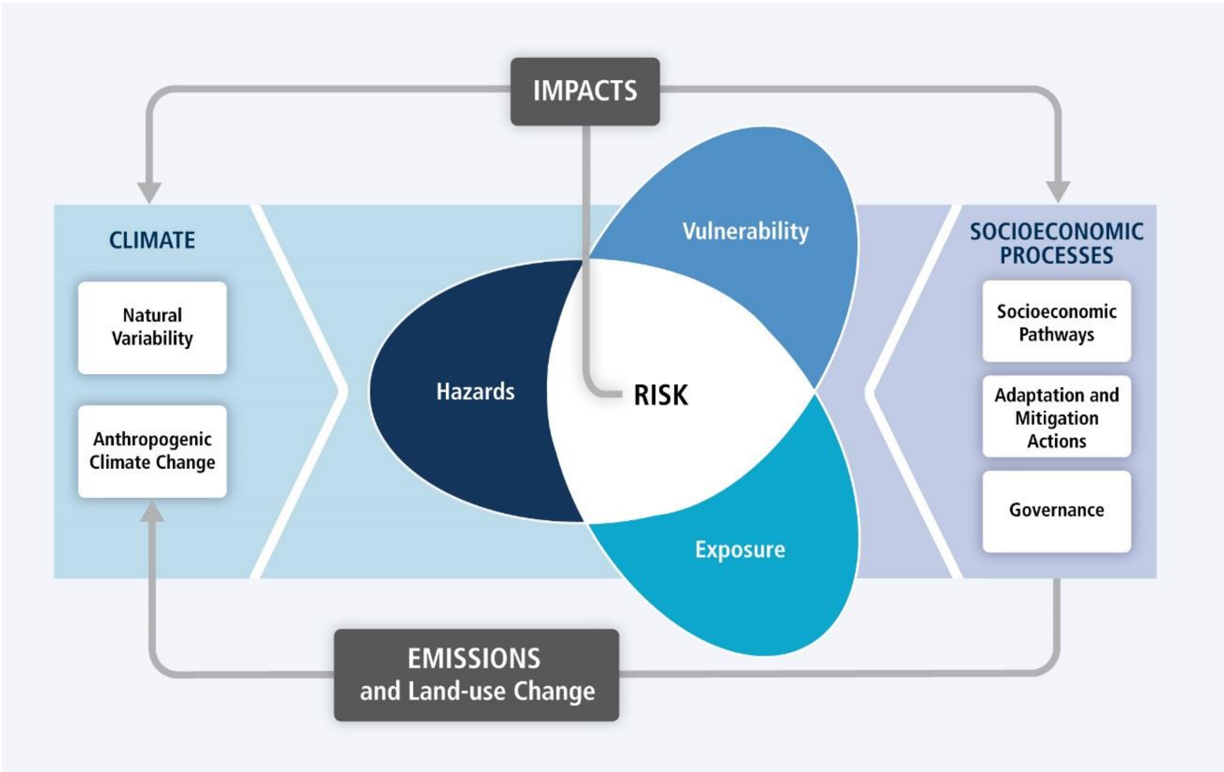
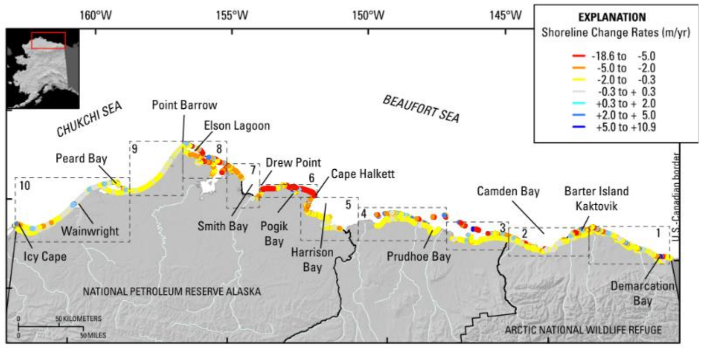


Figure 1. Conceptual diagram of the relationship between vulnerability, exposure, and hazards as they relate to community risk. This diagram focuses specifically on climate-related hazards (IPCC 2014).

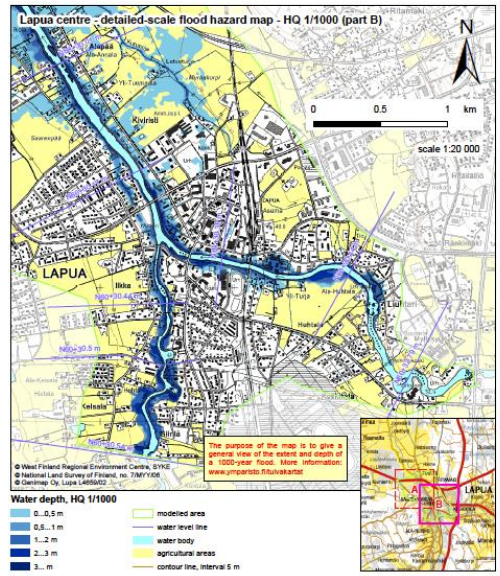
1.3 WHAT IS HAZARD MAPPING?

Natural hazard maps are spatial representations of the physical processes that could cause damage in a community, adversely affect ecosystems where harvesting takes place, etc. (Cova 1999; Tarolli and Cavalli 2013). Hazard maps typically highlight spatial variability in the magnitude, frequency, and/or likelihood of a hazard. They can be made for a single hazard, or can combine multiple hazards. Figure 2 presents three examples of hazard maps, each with differing approaches to displaying hazards. In Figure 2a, hazard severity is represented as varying coastal erosion rates; Figure 2b delineates a pre-defined hazard based on estimated water depth for a 0.1 % probability flood; Figure 2c maps the hazard of being flooded during a 1% probability flood. It should be noted that the susceptibility of different systems to damage from a given hazard can also vary, however this would be regarded as “vulnerability” information that would typically be layered on top of a hazard map and requires other mapping procedures (Cova 1999; Cardona et al. 2012; IPCC 2014).

(a) Shoreline erosion rates along Alaska's Northern Coast (from Gibbs & Richmond, 2015)



(b) Flood depths for the 0.1% probability flood in Lapua, Finland (from Leiviskä, 2016)



(c) Probabalistic flood map (i.e., likelihood of area flooding) for the 1% probability event (from Beven, et al. 2014)

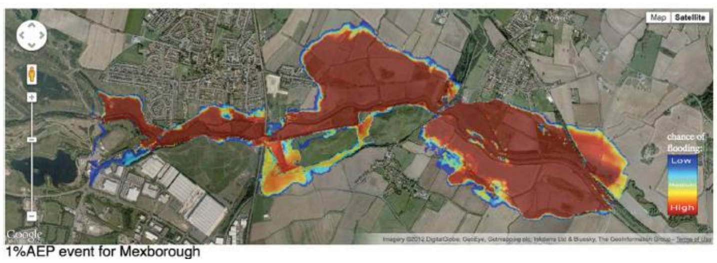


Figure 2. Examples of three different approaches to hazard mapping: (a) severity represented as variation of coastal erosion rates, (b) the delineation and severity of a pre-defined hazard of an estimated frequency as the 0.1 % probability flood depth, and (c) a probabilistic flood hazard map.

Hazard maps are created using datasets and analysis techniques specific to the physical processes and phenomena that define the hazard in question, often referred to as a "hazard model" (Cova 1999; Schneider and Schauer 2006; Kappes et al. 2012). For instance, a different set of data and calculations, or hazard model, is needed to delineate a flood zone versus a map of the variability in permafrost degradation rates. In each case, very different physical processes are at play. A hazard model is best understood as a computational algorithm, often incorporating physically based equations and software platforms (e.g., geographic information systems, hydrologic models, etc.) that combine different parameters, including spatial and temporal variables to produce a spatial representation of a hazard. The datasets used as inputs for a hazard model can be acquired from existing sources (e.g., topographic maps or previously collected geotechnical data), remotely sensed or air photo imagery, or may require original fieldwork to collect data (e.g., surveying cross-sections of a river for use in a floodplain mapping model).

1.4 CLIMATE CHANGE AND NATURAL HAZARDS

Many natural hazards are the direct result of, or are heavily influenced by, short-term meteorological and longer-term climatic conditions. Changes in climate can greatly influence existing hazard profiles (e.g., severity, extent, duration), in addition to activating new hazards (Serreze et al. 2000). To date, observed trends show that climate change is happening most quickly in the high latitudes of the northern hemisphere relative to other parts of the globe; a pattern that is projected to continue in future (IPCC 2013). As climate continues to change, communities are witnessing impacts in their regions. Landscape changes have been reported by numerous communities (Calmels and Laurent 2014; JMRFN 2013 and 2014) and these changes are likely to increase with the current trend of global warming.

Figure 3 demonstrates schematically how climate conditions are a key driver of the hydrologic and landscape processes that produce hazards. Variations in climate have always played a role in triggering impacts from a hazard, but there is increasing recognition that global climate change – long term trends in the average conditions – has impacted frequency and potential impacts of hazards. For instance, flooding is driven by precipitation and a watershed's water budget, the latter of which is heavily influenced by temperature, humidity and wind. Changes in any of these can impact the timing and volume of flow in a given location. Wind is also one of the main forces behind wave action, which is a principle driver of coastal erosion. It is far more damaging on coastlines where ice cover used to protect the shore. Permafrost degradation occurs as a result of warm ambient temperatures along with increases in precipitation that can change soil properties. Landslides too, are often triggered by heavy precipitation, degradation of permafrost, and changes to land cover, the latter of which is influenced heavily by the climate suitability of local plant species.

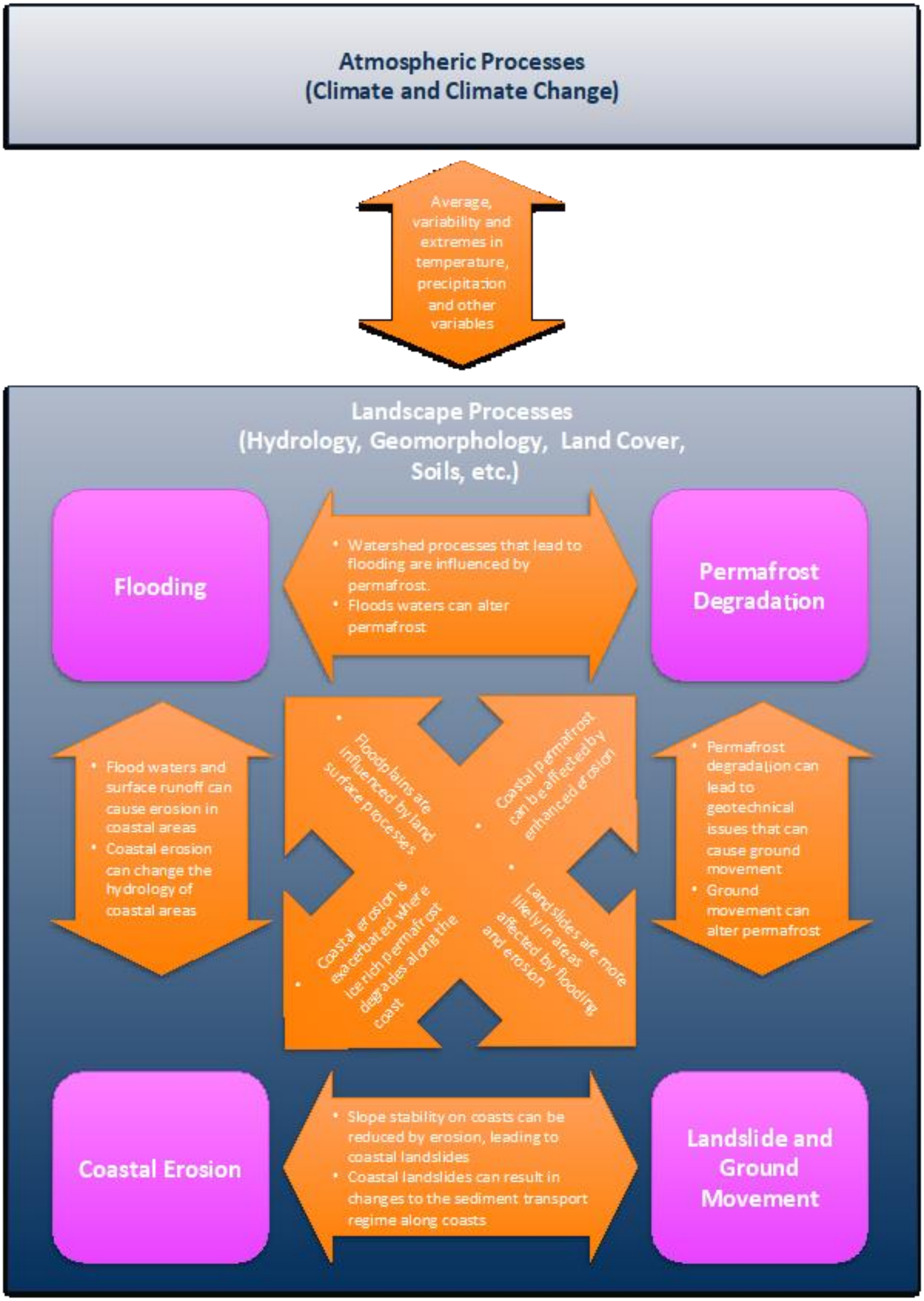


Figure 3. Summary of interactions between different natural hazards, climate and climate change.

Recognizing the relationships between climate change and hazards, researchers are developing methods to account for climate change in hazard mapping. In addition, as climate change impacts are being experienced in many parts of the north, decision makers are increasingly aware of hazards, increasing the demand for hazard mapping in many locations.

1.5 TRADITIONAL KNOWLEDGE AND HAZARD MAPPING

Many researchers will choose to go beyond basic community engagement (to gain local knowledge) and will attempt to include traditional knowledge (TK) in their mapping approach. Traditional knowledge is a central feature of the indigenous heritage and culture of northern communities. Ensuring that hazard mapping projects honor this system of understanding and experiencing the natural world can be achieved with dialogue between western scientists and indigenous representatives. It should be acknowledged that traditional knowledge is not a form of qualitative scientific data, but a holistic worldview that encompasses values, practices, observations, teachings, and other cultural assets (Houde 2007; Leduc 2007). Traditional knowledge can add significantly to collective understandings of natural hazards, and can be integrated into the analysis and the hazard mapping process. The cultural importance and centrality of traditional knowledge to Indigenous identity and values means that Western scientists must make extra efforts to work cooperatively with Indigenous communities on hazard mapping. There are many examples of TK being successfully linked with Western science. However, the methods for collecting this information, as well as standards regarding the use and storage of traditional knowledge reach beyond the scope of this report.

1.6 OVERVIEW OF THE HAZARD MAPPING PROCEDURE

The fundamentally different nature of flooding, ground movement, coastal erosion, and permafrost hazards requires the application of specific methods for mapping each, however there is a general framework of steps and decisions that is applicable across the board (Figure 4) (Kappes et al. 2012; ACF International 2013). The subsequent sections of this report provide greater detail on the specific steps and considerations outlined in this overall approach.

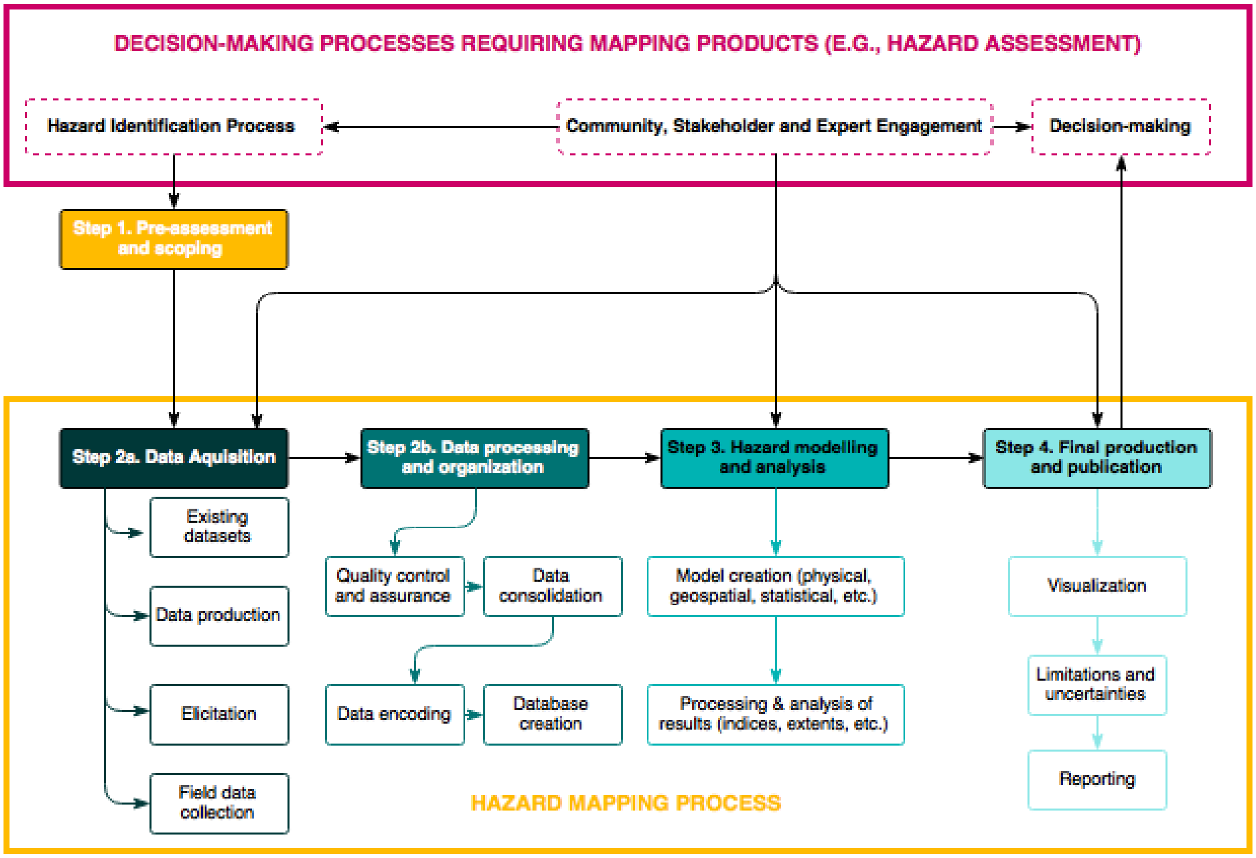


Figure 4. Summary of the processes involved in hazard mapping (adapted from ACF International 2013)

Reviewer Checks:

Does the proposal you are evaluating correctly define and consistently use terms such as hazard, exposure, vulnerability, and risk?

Have project proponents described whether traditional knowledge and/or climate change impacts will be a consideration in their hazard mapping project?

2 STEP 1: MAPPING PROJECT PRE-ASSESSMENT AND SCOPING

Before a hazard mapping project begins for a specific hazard, the project scope should be determined, typically through a "Hazard Identification" process during which a range of potential threats are identified, characterized, and prioritized (Public Safety Canada 2012). In Canada, this can be accomplished through an all-hazards risk assessment process, such as the Hazard Identification Risk Assessment (HIRA) (Public Safety Canada 2012; Vanguard EMC Inc. 2014), or other broad risk assessment processes. This process is presented in the pink box in Figure 4 and constitutes Step 1.

Prior to undertaking the hazard mapping process, the project team should question itself about the context, the purpose for such a project, and the long-term vision in terms of planning and development. This is typically an ideal time to initiate communication between the developers of information and the end users to ensure optimal utility of the mapping (Lemos et al. 2012; Kirchhoff et al. 2013b). Through meetings and workshops a community can try to answer the following questions:

- Why undertake a hazard mapping?
- What is threatened in the community?
- What hazards have occurred in the past?
- What new hazards are of concern in the future?
- Are there several hazards to consider?
- Have hazards bee studied in the area before?

It is very important to understand the reasons behind undertaking a hazard mapping process. The project team needs to determine why hazards have become a concern for the community.

If several hazards are to be considered it raises the complexity of the project; more data collection will be required as well as more modelling and analysis. As this will affect the length and cost of the project, this needs to be planned from the start to ensure the proper development of the project. Answers to these questions will also give a head start to any data collection/gathering. At this stage, the community and research team are only looking for very general information about the hazard(s), what community members have observed, and what they know of eventual prior work on the topic.

Even at this early stage, it is beneficial to determine the format of the end product and who will be involved in the overall process. If, for example, the hazard mapping is part of a planning initiative or if a planning initiative is soon to be started, a strong communication strategy needs to be implemented all along the project. This is a cue that planning professionals in the community should be a part of the hazard mapping so that the end product can be well understood and easily integrated into the planning initiative.

Another pragmatic step at this point in the project is to consider the following:

- Can we do this ourselves? Do we need outside help? If yes, to what extent?
- What kind of approach do we want to take?

An inventory of the local capacity, technical and financial means will determine the level of outside help needed. With this information the project team can decide what approach is best, either to manage and oversee the entire project or to leave this task to someone else while remaining the key decision maker.

All these questions will contribute to shaping the entire project: select a study area, identify end-goals, and determine the duration of the project, as discussed in the following sections.

2.1 STUDY AREA

Several factors should be considered when determining the study area. These include the following:

- Community motivation and interests;
- The level of detail required to inform decision making by the community;
- The number and spatial nature of hazard(s) under consideration;
- Previous occurrence and impacts of the hazard(s) of interest; and
- The time and budget available to complete the project.

The study area can be determined based on exploratory research into the region. This can include an examination of overview physiographic information, such as topographic maps, air photos, and previous hazard assessment reports (APEGBC 2010). It is important to recognize the significance of local and/or regional spatial scale for local community interpretation. Keeping the scale of hazard assessment local or regional also facilitates stakeholder engagement in the design and process of the initiative. When determining a study area, it is essential to a project to have completed foundation research by gathering data and information which would define a specific region to be further investigated. It is also important to remember that the planned region may need to be altered depending on exploratory findings. For this reason, a hazard mapping project should have an idea of the area to be studied as opposed to a quantitatively selected distance.

2.2 IDENTIFY END GOALS

Hazard mapping initiatives can have different end goals depending on the end-user. In many cases, the people conducting the mapping (i.e., consultants and/or academics) may not necessarily be those using the end product or developing the initial proposal for a mapping project. As a result, it is helpful for end-users to provide a clear statement of the mapping objectives and tangible project outputs. This is often achieved through direct involvement of the community affected by, or with experience of the hazard in question.

To assist in creating end goals for the hazard mapping initiative, it is helpful to discuss the vision the community has for its future. This can ensure that the end goals of the project are in line with the community's vision. This will help to guide the project and validate its results, as well as build and maintain partnerships with communities. The aim of engaging stakeholders is not only to include their direct perspectives to guide the research, but also so the results can be used and incorporated into decision-making to produce mitigation and land-use planning procedures for future hazard events. With that foundation, specific objectives can be developed to accomplish end goals.

2.3 DURATION OF THE PROJECT

The duration of the project is dependent on a variety of factors and greatly influences the types of datasets and analytical tools that can be employed in a mapping study. Major factors are:

- The size of the study area;
- The capacity of the project team (number of people and resources);
- The complexity of the hazard(s) and the magnitude of its impacts; and
- External factors such as available funds and time permitted by the funders.

The duration of the project, the size of the study area, and the capacity of the project team can be highly interrelated. For example, when mapping a large area with no prior data on hazards, a small team of 2-4 people would require several field campaigns and therefore several years.

The "in house" expertise also influences the project duration. Using outside help and working with stakeholders requires coordination and communication from the project team, often resulting in a longer project.

The complexity of the environmental processes underlying hazard events, and the number and magnitude of impacts, will influence the duration of the project. The more complex the processes and impacts, the longer the project will need to be.

Finally, the duration of the project is often predefined either by the funding available for the project or the time permitted by funders. Longer projects will cost more, but will also allow for more meaningful community engagement and deeper investigation of complexities.

The more funding available, the longer the project and the more in-depth the research study can be. This can also be influenced by the capacity of the stakeholders involved in the project. These factors will also contribute to the type of methodologies used to produce the end product, the hazard map. Capacities and assets for hazard mapping within a community extend beyond technical abilities to include management, leadership and communication skills, access to information and knowledge, availability of technology, effective governance structures, and many other factors (Munang et al. 2009; Vera et al. 2010; Cochran et al. 2013).

Reviewer Checks:

Does the proposal you are evaluating the end user and stakeholders and involve them in the mapping process from the beginning?

Are the objectives of the hazard mapping project clearly articulated, realistic given the time and budget available, and consistent with the general needs and landscape of the community being mapped?

Will the proposed work begin with the pre-assessment steps described above, or has this work already been completed prior to applying for funding?

3 STEP 2: DATA ACQUISITION; DATA PROCESSING AND ORGANIZATION

After determining the hazard(s) of interest and completing the scoping described in Step 1, Step 2 is focused on gathering the necessary datasets and information about the hazard and the study area in Figure 4. As a starting point for data acquisition, all hazard mapping initiatives should develop an inventory of the necessary data required to meet project objectives. This includes a full literature review of the study area. Past hazard mapping documented in publications should be researched and summarized in a manner that characterizes and critically assesses the applicability of past work to the local context. This review will provide the researchers with essential knowledge regarding the subject matter in relation to that region in addition to knowledge of existing datasets and the most scientifically appropriate and feasible hazard mapping models. The literature review will also provide detail regarding the amount and type of new data that will be needed for that specific region for the hazard mapping initiative.

3.1 DATA ACQUISITION (STEP 2A)

For most hazard mapping methods, there are several overarching data acquisition methods to consider. A hazard mapping project will typically include some combination of data production (e.g., digitizing hard-copy records, processing remote sensing data), elicitation (e.g., surveys and interviews with community members and experts) and field data collection (e.g., field sampling, surveying, etc.) (Figure 5).

Regardless of the methods selected for collection of new data, all projects should begin by collecting and assessing the quality and suitability of existing data. Data may have been collected for other projects, but applicable for mapping hazards. In certain cases, the existing datasets collected at this stage can be sufficient for completion of a hazard mapping model. For a hazard map to be completed based exclusively on existing data, the quantity and quality of the data needs to be well matched to the goals and objectives of the project. In most northern communities, it is likely that existing published data can give only a general sense of hazards, but if this is acceptable to end users, there is no need to go to greater effort to collect new data. Assessing the availability and quality of datasets for a specific purpose is often referred to as a “Data Gap Analysis.” This process is highlighted in Figure 5.

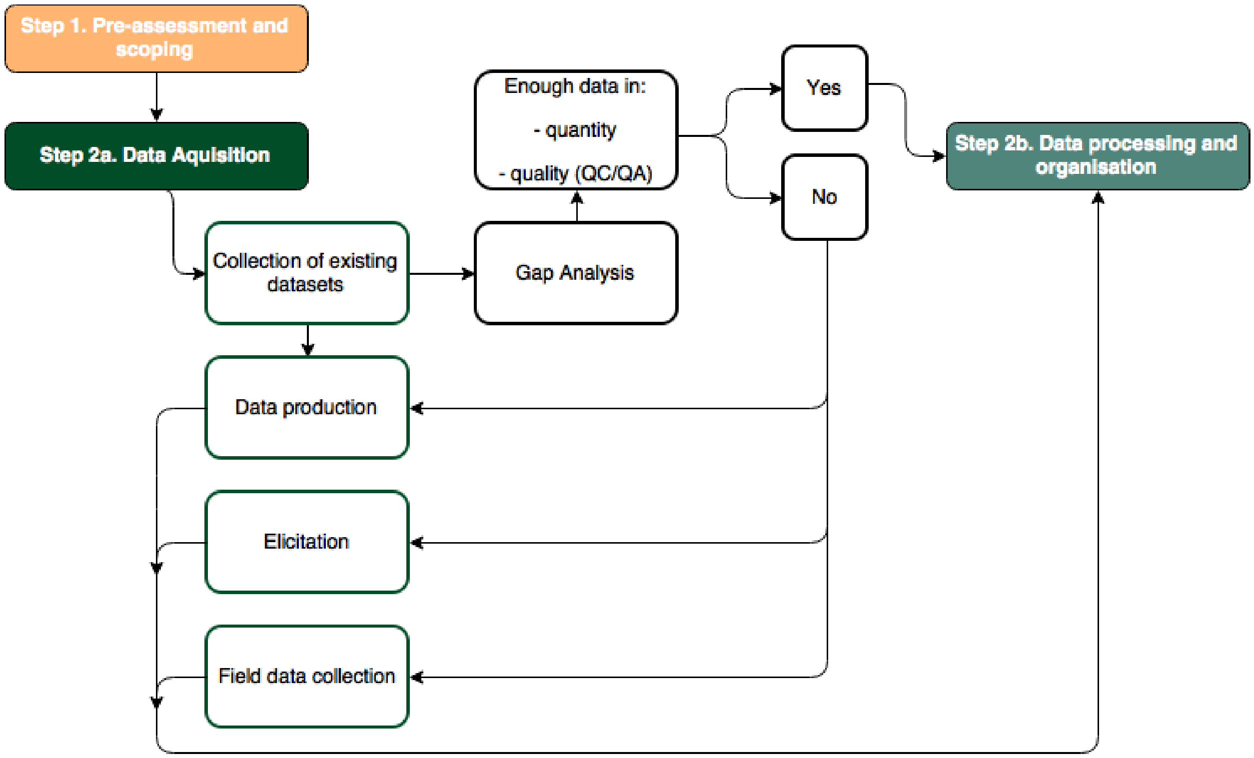


Figure 5. Decision process for data acquisition.

The purpose of the gap analysis is to identify discrepancies between current and ideal states of the data required to complete a hazard map (Canada 2008). The datasets collected in Step 2a and 2b are directly dependent on the analysis to be completed in Step 3. As such, this forms the criteria for the gap analysis (i.e., determining if you have all the data in sufficient quality to successfully perform a specific analysis in step 3). The data requirements for the planned hazard mapping model will be compared to the list of existing datasets. Data quality is also an important part of the gap analysis.

At this stage, the existing datasets collected will be submitted to a process of data quality control/assurance (QC/QA) to determine if they can be used in the later steps of the project (e.g. some new data may need to be collected if existing data is of poor quality or non-compliant with certain requirements). If new data are collected, another round of QC/QA will need to be performed.

For many northern Canadian hazard mapping projects, the gap analysis results will indicate the need for more data acquisition. The following subsections will describe three overarching approaches to acquiring new data: data production; elicitation; and field data collection.

3.2 DATA PRODUCTION

Data production refers to methods such as digitization of historic data and remote sensing. Converting information into digital format is necessary for integrating old documents into a database. This may include scanning reports available only in hard copy, or maps available in hard copy, or conversion of maps from raster to vector formats in order to allow analysis within a geographic information system (GIS). This can be a lengthy process in which the quality and accuracy of the data may be reduced; i.e. when digitizing old maps, the features on the map can be blurry and therefore subject to interpretation. Throughout the digitizing process it is important to monitor the level of error, and to document observations pertaining to accuracy. Discussion with local experts, or cross-validation with TK can often address uncertainties regarding accuracy. This information will then be included and used in the final QC/QA.

Remote sensing describes the practice of collecting information about an area without being in direct physical contact with that location. Remote sensing can be used to measure and monitor important biophysical characteristics and human activities on earth (Jensen 2009). Often, air photos and satellite imagery are collected as part of general land surveys, or because of automatic settings of a sensor, but the data are simply catalogued and never analyzed. Acquiring air photos and satellite images can be very valuable to a hazard mapping project because they can be used to look at landscape features and hazard-relevant factors without having to conduct costly field research. The analysis of satellite images can greatly contribute to detecting and mapping natural hazards across spatial and temporal scales (if there are repeat images over time). One area where remote sensing can be particularly useful is for flood hazard mapping. Imagery is very useful for identification of a floodplain or flood-prone areas (DRDE 1991). In the case of ground movement hazard mapping, remote sensing can identify landslides, on both large and small scales, and other movements like chaotic blocks of bedrock or mudflow tongues (DRDE 1991).

3.3 ELICITATION

Elicitation is a method of data collection where the project team seeks the input of communities, stakeholders, and/or experts through meetings, interviews, focus groups, surveys, mapping sessions, etc. Information collected with this method can include the locations of areas that are particularly vulnerable from a social perspective, locations of landscape changes that may relate to the hazard, concerns and issues regarding the hazard, descriptions of past hazard events (including their magnitude), etc. In northern communities where people have been observing and living off the land for generations, there is a very good chance that this method of data collection would be productive for many hazard mapping projects. It is important to consider partnerships with indigenous communities that might allow hazard-related linkages between western science and traditional knowledge. It should also be noted that elicitation involves in-depth contact with community members. As a result, a project team and proposal reviewers must be respectful of any ethics permitting processes. Permitting requirements vary by institution and by jurisdiction and application processes can be time consuming. Ideally, the time required to do this should be considered at the pre-scoping step of the project.

3.4 FIELD DATA COLLECTION

Where field data collection is necessary, it can be a delicate and challenging step in a project. In this step, a project team has determined that existing data are not sufficient and that data production and elicitation will not yield the details required to complete a hazard model. The project team will need to collect high-quality data essential to the project over a limited period of time. The success of the field data collection is crucial for a project. Fieldwork is primarily considered necessary when known gaps in data can't be filled using elicitation or data production methods, or when researchers wish to verify or "ground truth" information that they have learned from other data sources.

Fieldwork is a complex practice where many things can go wrong for various reasons. Bad weather, broken tools, trip cancelations, or interpersonal conflict are a few examples of issues that can challenge successful completion of a fieldwork program. When a problem happens it requires a great deal of adaptation to successfully continue. Therefore, preparation is essential. Four steps are recommended to prepare for field data collection:

- **Acquisition of necessary permits (e.g. Federal, Territorial, First Nation/Community, Institutional, etc.)**
  Permitting requirements for fieldwork vary widely based on what fieldwork is proposed and the location where the research will be completed. In general, destructive techniques, or approaches that require collection of large samples have more complex permitting requirements.
- **Preliminary analysis and reconnaissance of potential field sites**
  Even in small areas, it is impractical to visit all locations of a study area and to collect all kinds of field data. Preliminary analysis and reconnaissance are used to develop a shortlist of sites for fieldwork. The sites selected in preliminary analysis are considered "representative" of larger-scale patterns of interest, and are also logistically feasible to reach. Preliminary analysis can consist of a review of whatever data already exist, consultation with community members, or selection of sites based on logistical considerations. For example, a preliminary analysis could mean using geology and slope as the factors determining the presence of permafrost to create a preliminary map. A list of deposits vulnerable to permafrost degradation would be established and the orientation of slope would be taken into consideration as well. The field work team would then use the preliminary map to target their site visits.
- **Formation and training of the field team**
  A minimum of two people is necessary for the safe conduct of any field work. Team members

must be complementary to one another, and should possess outdoor, observational, investigative, and communications skills. Training, comfort in remote locations and flexibility are essential for successful fieldwork.

- **Planning and logistical coordination**
  Field work is most likely to be successful when it is planned using local input. Local knowledge of the area and the hazard(s) provides insight about the possible issues and dangers of traveling on the land, as well as specific knowledge of areas to avoid because of potential cultural sensitivity. For this, proper communication and/or meetings should be arranged with the communities and/or local stakeholders prior to beginning field work. Other logistical considerations range from transportation and shipping through to emergency preparedness. A project team proposing fieldwork should clearly demonstrate how they plan to reach the field, what they plan to do while there, how they will manage safety, and how they are prepared to manage the unexpected.

Fieldwork itself is a time consuming process. In addition, instruments that are deployed during fieldwork will require time to collect meaningful data. The amount of time required varies widely – anything from a few days (in limited cases) to many years. Consideration should be given to whether meaningful data can be collected within the time available.

3.5 STEP 2B: DATA PROCESSING AND ORGANIZATION

After completion of the data collection, all data will be regrouped and organized into a single database for the project. All types and formats of data need to be included: GPS points, field notes, satellite images, GIS layers, meeting notes and observations, etc. This step can involve quite a lot of data entry depending on the type of type of data collection method used. For example, if surveys were conducted on paper, the results will have to be entered into a digital form. Even with data in digital format, some transformation may be needed, like GPS to GIS transfer or the integration of field notes into GIS layers. At this point creating a data dictionary that centralizes the metadata of all files can be a very valuable tool not only for the present project but also for future use of the data. With a data dictionary it is very easy to search through the entire database with a just a few key words to find files relevant to certain topics or analysis. It consolidates the database and makes it accessible to anyone new to the project.

Data processing also deals with the issues of privacy and confidentiality. Some of the data collected may be subject to confidentiality agreements imposed by a community or by the ethics panel review, especially when the data was obtained through elicitation. It is very common that names of the participants in interviews, focus groups, or mapping sessions be kept private and encoded. It is also customary to sign a confidentiality agreement with the community when using and/or collecting traditional knowledge data. The conditions for collecting and using such data are usually to not distribute or share the digital format with anyone (not even the funding organization), and to not use the data for any other purpose than the current project. The final report including all figures can be publicly distributed in most cases.

The process of QC/QA is essential. It should be integrated as part of any data inventory development processes as it improves transparency, consistency, comparability, completeness, and accuracy (Environment and Climate Change Canada[1]). Quality control is focused on fulfilling quality requirements, whereas quality assurance is focused on providing confidence that quality requirements are fulfilled (Manghani 2011). It is important for the project team to develop and implement a QC/QA process to ensure the quality of the data collected.

Many factors can influence data quality (Canadian Standards Association 2012; Hamilton 2015):

- Characteristics of the data
- Methodology of data collection
- Instruments employed
- Human error in data processing and preliminary analysis

Methodological, instrumental, and human error factors apply to all data used in the project, however it is often more difficult to assess these factors for pre-existing data than it is for data collected during a hazard mapping project. Indeed, assessing these three factors for existing datasets requires access to detailed metadata which is often very hard to find.

For new data collected during the project, the methodology, instrumental, and human error factors can be limited by implementing data collection protocols that answer the following questions:

- Is your collection method appropriate to the data?
- Has the method been proven effective for this type of data collection?
- Are the instruments used appropriate for this method?
- Are the instruments properly calibrated?
- Is the data collection team trained and qualified enough?
- Do all team members follow the same technique?
- Have standard operating procedures, or field protocols, been created and used?
- Is there a system for maintaining and ensuring consistent recording of field notes?

The pre-assessment and scoping of the project along with the literature review and the collection of existing data should help answer the questions referring to the methodology error factor. Human error can be greatly limited by providing all team members with the same high level of training prior to the data collection process and, if possible, ensuring that a senior member is always present at

[1] https://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=C64B1AFB-1

the time of collection. During the data collection process, human error can be reduced by standardizing and encoding the note-taking. Finally, the level of instrumental error can be greatly lowered by the use of updated software and recent instruments, and by the level of familiarity of the data collection team (need for proper training) with the instrument.

Reviewer Checks:

Has the proponent determined whether existing data, and planned new data collection are appropriate for the type of hazard being mapped?

Does the proponent describe steps to make sure that the planned data are in a format that is useable, and the quality of the data collected will be verified?

Do the proposed workplan and timeline account for the time it will take to obtain necessary permits and to successfully collect meaningful new data if they are required?

4 STEP 3: HAZARD MODELLING AND ANALYSIS

The initial steps (Figure 4, Steps 1, 2a, and 2b) of a hazard mapping project are broadly applicable across hazard types. Approaches to Step 3 (Figure 4) diverge for the four hazard types that are considered in this report (coastal erosion, permafrost, landslide and ground movement, and flooding). In this section, the data acquisition approaches described above are reviewed for each of these hazard types, and then approaches to hazard modelling and analysis are described for each. Table 1 provides an overview of how often each of these data acquisition approaches is used for each hazard type.

Table 1. Typical frequency of use of data collection methods

Data acquisition type	Coastal erosion	Permafrost	Ground movement	Flooding
Existing datasets	ALWAYS	ALWAYS	ALWAYS	ALWAYS
Data production	VERY OFTEN	OFTEN	VERY OFTEN	OFTEN
Elicitation	OFTEN	RARE	OFTEN	VERY OFTEN
Field data collection	OFTEN	VERY OFTEN	VERY OFTEN	OFTEN

The mapping methods presented in each hazard type described often involve both qualitative and quantitative methods. In general, quantitative approaches use an equation-driven ranking system based in physics, chemistry, thermodynamics, or other fundamental equations to weigh the datasets or variables in the model and put more importance on certain datasets compared to others. The hazard modelling can also be completed with a qualitative approach without quantifying the importance placed on the datasets. This practice emphasizes expert judgement over the more deterministic quantitative approach. Approaches can be partially qualitative and partially quantitative, however, one is usually dominant.

A qualitative approach for hazard mapping does not use a ranking system that applies weigh on the datasets used by the model or GIS analysis. The mapping for these approaches is heavily based on one or several datasets that are considered as dominant factor(s) for locating the areas vulnerable to the hazard in question. A greater importance is given to one or several datasets in the analysis but this process is not quantified numerically. For example, when mapping ground movements, a greater importance can be given to topography and hydrology which will be considered primary factors; soil texture and geology would be secondary factors. The analysis would proceed like this; polygons representing steep slopes and badly drained terrain (topography and hydrology) would be selected to represent the areas vulnerable to ground movement. Then the type of soil texture and geology would determine the level of vulnerability inside the vulnerable areas.

A weakness of qualitative approaches is that interpretations may vary depending on the experts who are participating in the project. This problem can be managed within a hazard mapping project by either defaulting to a higher hazard level when there is uncertainty and explaining this in supporting material for the map, or by using shading or some other symbol to indicate uncertainty.

By contrast, a quantitative approach will combine fundamental equations with many sources of data to numerically estimate hazard. Many kinds of data can be used, however, there will generally be some degree of spatial interpolation to infer landscape characteristics from point data.

A weakness with quantitative approaches is that they can be highly precise (e.g. the estimated hazard will be a very specific number), but the quantitative estimate may also be inaccurate. In other words, just because a quantitative approach results in a very specific hazard value does not mean that the specific value is correct. Purely quantitative approaches must, by necessity, simplify immensely complex systems and make assumptions about some landscape characteristics.

Because of the known weaknesses of both these approaches, it is common to see concurrent use of qualitative and quantitative methods. This can be done in several ways.

- The qualitative approach can be applied to the primary factor(s), the quantitative approach to the secondary factor(s). For example, polygons representing steep slopes and badly drained terrain (topography and hydrology) would be selected qualitatively to represent the areas vulnerable to ground movement. Then a ranking can be applied to the secondary factors in order to refine the vulnerable areas and apply different levels of vulnerability.
- On the other hand, a quantitative ranking can be used in the first steps of the analysis and apply a qualitative method afterwards. This has been used by Benkert et al. in 2015 to map landscape hazards. A quantitative ranking system was applied to slope, surface material, and permafrost probability data, and a qualitative approached was then used on the hazard classification to generate the final map which was also cross checked against field observations.
- Regardless of the methods used to complete a hazard map, a round of verification involving modification and/or reclassification of areas can follow the initial hazard classification. This step ensures a high quality of the final map and brings a strong level of certainty to the methodology. This approach allows more flexibility and leaves more space to a case by case analysis. For example, a set of data may not be incorporable to the model or analysis because it didn't meet some of the QC/QA standards, however this set of data can still be used as a guide at a certain point in the analysis.

In data sparse regions of the North, both qualitative and quantitative approaches have merit and should both be considered when planning a hazard mapping project. This is particularly true of hazard maps that consider climate change impacts. In the case of hazard mapping, the level of uncertainty regarding climate projections, particularly for parameters such as frequency of extreme rain, snowfall, or storm events, coupled with uncertainties in the hazard modelling itself, purely quantitative modelling is unlikely to be realistic or achievable.

4.1 COASTAL EROSION HAZARDS

Coastal erosion refers to the loss of material (sediment and rock) from a shoreline due to dynamic forces such as wave and tidal action, wind, and anthropogenic impacts such as natural resource extraction and changes to land cover (British Geological Survey 2012). Geochemical weathering can also play an important role in coastal erosion (Stallard 1995; Davidson-Arnott 2010). For Northern environments, the short open-water season, extensive sea and land ice coverage, and presence of permafrost play central roles in mediating coastal erosion rates (Forbes and Taylor 1994; Lantuit et al. 2012). In many parts of Canada's northern marine coasts, sea ice has historically been present either permanently, or for a large part of the year and protects many reaches of shoreline from erosive forces (Forbes and Taylor 1994). In cases where ice is now being mobilized due to melting or hydrodynamic forces triggered by climate change, contact with the shoreline can result in enhanced scouring and erosion compared to wave or wind action alone (Forbes and Taylor 1994).

The processes that lead to coastal erosion should be understood in the context of the overall system of sediment transport (Bush et al. 1999; Rachold et al. 2005; FEMA 2015). A reach of shoreline will very likely experience both erosion and deposition, depending on the orientation of offshore currents, direction and intensity of waves, potential sources of sediment and its geological and inland characteristics (Davidson-Arnott 2010).

From a hazard perspective, erosion is typically regarded as a greater concern than deposition because it results in loss of shoreline material and stability, which is of concern to community assets, coastal access, and local ecology (Ford and Smit 2004; Baron et al. 2015). That being said, understanding erosion hazards requires examination of the net change in shorelines over a period of time and identifying areas susceptible to, and types of events that lead to significant erosion (Gibbs et al. 2015). In isolated cases, processes such as deposition and isostatic rebound are relevant considerations for things such as access to harbors or safe mooring locations. Figure 6 provides a conceptual summary of the dynamics involved in coastal erosion, highlighting the various climate and non-climate processes involved. Different reaches of shoreline will be subject to varying forces and their unique properties will ultimately determine the potential for erosion.

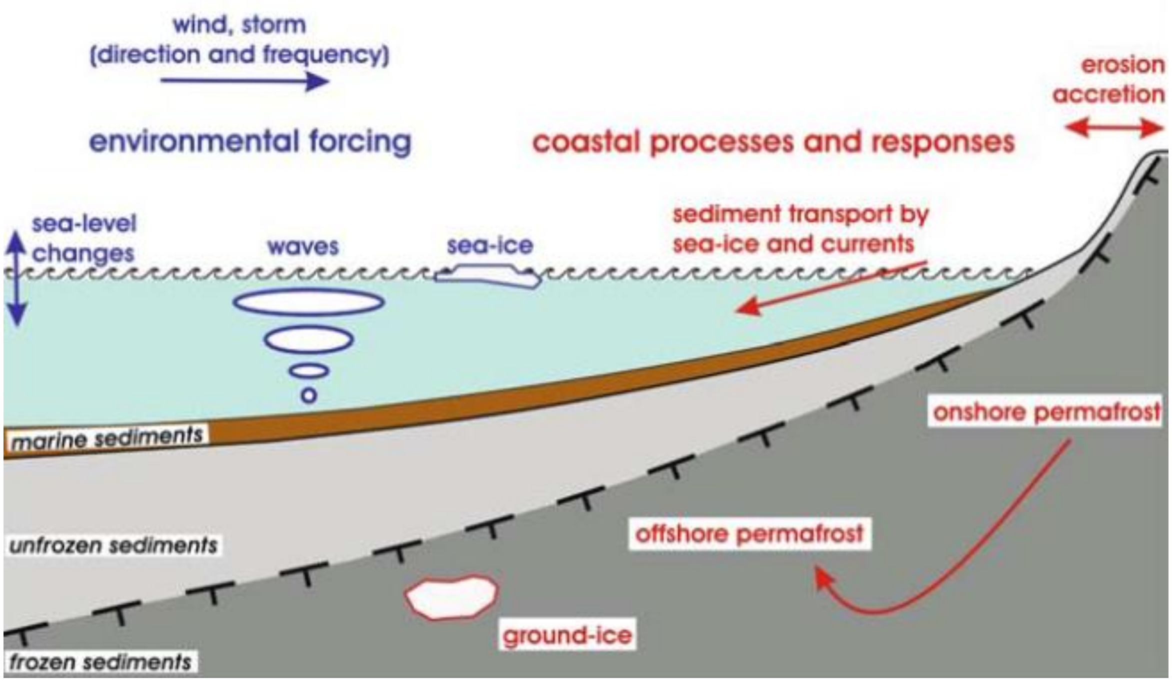


Figure 6. Conceptual diagram of coastal dynamics and processes driving erosion (from: Rachold et al. 2005)

4.1.1 Climate and Anthropogenic Drivers of Coastal Erosion

Several studies of arctic coastal erosion have demonstrated accelerated rates of sediment loss over time, with climate and climate change being prominent factors in this trend (Lantuit et al. 2012; Baron et al. 2015; Gibbs and Richmond 2015; Hatcher and Forbes 2015). From a climate standpoint, the most significant drivers of Northern coastal erosion can be summarized as follows:

- Sea-level rise due to global climate warming and the melting of sea ice. The exposed extent of shoreline is greatly increased from even small increases in sea-level, especially in low-lying coastal zones.
- Wind action and storms that lead to waves and disruption of sea-ice;
- Degradation of permafrost due to changes in temperature, anthropogenic activities and related environmental change (e.g., change in or loss of vegetation) leading to less resistance to erosion;
- Inland precipitation resulting in erosion of landward coastal areas; and
- Lengthened open-water season caused by warmer temperatures leading to decreased sea-ice coverage, which in-turn exposes shorelines to more erosion from coastal waters and mobilized ice (Rachold et al. 2005; Davidson-Arnott 2010; Lantuit et al. 2012).

Climate change is an important driver for coastal erosion in northern communities. Warmer ambient air temperatures projected with climate change are likely to result in the increasingly significant loss of sea ice coverage, degradation of coastal permafrost, and rise of sea levels. All of these factors are important drivers of coastal erosion. As northern climates change, vegetation on shorelines that regulate sediment transport is also likely to become more vulnerable to stress as ecozones shift (Hinzman et al. 2005; Bhatt et al. 2010). Climate change is also likely to alter wind and wave regimes for coastal communities, however the specific effects are highly uncertain, making it difficult to suggest whether wind and wave intensities will increase or decrease.

Increasingly, coastal erosion modeling and mapping are moving toward incorporating estimates of sea-level rise due to climate change in erosion assessments (Thorne et al. 2007; KWL 2011; Hatcher 2014; Baron et al. 2015). This is typically accomplished using estimates of global sea level rise, adjusted for locally relevant conditions, such as El-Nino, local tidal differences, etc. An important element of sea level rise in the Canadian North is tectonic processes, resulting in subsidence and uplift (KWL 2011). In the Canadian North, the post-glaciation isostatic rebound effect is so great that despite rapid rates of global sea level rise, relative sea levels will decrease by up to around 1 meter by 2100 (Lemmen et al 2016).

The presence of shoreline protection infrastructure and other human modifications to the shoreline (e.g., offshore breakwaters, harbor structures, man-made beaches and landform) can greatly influence the overall geomorphology of a coastline and the associated erosion patterns. Coastal protection infrastructure can consist of man-made berms, seawalls, revetments, or other structures designed to protect natural shoreline from wave forces. These structures are typically designed to withstand certain levels of force. In northern communities, the presence of such infrastructure can also affect the movement and accretion of ice along coasts (Hatcher 2014).

4.1.2 **Datasets & Data Acquisition**

Coastline morphology changes rapidly over time and erosion of coastlines frequently poses challenges to infrastructure and culturally-valued places in northern communities. However, because coastal erosion can quickly change, previously collected data are not always reliable. As a result, there is likely a need to collected updated observations of shoreline conditions. This may be accomplished through remote sensing or field methods. Nearshore bathymetry is also an important input to coastal erosion mapping and this information may not be readily available unless previous studies have collected such data. There will often be a need to discuss the hazard levels with the local community (i.e., where is erosion the most critical).

The processes that cause coastal erosion, along with the factors that influence the susceptibility of a given area to these processes are generally well-known and may be discerned through a review of existing shoreline characterization documents, geotechnical reports and coastal flooding studies if such studies exist for the study area. As is described further in Section 4.1.4.3, coastal erosion hazards are often mapped by analyzing historical rates of change in the position of the shoreline. The fact that coastal systems are distinct features on satellite imagery makes this hazard class well-suited to remote sensing analysis. Such analysis is typically done using remote sensing data acquired through from aerial photography or satellite sensors. While much of this data can be obtained freely, or at a minimal cost, it requires significant time and effort to process, and in some cases digitize. It may also be necessary to extract and digitize information from previous reports into GIS systems, for example soil characteristics, topography, bathymetry, etc.

Beyond the aforementioned variables and their associated datasets, topographic maps, historical flood assessments, geotechnical, hydrology, and coastal engineering reports can provide useful information for understanding the physical environment in which coastal erosion occurs. It is often possible to obtain the design criteria and standards for coastal infrastructure to understand the range of hydrodynamic and erosive hazards that infrastructure is intended to protect. Typically, these protections are designed after some degree of geotechnical assessment by engineers or other professionals. If these data can be accessed, they can be very valuable for hazard mapping. Comparisons between datasets from various time periods can also assist with historical change analysis.

For the Canadian Arctic specifically, the following existing datasets and resources would be relevant to consider, including:

- Environment Canada's "Shoreline mapping vector data for the Canadian Arctic", which provides a geospatial database of shoreline characteristics for almost 7000km of Canada's Arctic shoreline in the Beaufort Sea area (http://open.canada.ca/data/en/dataset/a974294b-caf6-452c-a97b-08990c94f50d);
- NRCAN's Climate Change Geoscience program report library, which is a repository of reports and datasets that may be relevant to analyzing a wide range of datasets that address arctic coastal erosion (http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/shorte.web&search1=sprogc=cc4???;cc5???;3432??). This resource includes CanCoast, an ArcGIS-based geodatabase by the Geologic Survey of Canada for the analysis of coastal sensitivity to climate change. Coastal attribute layers including physical features, materials, and processes (e.g. geology, sea level change) can be grouped for a given shoreline. Specific layers in CanCoast include landforms, tidal range, wave height, topographic relief, sea level rise, and ground ice conditions for coastal permafrost regions;
- National Oceanographic and Atmospheric Administration (NOAA) World Data Service for Geophysics Shoreline/Coastline Resources contains as database of several key datasets, such as coastline geometry, wind and wave data, bathymetry and other datasets (https://www.ngdc.noaa.gov/mgg/shorelines/);

- Wave and other moored marine buoy observations (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/waves-vagues/index-eng.htm). Databases contain over 6 million observed wave spectra from over 500 locations in the Canadian area of interest (35 to 90 degrees North and 40 to 180 degrees West), as well as meteorological and marine surface parameters; and
- Tides and water level data (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/maps-cartes/inventory-inventaire-eng.asp#divGoogleMaps); Canadian tides and water level data; station information, digital data inventory of observed water level data available for download.

The Canadian Hydrographic Service undertakes hydrographic surveys to measure, describe, and chart the physical features of Canada's oceans and navigable inland waters. The Service uses these data to produce navigational products. The hydrographic information is made available for navigation but also for research and development of applications in engineering, ocean research, and renewable and non-renewable energy sectors.

Specific information products include:

- Bathymetric charts: These charts contain information on the depth of navigable marine and fresh water bodies in Canada.
    - Bathymetric maps: CHS's bathymetric maps contain detail about the nature of the seafloor and the material beneath it. These maps are generally of interest to users whose prime focus is not navigation. Although CHS no longer produces lithographically printed versions of bathymetric maps, a large number of bathymetric maps from our Natural Resource Map series is available for free download. This data is available under a free license from the following link: http://www.chs.gc.ca/data-gestion/bathy/nr-rm-lic-eng.asp.
    - Bathymetric gridded data: CHS offers 500-metre bathymetric gridded data for users interested in the topography of the seafloor. This data provides seafloor depth in metres and is accessible for download as predefined areas. Although the current bathymetric gridded data collection is limited, it will be continuously expanding as more data becomes available. This data is available under license from the following link: http://www.chs.gc.ca/data-gestion/bathy/500-lic-eng.asp

In cases where there are gaps in existing datasets, fieldwork, modelling or other data generation methods may be required. Figure 7 provides an overview of the key variables generally required for coastal erosion mapping at the community-scale and highlights some of the existing sources of data, field methods and data production methods. Depending on the scope and overall mapping methodology employed in a given coastal mapping project, only a subset of these data may be required.

In Northern coastal communities, there are very important socio-cultural and economic connections to the sea and sea ice. Many Northern coastal communities have long a histories with the sea and members can offer rich insight into the processes and factors that influence erosion locally (Ford et al. 2008; Ford and Pearce 2010). Although elicitation of information on coastal erosion can offer great insight into local conditions, great care needs to be taken to ensure that local and traditional knowledge are respected. Traditional knowledge should be regarded as an integral part of the worldview of Northern, particularly indigenous communities, and best practices for collaborative research with these communities should be followed.

Characterization of the shoreline will often require fieldwork in order to collect information on one or more of the aforementioned variables. Fieldwork is often conducted on a reach-by-reach basis by surveying transects perpendicular to the shoreline and collecting information on a variety of variables, including topography, bathymetry and coastline profile (including offshore bathymetry), assessment of vegetation, measurement of wave heights and distributions alongshore, inspection of coastal infrastructure and soil sampling. (Commonwealth of Massachusetts 2014; Hatcher 2014; CVC 2015). In Northern contexts, surveying the extent and characteristics of ice is also critical (Hatcher 2014). This can include ice coring and geophysical investigations to determine the thickness and other characteristics of sea ice. It may also be necessary to survey the shoreline to inventory, and visually inspect infrastructure to assess its conditions. Geographic position system (GPS) technology is often employed to develop a digital record of records in the field.

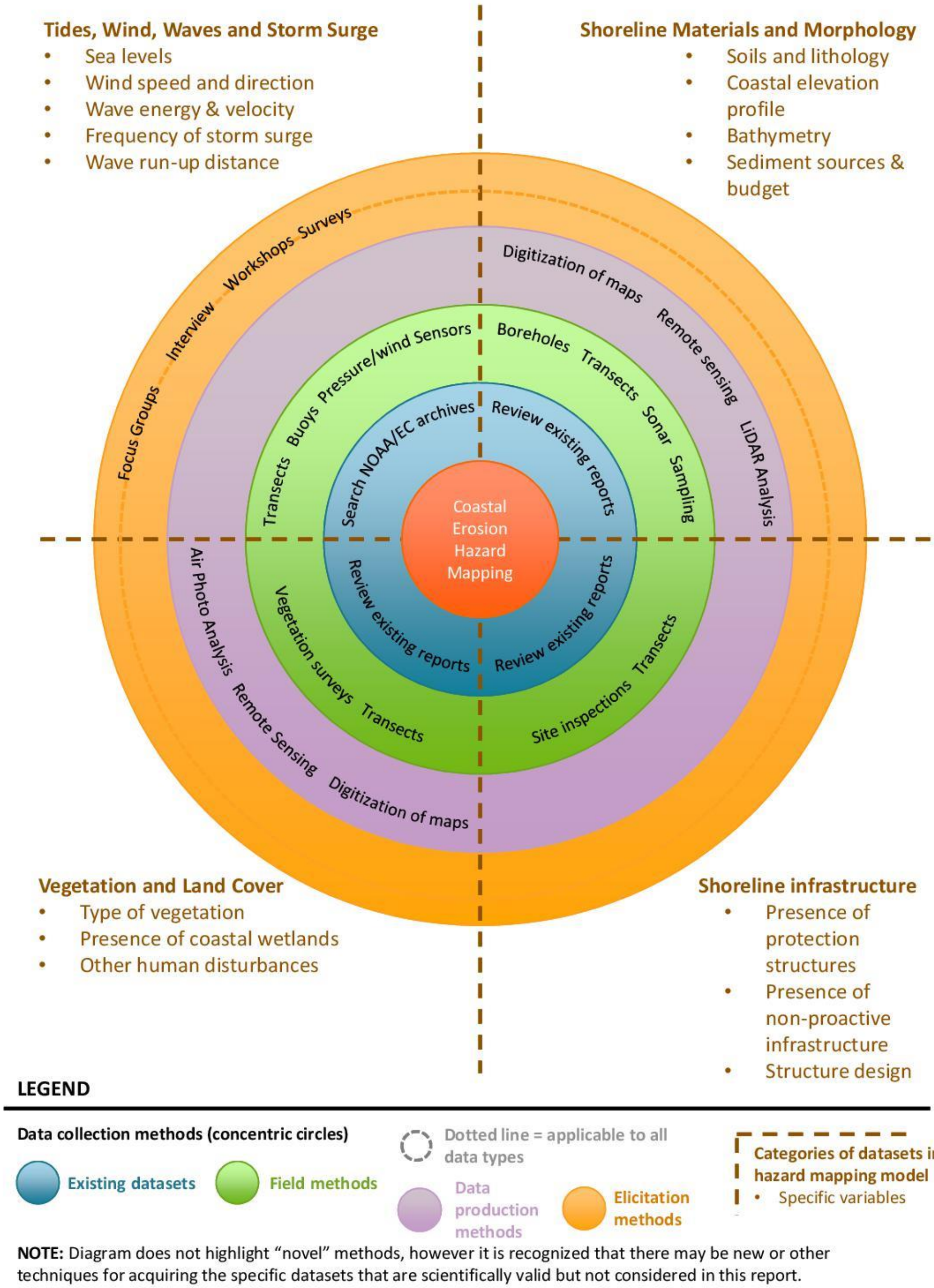


Figure 7. Summary of coastal erosion hazard mapping variables and common approaches for data collection

4.1.3 Data Standardization and Organization

There are no currently established standards or best-practices for data standardization and organization of coastal information, aside from those generally pertaining to hazard information. That being said, there are some key examples of online database systems that are used to house and update official sources of coastal information, such as BC's Coastal Resource Information System (http://geobc.gov.bc.ca/base-mapping/coastal/index.html).

4.1.4 Coastal Erosion Hazard Models and Mapping Techniques

Because not all shoreline characteristics and contexts are the same, coastal erosion analysis will typically begin with understanding the factors in Figure 6 in a qualitative manner, so the most appropriate mapping methodology can be implemented, given the local conditions. Despite the fact that different shorelines can be subject to varying levels of erosion, coastal processes, sea levels and sediment budget factors are typically the focus of coastal erosion hazard mapping models and analysis used to quantitatively characterize erosion (Guthrie and Law 2005).

Coastal hazard mapping is typically done on a reach-by-reach basis and the resultant outputs typically consist of linear features for representing the hazard level for each reach, or a polygon representing the potential extent of area that could be impacted by erosion over a specified time. The specific input data for coastal erosion models vary greatly depending on the model, however the key variables highlighted in Figure 6 are generally represented.

It should be noted that, there is not a standardized process for selecting and applying a specific coastal erosion hazard mapping model. That being said, certain jurisdictions have adopted guidelines for assessing coastal hazards broadly that include combined mapping of coastal flooding and erosion. Ontario has mandated that Conservation Authorities map shoreline hazards, including erosion, along the Great Lakes (e.g., see: Shoreplan Engineering 2005). British Columbia has also defined a similar set of guidelines, however in both cases, there is no specified model for mapping coastal erosion hazards. The U.S. Federal Emergency Management Agency (FEMA) has also developed guidance on coastal erosion hazard mapping that does not prescribe a single method, but offers alternatives that need to be selected based on local conditions and the types of shoreline being assessed (FEMA 2015).

For many Northern communities, analysis of coastal hazards will require wave run-up analysis (Jones 2005). In many cases, it is not necessary to have raw data related to each of these aforementioned factors to calculate wave run-up, as relationships between them can be used to derive estimates (Jones 2005). For instance, offshore wave height can be a good proxy storm surge wave forces, referred to as wave run-up, on the shoreline (Senechal et al. 2011). Typically, these factors are combined in an estimate of overall wave force, such as TWL, which at a minimum requires an estimate of wave height and offshore water levels (Baron et al. 2015; FEMA 2015).

4.1.4.1 Physically-based and empirical quantitative models of shoreline change

Physically-based dynamic models that aim to quantify the amount of erosion for a specific reach of shoreline are event-based, meaning they are generally applied to estimating erosion from large storm events. They consist of a system of equations for relating event water levels and shoreline properties to the potential loss of material under storm conditions. Most of these models focus on quantifying wave run-up and its effects on sediment transport using conservation of mass and energy equations (Jones 2005; Senechal et al. 2011; FEMA 2015). Figure 8 is a conceptual diagram of the effect of a shoreline's slope, aspect and the wave regime on potential erosion rates from Ruggiero et al. (2001). This is an example of one such physically-based model, however there are also more complex versions that incorporate 2- and 3-dimensional dynamics. Often, a freeboard and/or additional setback is added to wave run-up limits as a way of accounting for erosion hazards along shoreline (Jones 2005; KWL 2011). In the Northern context specifically, Dormoy (2014) used a physically-based model of coastal erosion that incorporates the effects of permafrost, which is an important control on the erodibility of coastal soils in these regions.

Physically-based models can be derived using statistical relationships between various variables, for example relating wind speed and direction to wave run-up using an empirical formula. However, a key limitation with statistical approaches is that they have embedded assumptions about the shape and characteristics of a given shoreline for which the formula was developed, meaning that a statistical relationship for one environment may not transfer well to another environment (Jones 2005).

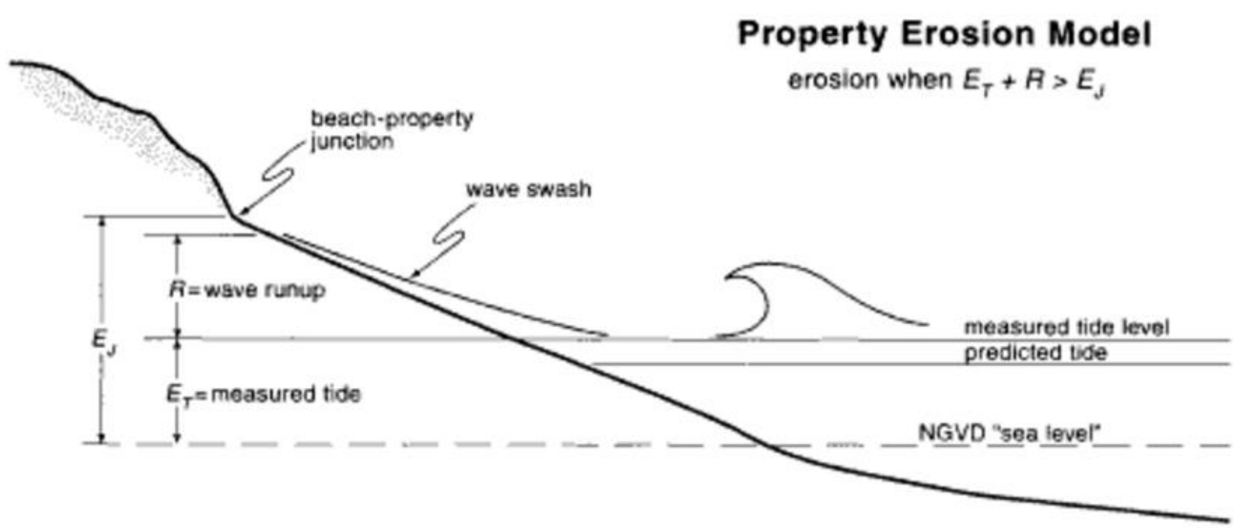


Figure 8. Conceptual diagram of a coastal erosion hazard model (from Ruggiero et al. 2001)

4.1.4.2 Vulnerability-based models

The concept of vulnerability, or susceptibility, to erosion can be used to overlay various layers of information about the characteristics of a coastline, usually in a geographic information system (GIS), to develop a map of erosion hazards (Guthrie and Law 2005; Meidinger 2011). Vulnerability-based models typically require indicators that are associated with specific processes which independently would exacerbate erosion. Examples include mapping based on a checklist of morphological characteristics as is presented in Bush et al. (1999) and summarized in Table 2.

Table 2. Checklist of indicators for evaluating shoreline change (from Bush et al. 1999)

Shoreline Change	Indicator
Severe erosion	Dunes absent with overwash common
	Active wave scarping of bluffs or dune remnants
	Tidal channels exposed in surf zone
	Vegetation absent
	Man-made shoreline structures now on beach or offshore
	Beach scraping (piled sand) evident
Erosion	Dunes scarped or breached
	Bluffs steep with no talus ramp
	Peat, mud, or tree stumps exposed on beach
	Beach narrow or no high-tide beach (no dry beach)
	Overwash passes or fans; artificial gaps (for example, road cuts)
	Vegetation ephemeral or toppled along scarp line
Accretion or long-term stability	Dunes and beach ridges robust, unbreached, vegetated
	Bluffs vegetated with stable (vegetated) ramp at toe
	Beach wide with well-developed berm
	Overwash absent
	Vegetation well-developed

4.1.4.3 Mapping based on historical rates of shoreline change

One common approach to understanding shoreline erosion vulnerability is to quantify and compare historical rates of shoreline change. These rates of historical change can then be used to extrapolate to the future with the assumption that current spatial patterns vulnerability will persist into the future under condition of intensified climate drivers of erosion. Utting and Gallacher (2008) provide an example of one such project from Nova Scotia.

Historical coastal change rates have also been estimated from remote sensing datasets in Northern communities of Iqaluit, NU (Hatcher and Forbes 2015) and the settlement of Herschel Island, YK (Radosavljevic et al. 2015). In the northern context, there have also been a few large-scale projects that have mapped coastal hazards along the Arctic coast using this approach, including the entire Alaska coastline (Gibbs and Richmond 2015) and the Beaufort Sea in the Northwest Territories (Environment Canada 2015). Figure 9 provides an example output of how historical analysis of shoreline change can be used to understand the spatial and temporal variability in a hazard within a given community and overall rates of change.

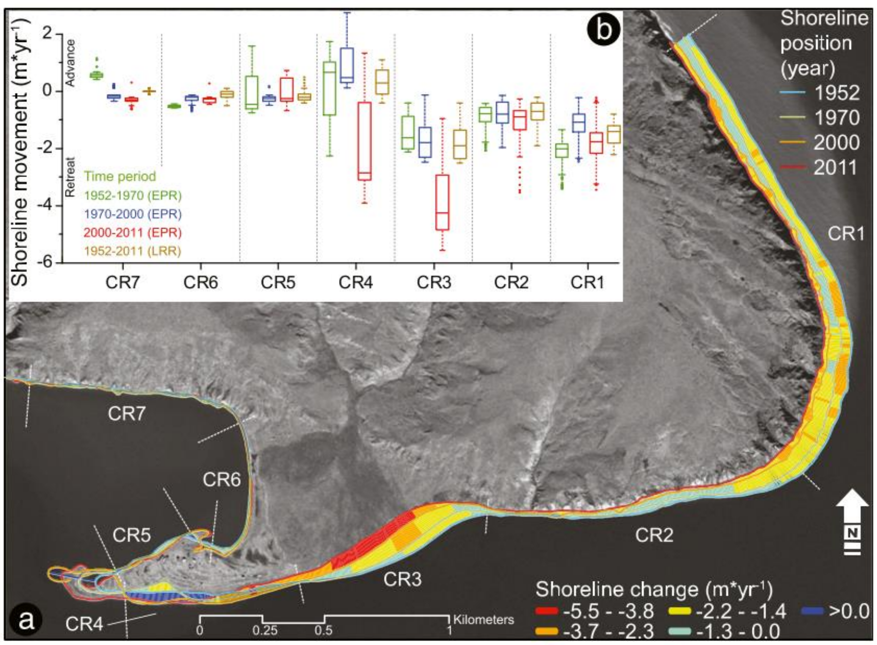


Figure 9. Example results of a shoreline change analysis from Radosavljevic et al. (2015) highlighting the position of shorelines over time for various profile locations and the variability in estimated change rates.

4.1.5 Summary of Considerations in Coastal Erosion Hazard Mapping

- Coastlines are adjoining and the characteristics of an individual reach are dependent on its own properties, but also adjacent ones and the overall coastal setting.
- Existing data, elicitation, data production, and field methods are all likely to provide information useful to hazard mapping of coastal erosion hazards.
- Mapping can be based on overlaying shoreline features, such as surficial geology, vegetation cover, shoreline profile, etc. using a vulnerability-based approach, or a physically-based model of the processes that cause erosion (wave-run-up, scouring, etc.)
- Remote sensing and regular measurements of the shoreline position can be used to determine rates of shoreline change.
- Wave energies, which are a significant driver of coastal erosion, are greatly influenced by sea levels. As such, coastal erosion mapping is increasingly moving toward incorporation of various sea level conditions to address this change.
- Many northern coastlines contain permafrost. The changing climate will continue to affect permafrost conditions along most northern Canadian coastlines, as the result of an average warming of air temperatures, and increased coastal exposure to more open (ice free) and, on average, warmer ocean waters. In areas with rising relative sea levels, these effects will be stronger still.

4.2 PERMAFROST DEGRADATION

Permafrost is defined as any type of ground that remains at or below 0°C for at least two consecutive years (French 2007). Permafrost degradation refers to the decrease in the thickness and extent of permanently frozen ground (Smith, 2010, Permafrost Subcommittee, 1988). It has an important influence on the biophysical environment and processes largely because it can contain ice as pore ice, ice lenses, ice wedges, and other massive ice bodies (Mackay, 1972). Approximately one-fifth of the world landmass and one-half of Canadian landmass is underlain by permafrost which is classified in four zones (Lyle, 2006). Continuous permafrost corresponds to areas where 90% to 100% of the landmass is underlain by permafrost; you move further south permafrost covers less and less landmass. Discontinuous permafrost corresponds to area where 50% to 90%, sporadic discontinuous corresponds to 10 to 50% and isolated permafrost corresponds to 0 to 10% (Lyle, 2006). Permafrost commonly occurs within this periglacial environment. The periglacial environment is a cold climate, frequently marginal to the glacial environment, and is characteristically subject to intense cycles of freezing and thawing of surficial deposits.

Permafrost characteristics that are pertinent to modelling and mapping of hazard include the thickness of the active layer, thickness of the permafrost itself, the amount of ice contained within the permafrost (ground ice characteristics and volumetric excess ice content), and its temperature. These data contribute to determine the type of permafrost, and its structure which allows understanding the degradation process and the level of vulnerability of the ground to permafrost thaw.

Surficial geology is the base of all permafrost mapping. The types and structures of the deposits play an important, decisive role in the presence, distribution, and vulnerability of the ground to permafrost thaw. In addition to surficial geology, some landforms are directly associated with, or are the result of the presence of permafrost (e.g., palsas, pingos, ice wedge polygons, thermokarst lakes, etc.).

Presence of water is another important factor in the distribution of permafrost. Water has a high heat capacity, it stores the heat and radiates it into the ground. Therefore, the presence of a lake indicates that an unfrozen layer exists underneath it (French 2007). Presence of stagnant water, even shallow, in permafrost area may indicate that it is degrading; moreover, if the water stagnates it will most likely accelerate the degradation process. Lakes, rivers, and wetlands are usually available among existing data. Remote sensing can also be used to obtain a wet terrain map (Stevens et al. 2012) which gives more detail than the existing datasets.

Land cover, type of vegetation in particular, is important to take into consideration in the discontinuous and continuous permafrost zones, some species of trees offer a better canopy cover which provides shade and intercept snow fall (French 2007), two factors that influences the presence and distribution of permafrost. On a local level, vegetation field observations can help with mapping the presence of permafrost; e.g. in the Jean Marie River (NWT) area researchers have witnessed the presence of permafrost in coniferous forest (sometime specific species, with black spruce being a particularly good indicator) and never in deciduous forest (JMRFN et al. 2013 and 2014). However, these observations cannot be generalized to large areas, indeed permafrost can be present in coniferous forest in different environments. Existing vegetation datasets can be found for certain areas, if not, they can be produced using remote sensing and air photo interpretation. Direct observation form the field are also very important to give site specific descriptions.

In many parts of northern Canada, community infrastructure has been built overtop of permafrost that is now thawing. Degradation of permafrost is damaging buildings (cracks in walls and foundations, entire buildings shifting), as well as roads and air strips. Also, severe landscape changes can already be observed in northern regions where community members have reported the disappearance of frozen mounds, an increase in muskeg areas, more forest fires and changes in the vegetation (JMRFN et al. 2014). There are considerable risks to development in areas where permafrost may thaw, inducing thaw settlement, thermal erosion, landslides, and other types of mass movements (Grandmont, 2012). As climate changes and communities grow, there is an urgent need to map the distribution of permafrost and its vulnerability to thaw.

4.2.1 **Climate and Anthropogenic Drivers of Permafrost**

As climate change continues in the northern regions, the terrain within the discontinuous permafrost zones where permafrost is warm, is likely to undergo considerable change (Romanosky et al., 2010; Smith et al., 2010; Bonnaventure et al., 2012). The distribution of permafrost zones is strongly linked to climate and, specifically, air temperature. The colder the mean annual air temperature (MAAT), the more likely to find permafrost covering large landmass. In general, the southern limit of discontinuous permafrost corresponds roughly with the 1°C MAAT, with some anomalies around the Hudson Bay (Bonnaventure 2012; Brown 1970); the southern limit of continuous permafrost corresponds with a MAAT of -6°C to -8°C (French et al. 1993). Permafrost mapping for northern communities is achieved at the very local scale and, as stated before, the permafrost zone itself won't affect the mapping. However, even on a local scale, there can be significant variation in air temperature between the top of a hill and the bottom of a valley which can influence the distribution of permafrost. This type of data can be collected by field monitoring. Other types of climate data, like climate models predicting the MAAT increase, can be used for mapping the vulnerability to thaw and to try to predict the degradation rate of permafrost. Scientists have been working on simulations suggesting that half of the area covered by the upper 3-4m of permafrost could thaw by 2050 and as much as 90% by 2100 (French 2007).

Snow cover also plays a role in the presence and distribution of permafrost because it is a good insulator; a heavy snowfall in autumn inhibits frost penetration while a winter a slow snowfall does the reverse (French 2007). Snow cover can be directly related to relief, certain areas favor snow accumulation, like the valley bottom, and the snow cover remains later in the spring on slopes facing north than on the ones facing south. Snow cover data can be mapped using remote sensing methods. It can also be monitored in the field to collect site-specific data. At the scale of a community, or along linear infrastructure such as a road or airstrip, redistribution of snow by wind, or from snow clearing is relevant to permafrost conditions. The insulating effect of snow, and the thermal impact of meltwater from snow can contribute to enhanced permafrost degradation.

4.2.2 Datasets and Data Acquisition

Figure 10 presents the datasets needed for a permafrost mapping project and their method of collection. In permafrost mapping, field data collection is typically a very prominent part of the project, but other data sources are still informative. Specific information about permafrost thickness, conditions, and structure is typically not available from existing data, can't be inferred using data production, and is likely not known by community members. Permafrost data takes time and specific expertise to collect. It is relatively expensive and is collected only at a local scale. Therefore, it is rare to have access to this kind of data if a permafrost mapping project hasn't been conducted before for a given area. Also, permafrost conditions can change from one region to another depending on numerous factors. As a result, it is difficult to extrapolate the results of one study to a large area without conducting more field work. However, data such as permafrost zones (sporadic, discontinuous, continuous), surficial geology, and climate are often available, and can be useful to guide the work.

In terms of data production, GIS has been used for quite a while; one example is to create slope and aspect maps from digital elevation models (DEM). Remote sensing is also increasingly helpful. For example, satellite images can be used to create vegetation classification, and to obtain soil moisture data or snow cover/thickness data. Each of these can then be related to likely permafrost conditions. Elicitation has not been heavily used in permafrost hazard mapping. Historically, hazard projects have been more oriented on geophysical processes. However, more recently, community meetings have been held and community members provided input and contributed to permafrost hazard mapping projects (JMR et al. 2013, JMR et al. 2014).

When starting the process of permafrost mapping, the first information to look for is data regarding the permafrost zone for the study area on interest. Permafrost zones (continuous, discontinuous, sporadic, and isolated patches) cover very large areas and can guide the project team to look for specific landforms or permafrost characteristics typical of each zone. While this data layer will probably not be integrated into the GIS analysis or model because of the very local size of the study area, it is useful data for scoping and initial steps of data gathering. Other information that may be researched by the project team and wouldn't be integrated to the GIS analysis or model, could include the quaternary history or the processes of permafrost formation in the region. This sort of information gives a context to the mapping and allows researchers to understand the physical processes influencing permafrost for a location.

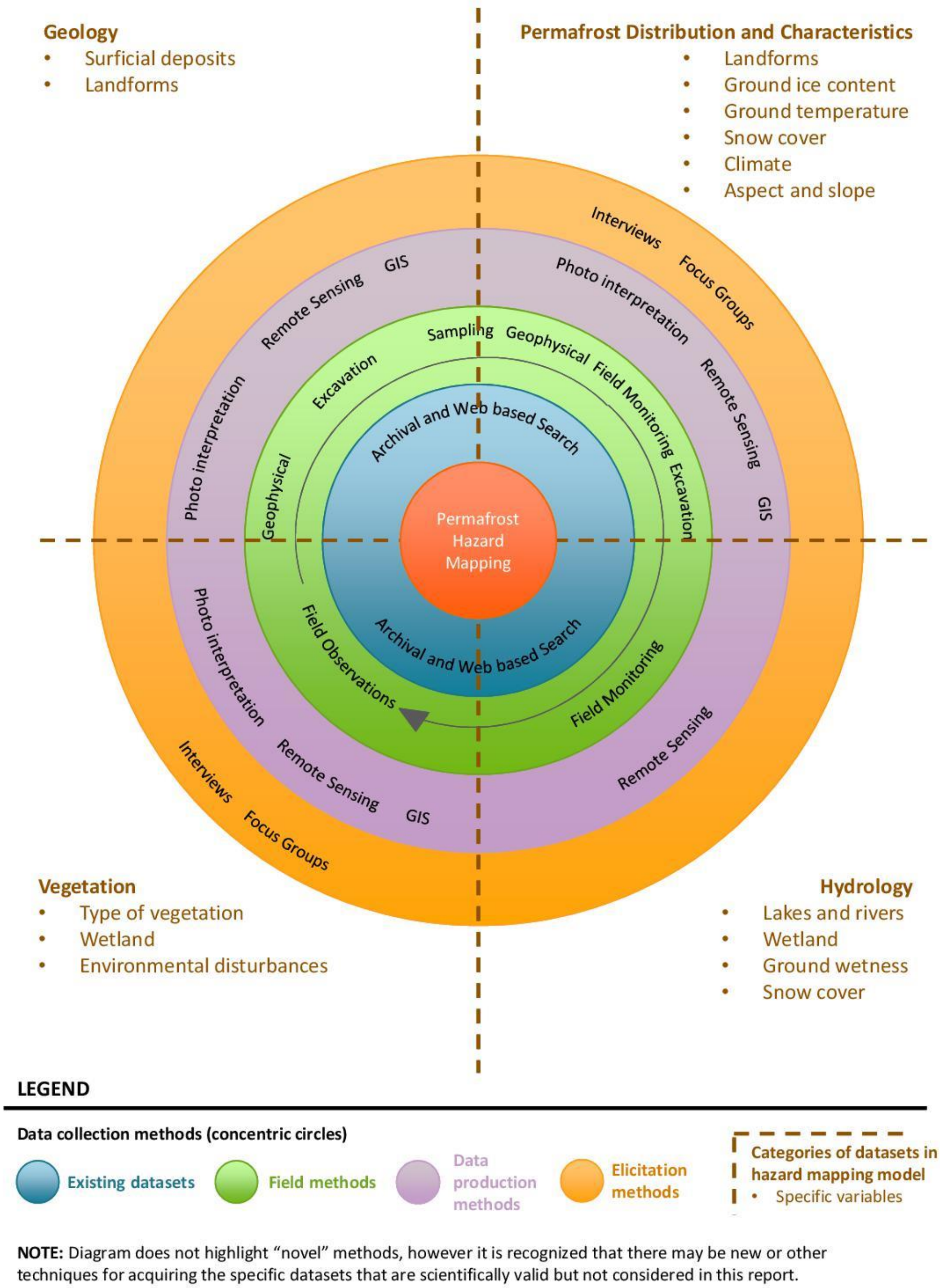


Figure 10. Datasets for permafrost mapping and their method of collection

When conducting fieldwork, methods range from low-cost surveys of active layer depth through to drilling permafrost cores and geophysical methods. Permafrost cores can be collected either using heavy machinery or with a light portable drill. Core samples from drilling are usually brought back from the field for analysis in laboratory where the types and textures of deposits are identified and the ice content is measured. These methods offer the collection of local data only and several boreholes are required in order to extrapolate the results to the entire study area. If permafrost is found in several types of environments in the study area, each of them will be investigated and sampled. These methods give a vertical profile of the ground and its characteristics. In addition, each borehole can be instrumented with sensors to measure and record ground temperature at multiple depths.

Electrical resistivity tomography (ERT) is a non-invasive geophysical technique that measures the ability of the ground to conduct the electricity (NCE, 2001). Frozen ground has poor conductivity, making it distinct from unfrozen soil and water which has relatively good conductivity. Software is used to filter and process resistivity data in order to map the resistivity distribution and characterize permafrost and the content of ice in the ground.

Ground penetrating radar (GPR) is also a non-invasive geophysical method used in permafrost research to map structures and composition of the ground (Guo et al. 2015). GPR helps to distinguish between ice and liquid water but not dry permafrost i.e. bedrock, in other words it does not reveal the actual composition of the ground (Gruber 1996). The large contrast between the electromagnetic properties of ice, water and some sediment makes GPR a particularly effective method for mapping permafrost structure and thermal conditions (Moorman 2007). It maps the contacts (threshold) between the surface, the active layer, the thaw front, and the different deposits and also gives a vertical profile of several meters of the ground.

ERT and GPR are two geophysical techniques that provide both a horizontal and vertical profile of several meters of the ground. Like all geophysical techniques, confidence in the interpretation of the ERT and GRP results increases when complimentary information is available, like data from boreholes, ground temperature measurements and probing of active layer (NCE 2015).

Elicitation has not been heavily used in permafrost hazard mapping. However, meetings with communities and/or local stakeholders are usually held during the permafrost mapping project. These meetings are used to inform of the project to obtain local input. Local input includes discussing permafrost with the local population and providing support and guidance in the preparation of field work and possibly during the field data collection itself. Communities and/or local stakeholders have contributed to permafrost mapping in this way, but rarely in a data gathering process per se. It is only recently that interviews and focus groups have been used to map landscape changes related to permafrost thaw observed by community members. Community members in northern communities still travel a lot on the land for hunting, trapping, fishing, and plants and berry gathering. They are very familiar with the landscape and witness the changes occurring year after year. Data collected can relate to past and present landforms, land movement, environmental disturbances, and landscape changes indicator of permafrost presence. This method would only be used in addition to existing data collection, field data collection and data production in order for the mapping to be scientifically sound.

4.2.3 Data standardization and organization

Permafrost mapping does not require specific methods to process and organize datasets, please refer to the data processing and organization described in Section 4.2.2.

4.2.4 Permafrost Hazard Models and Mapping Techniques

Methods to map permafrost-related hazard can be broadly categorized in two groups; the vulnerability mapping approach, and the remote sensing based approach. The vulnerability mapping approach is commonly used to map permafrost around northern communities; it shows the distribution of permafrost and estimate its vulnerability to thaw. The remote sensing based approaches are used less often for community mapping. It is usually used to map larger areas. However, with high resolution data, some of these models are applicable to a community scale.

It should be noted that approaches and models can be built in many different ways; those presented below should not be considered as the only existing reliable approaches and models.

4.2.4.1 Vulnerability approach

The vulnerability approach is governed by the type of data collected. In this context, vulnerability refers to close the permafrost is to degradation. The project team decides which datasets they are feasibly able to collect (within available time, budget and capability) and then decides what model or analysis to use. A review of permafrost hazard maps reveals that that models (often simply called analysis) are designed specifically for a project as opposed to using a predefined or pre-existing model.

Figure 11 shows a generalized model which has been used for merging datasets and developing a hazard ranking. Versions of this general model have been used in in The Yukon, Northwest Territories, and Nunavik (Benkert et al. 2015, L'hérault et al. 2013, JMRFN et al. 2014). There can be as many datasets as the project team decides to use (usually a minimum of three). A weight or rank is attributed to each of the dataset to describe the degree to which they control the hazard at the community scale. Some projects don't use a quantitative ranking; all datasets can have the same weight in the model or be evaluated on a qualitative basis (JMR et al. 2014). Some use a more quantitative ranking system (see Table 3). The result is a cumulative ranking map which can have many different classes showing the degree of vulnerability to degradation. The many classes make the map quite difficult to read and interpret and are usually considered as a draft. A final step regroups the classes into three or four classes, displaying the final levels of vulnerability to degradation.

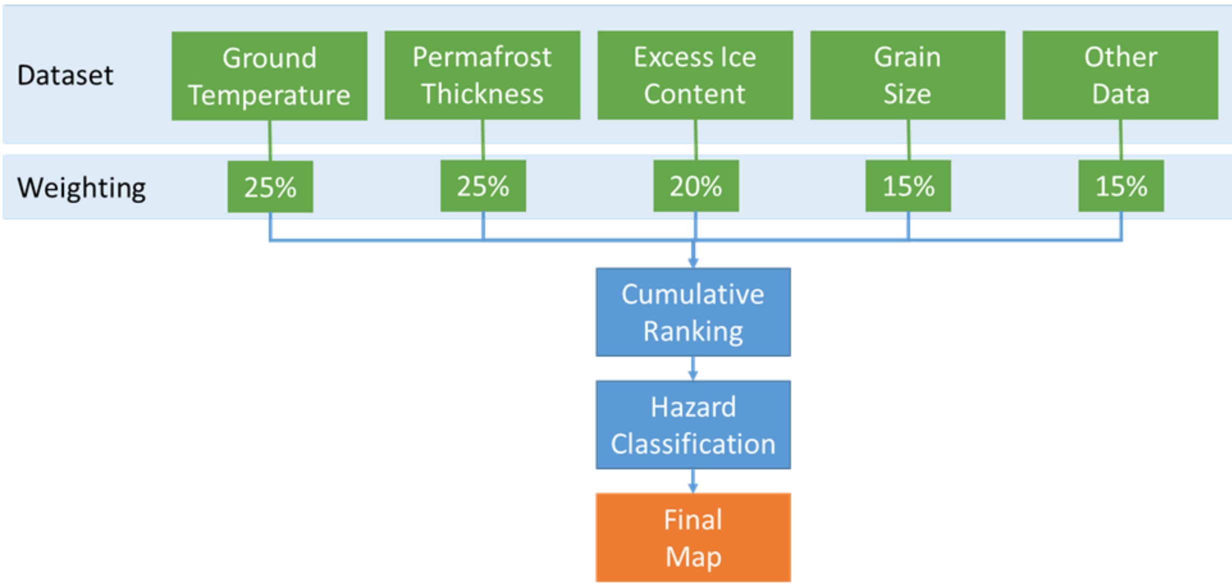


Figure 11. An example of a generalized model for a vulnerability approach. The datasets used and weighting will vary by project.

The models do create a final map, which in some cases, can be refined and verified by performing an in depth photo interpretation (also guided by field observations) of the study area. This allows to properly smooth the edges of the different vulnerability classes, to clean up/un-pixelize the classes, and in certain cases, reclassify certain polygons as shown in Figure 12. Table 3 shows examples of permafrost mapping using different approaches.

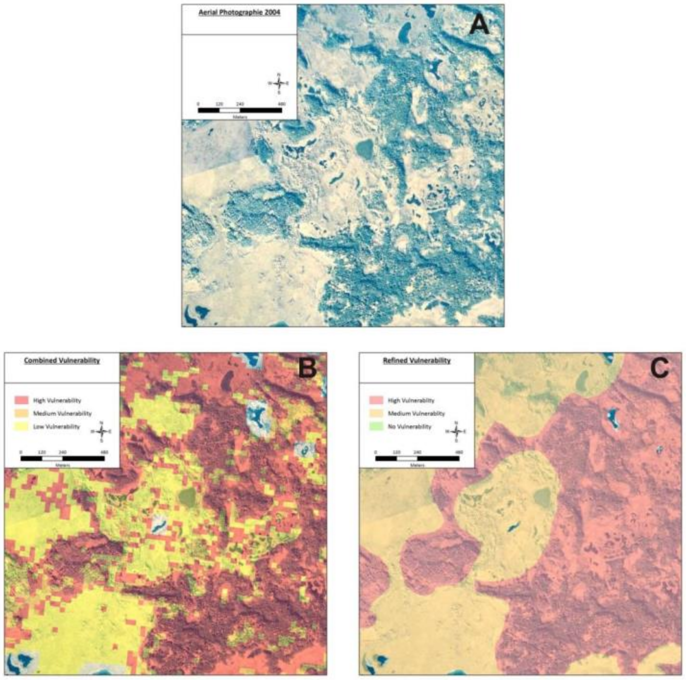


Figure 12. A; air photo used for the photo interpretation, B; final map produced by the GIS analysis, C; refined final map after photo interpretation (JMRFN 2014).

Table 3. Examples of three permafrost mapping projects that used a vulnerability approach

Permafrost mapping project	**Dawson City Landscape Hazards (Benkert et al. 2015)**	**Production de cartes des caractéristiques du pergélisol afin de guider le développement de l'environnement bâti pour quatre communautés du Nunavik (L'hérault et al. 2013)**	**Food Security Vulnerability Assessment Related to Permafrost Degradation in the Jean Marie River First Nation (JMR et al. 2014)**
Datasets	• Slope angle • Slope aspect • Surface material • Permafrost probability (includes air temperature, elevation, solar radiation)	• Surficial deposits • Permafrost characteristics • Slope angle	• Surficial deposits • Permafrost characteristics • Vegetation
Ranking	Yes	Yes	No
Final vulnerability classes	• Low • Moderate • Moderately high • High	• Terrain potentially good for construction • Terrain potentially good for construction but limited to certain type of foundation • Terrain unfavorable to construction	• Low • Medium • High

4.2.4.2 Remote Sensing Based Approach

As previously mentioned, remote sensing-based approaches were historically used for areas larger than a single community. However, technology advancement means that there are now a number of cases when remote sensing-based approaches have been used for communities in Nunavut (3vGeomatics 2015) and for mapping the surroundings of roads (Stevens 2012). It can be applicable to smaller areas as long as the resolution of the data is high enough (30m or less). This approach is typically based heavily on the use of remote sensing with LiDAR, InSAR, RADARSat or other technologies and usually involve statistical and/or spatial modelling. Nevertheless, field data collection would still be required, either to collect datasets or to verify and validate the results of the models. Two examples of remote sensing-based approaches are described below: the seasonal activity models, and the active layer model. These models, and others, also use permafrost characteristics, geology, land cover, climate scenarios, hydrology, landforms, slopes and aspect, etc., to support the remote sensing models.

One remote-sensing hazard model is the seasonal activity model. This used as part of the process for mapping seven communities in Nunavut. Permafrost instability, permafrost characteristics, hydrology, vegetation, landforms, and a DEM were used in this project to map permafrost instability, land cover and active layer. The simplest form of the seasonal activity model uses a fixed thawing start date and length of the thawing season (June 1 to September 30) and assumes constant heating and soil homogeneity (3vGeomatics 2015). The modelling also uses synthetic aperture radar interferometry (InSAR) technology and RADARSAT satellite images. The results for the communities of Nunavut is called a Development Suitability Map with four final classes (unsuitable, marginal, possible, and suitable). A confidence factor of either low, moderate or high is offered for each map.

4.2.5 Summary of Considerations in Permafrost Hazard Mapping

- Climate change is causing permafrost to degrade either through the process of increased MAAT or increase of the precipitation.
- In areas where warm permafrost conditions are dominant (mean temperatures of −3°C to −0.1°C) (Lewkowicz, A. et al, 2011), is it very likely that permafrost will thaw after disturbances like forest fire, vegetation clearance, or construction.
- Permafrost conditions and surficial deposits are mandatory to permafrost mapping. The use of other datasets depends on availability of existing datasets and the choice of data collection method.
    - Ground temperature, permafrost thickness, and excess ice content are key permafrost characteristics that contribute to overall permafrost vulnerability

to thaw. These characteristics are influenced by a vast number of surface, subsurface and climatologic variables.

  - While existing data and data production may be informative, field data are generally required to complete permafrost hazard mapping. Use of elicitation is an emerging practice that helps capture impacts of permafrost thaw on other aspects of human and natural systems.

- Field methods can range in complexity from relatively straightforward surveys of active layer depth through to more complex drilling and geophysics campaigns. If collection of ground temperature data is deemed necessary, at least one year of data are required in order to determine permafrost temperature curves.

4.3 LANDSLIDES AND GROUND MOVEMENT (SUBSIDENCE)

In ground movement studies, fieldwork is almost always required to visually identify and manually map (using GPS points) potential areas of slope instability. Soil tests may also be required to determine key geotechnical properties that influence ground movement hazards. Unless there is a documented history of ground movement in the local area, existing sources of information on this hazard will likely be rare and will require being mapped from scratch. This is particularly the case in Northern communities where ground movement hazards are associated with recently degraded permafrost and where ground movement hazards are new. Mountainous terrain has a much greater frequency of landslides and ground movement, and communities in these areas may have previous inventories or records of occurrences of such events.

The most common ground movement hazards for Northern communities are land and rock slides, subsidence and mass movement (Couture and Riopel 2008; RSI 2013). Although the physical processes involved in each differ, the common feature is a resulting displacement of ground. For this report, the definition of ground movement refers generally to the downward movement of soil or rock, or the failure of a ground slope (Fell et al. 2008; Natrual Resources Canada 2015; USGS 2016). This can include rapid destabilization of slopes leading to landslides, or more gradual shifting of the ground surface resulting in subsidence due, for example to permafrost thaw or thermokarst (RSI 2013).

The causes ground movement must be understood in the context of the geologic (e.g., parent material properties and weathering), geomorphologic (e.g., glacial-isostatic rebound, tectonic changes, freeze-thaw, depositional environments), hydroclimatologic, and anthropologic systems in which they occur. For instance, sudden events such as landslides generally occur in mountainous areas and are triggered by specific events, such as extreme rainfall or seismic activity. Slower ground movement processes, such as subsidence, creep and block flow can also occur in areas of low-relief under conditions of unstable or changing soil conditions, such as permafrost thaw and deepening active layers. While gravity is the primary driving force behind ground movement, other contributing factors are:

- Excessive rainfall or snowmelt causing ground saturation;
- Erosion by rivers, waves or glaciers causing steep banks;
- Surficial vegetation removal by forest fire, drought or disease;
- Changes in permafrost resulting in loss of soil stability;
- Seismic activity causing weakened or unstable slopes;
- Volcanic activity causing to loose ash deposits or debris flows; and,

- Anthropogenic modification of land (e.g., rock or waste piling, excavations, artificial vibrations, deforestation, or the development of man-made structures) (USGS 2004; Lyle and Hutchinson 2006; Huggel et al. 2012; Jagielko et al. 2012; Hong et al. 2014; USGS 2016).

4.3.1 Climate and Anthropogenic Drivers of Landslides and Ground Movement

Climatic conditions greatly influence the characteristics of soil as well as other earth surface processes that can result in ground movement. Climatic conditions can act as triggers for, and contribute to the overall environmental conditions that make certain areas susceptible to ground movement hazards. From a climate standpoint, the most significant climatological drivers of landslides include:

- **Precipitation:** Frequency, duration and intensity of precipitation events leading to increased ground saturation, potential for ponding, overland and saturated water flow and surficial erosion. Intense precipitation can act as a trigger for landslides, however the rain and snow regimes in a study area can greatly affect soil conditions over the longer-term (Pike et al. 2010b; Huggel et al. 2012; Salciarini et al. 2012);
- **Temperature:** Rapid changes in temperature can lead to equally rapid freeze-thaw events, which can be a trigger for landslides, ground heaving and other forms of mass movement (e.g., topple and rockfalls) Changes in ground temperature arising from changes in air temperature can also alter soil cohesion and other texture properties that can lead to ground movement. Melting of glaciers is also driven heavily by temperature and can contribute directly to ground movement, especially in mountainous areas (Evans and Clague 1994; Papathoma-Köhle et al. 2007; RSI 2013; Corominas et al. 2014);
- **Forest fires:** Frequency and intensity of forest fires leading to loss of vegetation and ground stability, including exacerbated permafrost thaw, which lead to slumps and slides. Forest fires are often triggered by climatological phenomena, such as lightning strikes and dry air conditions (Huscroft et al. 2004; Couture and Riopel 2008); and
- **Permafrost degradation:** Degradation of permafrost due to changes in air temperature and precipitation regimes, anthropogenic activities and related environmental change (e.g., biodiversity loss and changes), and other natural disturbances (e.g., forest fire). Permafrost is a key soil property that greatly influences the geotechnical characteristics of terrain and changes in permafrost can stabilize soil leading to ground movement. Permafrost characteristics that are most critical to ground movement hazards include the depth of the active layer, its continuity/extent across a land area (Huscroft et al. 2004; Lyle and Hutchinson 2006; Jackson et al. 2012; Grandmont et al. 2012; RSI 2013; Hong et al. 2014; Gunther et al. 2015).

The process by which ground stability is reduced as a result of several of the aforementioned climate drivers is summarized in Figure 13.

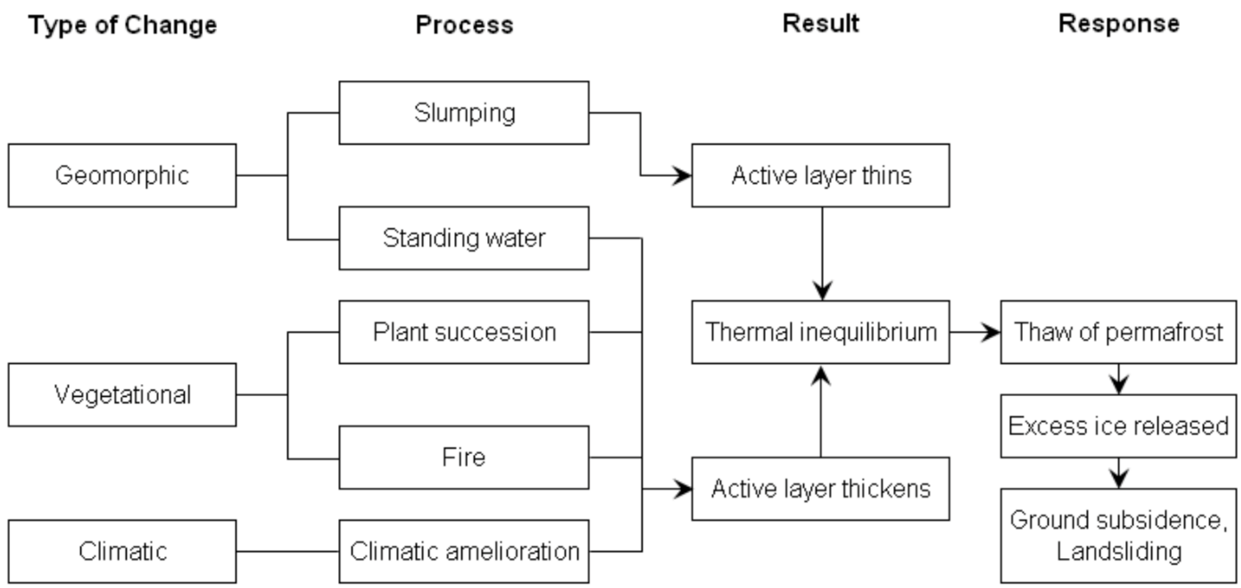


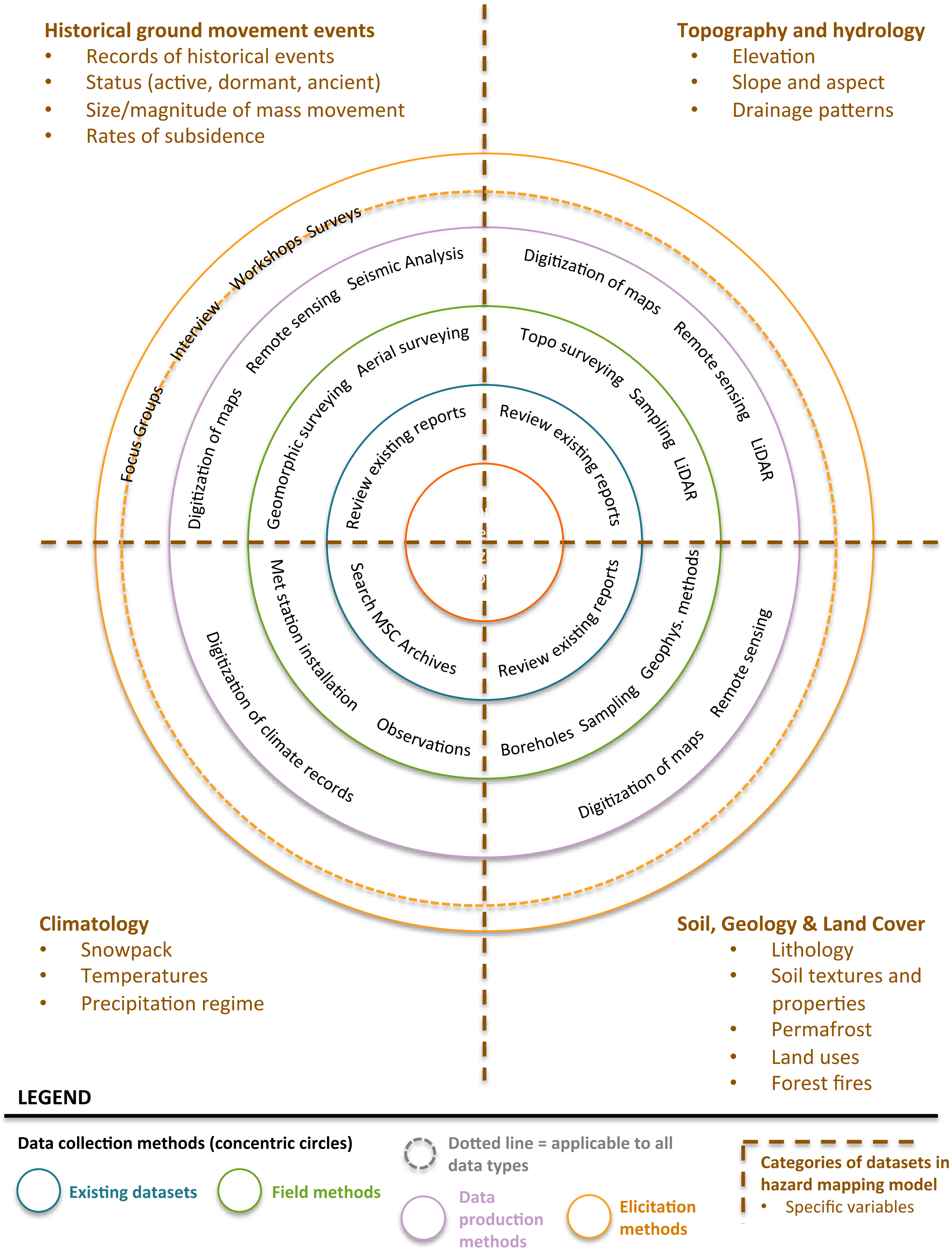
Figure 13. Summary of various climate-driven processes that ultimately lead to ground movement (from Lyle and Hutchinson 2006)

4.3.2 Datasets and Data Acquisition

Landslides and ground movement are typically mapped using a combination of geomorphologic, geologic, hydroclimatologic, and land cover datasets. In Northern environments, information regarding permafrost also critical, as it controls many key properties of the soils that mediate potential for mass movement, and sudden changes in permafrost can also trigger ground movement events (Couture and Riopel 2008; Grandmont et al. 2012).

Many landslide and ground movement mapping techniques also rely heavily on historical event characteristics and locations as inputs to empirical models for predicating ground movement and for validating mapping. The occurrence of historical ground movement events can also provide insights into the factors that contribute to ground movement locally. Additionally, a history of previous ground movement does make a given area more susceptible to other events in the future (Fell et al. 2008; APEGBC 2010). As such, historical geologic records, along with good-quality aerial photography and remote sensing datasets are often necessary in identifying these locations (Guzzetti et al. 2012). Often the type of event (active, dormant, ancient), and other parameters, such as its severity and spatial extent are mapped.

In addition to this list, Northern communities will require an assessment of permafrost extent and characteristics. Additional details on the datasets that might be required in a ground movement hazard mapping project are summarized in Figure 14 and detailed below.



NOTE: Diagram does not highlight "novel" methods, however it is recognized that there may be new or other techniques for acquiring the specific datasets that are scientifically valid but not considered in this report.

Figure 14. Summary of ground movement hazard mapping variables and common approaches for data collection

Good topographic information is necessary to identify both historical ground movement events, and potential resistance of a slope to collapse and whether or not permafrost may be presence and at what depth (APEGBC 2010; Jadda et al. 2011). Analysis of surface terrain, including variables of slope, elevation, aspect and local topography is a key element of ground movement analysis (Huscroft et al. 2004; BCG Engineering 2010; Guzzetti et al. 2012; Jagielko et al. 2012; RSI 2013). Because topography is closely related to surface water drainage, it is often used as a way of expressing the watershed hydrologic factors that influence ground movement hazards. Like most other datasets, the scale of the topographic data used to analyze potential ground movement hazards should be at an appropriate scale for the overall hazard assessment.

Field data collection may be required to augment the quality and/or resolution of datasets related to topography, soil, permafrost and other landscape information (Corominas et al. 2014). A significant challenge with field-based surveys aimed at identifying ground movement hazards is the fact that it is difficult to identify vulnerable slopes through observation due to their large size and extent on the landscape (Guzzetti et al. 2012). As such, fieldwork is generally aimed at collecting more detailed information about the soil properties and geotechnical conditions at particular sites where a ground movement events has taken place, or are deemed to be vulnerable based on landscape-scale analysis.

The mechanical properties of the soil and/or rock present in a given study area is a key determinant of overall potential for ground movement. In almost all studies reviewed for this report, surficial geology and/or soil properties were a key variable in the mapping, regardless of the specific model type implemented. Soil texture and geologic material type are key features, along with more technical properties such as shear strength and particle size/distribution for more detailed quantitative modeling (APEGBC 2010; Jackson et al. 2012). Soil saturation is an important variable because it influences the cohesion of soil, with wetter soils being more vulnerable to movement (Pike et al. 2010b; Salciarini et al. 2012). Presence of faults and other structural geology features are also used in susceptibility mapping, quantitative models and heuristic analysis of ground movement (Jackson et al. 2012; Jagielko et al. 2012).

Fieldwork typically involves collecting soil samples, drilling of test boreholes, test pits, topographic surveying and other in-situ geotechnical analysis (RSI 2013). Monitoring devices may also be installed to monitor soil and slope stability in real-time and this information can be used in future mapping of ground movement hazards (USGS 2015). Geophysical techniques, such as ground-penetrating radar and electro-resistivity methods, are also commonly used to collect data on soil and geologic variables required in ground movement hazard mapping and can be particularly applicable to permafrost properties (RSI 2013). Field methods also involve periodic topographic surveying, which can be done from the ground or using airborne technologies, such as LiDAR. These records of changes in topography can be used for subsidence mapping.

In remote communities, records of historical ground movement events may be sparse. Meetings with local experts and stakeholders can be a valuable tool for identifying and better understanding historical landslide events. Heuristic analysis is a common element in many landslide and ground movement studies and involves expert interpretation of geomorphological mapping and the overall environmental setting of a study area (Fell et al. 2008).

4.3.3 Data Standardization and Organization

There are no currently established standards or best-practices for data standardization and organization of landslide and ground movement information, aside from those generally pertaining to hazard information. There are however, numerous sources of standardized methods for geotechnical testing which have specified requirements, although these are implemented at the site-specific scale (e.g., see ASTM standards at: http://www.astm.org/Standards/geotechnical-engineering-standards.html).

4.3.4 Landslide and Ground Movement Hazard Mapping Models

Ground movement hazards can be mapped using different techniques depending on the ultimate use, scale and level of detail required in the map (Fell et al. 2008; Jackson et al. 2012; Corominas et al. 2014). It is generally recognized, that as the scale of assessment becomes more localized, assessments can become more quantitative and oriented toward calculations of annual probabilities of slope failure and amount of slope run-out of actual ground displacement (Corominas et al. 2014). This is in contrast to larger-scale assessments that use the concept of susceptibility to layer various geologic and landscape features within an overall rating system to identify areas of higher versus lower likelihood of ground movement occurrence (Fabbri et al.; Couture 2008; Fell et al. 2008; Sorbino et al. 2010; Jagielko et al. 2012).

Ground movement hazard mapping models are designed to determine how different areas within a landscape might respond to triggers such as permafrost thaw and extreme rainfall based on their properties, along with identifying the triggers themselves (Sorbino et al. 2010; Jackson et al. 2012; Salciarini et al. 2012). Two hazard models are reviewed below as they have particular relevance to application in northern environment. These include landslide mapping models, and ground subsidence models.

4.3.4.1 Landslide mapping models

Table 4 provides a synopsis of different landslide mapping approaches, each of which could be applied to different levels and scales of analysis. This table is based on a framework presented by the Geological Survey of Canada, based on international guidelines presented in Jackson et al. (2012). The mapping methodologies are broken-down into two different classes: (a) landslide inventories and (b) landside hazard susceptibility maps. These represent two types of mapping products, representing historical versus potential hazards, respectively. Within each class, it is possible to use a range of mapping methods, each requiring different analysis and modeling on a scale from qualitative through highly quantitative. Figure 15 provides a visual comparison of a landslide inventory versus susceptibility map.

Table 4. Summary of various landslide mapping approaches, breaking-down methods based on the type of mapping project (inventory vs. susceptibility) (from Jackson et al. 2012)

		Landslide Inventory	Landslide Susceptibility
Typically Qualitative	Distribution	Based on distribution of landslides or other terrain attributes	No recommended approaches
	Activity	Based on distribution AND activity of landslides or other terrain attributes	No recommended approaches
	Density	Based on distribution of areas of similar landslide density or densities of associated terrain attributes	No recommended approaches
	Geomorphic	Based on distribution of geomorphic features or associated terrain attributes	Based on interpretations of distribution of geomorphic features or associated terrain attributes
Qualitative or Quantitative	Subjective/ Relative	Not applicable	Based on a defined subjective algorithm
	Predicted movement	Not applicable	Based on predicted travel path or runout zone
	Stability Calculation	Not applicable	Based on slope stability calculations
Typically Quantitative	Relative variant	Not applicable	Based on a defined statistical and rigorous algorithm
	Probabilistic	Not applicable	Based on the statistical relationship between past landslide and parameters known to be associated with landslides

In general, the methods used for quantifying probability of ground movement are based on geotechnical analysis, with key tools including slope displacement analysis, rock fall runout analyses, climatological analysis, and seismic slope analysis (Bell and Glade 2004; Fell et al. 2008; APEGBC 2010; BCG Engineering 2010). The starting-point for landslide hazard mapping is understanding the type of hazard based on whether it is active, inactive, dormant or potential (APEGBC 2010).

Like all other hazards examined in this report, it is necessary to define the level of hazard of interest, which is based on the judgement of local stakeholders and is often codified in zoning bylaws and building codes. This can be done by comparing estimates of the likelihood and magnitude of ground movement hazards can be expressed based on criteria established in the national and provincial/territorial building codes (APEGBC 2010). For example, in BC, the design threshold for ground motion hazards in building design is the event with an annual probability of occurrence of 0.04%. It is generally recognized, that in many jurisdictions across Canada's North, there are no existing bylaws, meaning that analysis will require professional judgement.

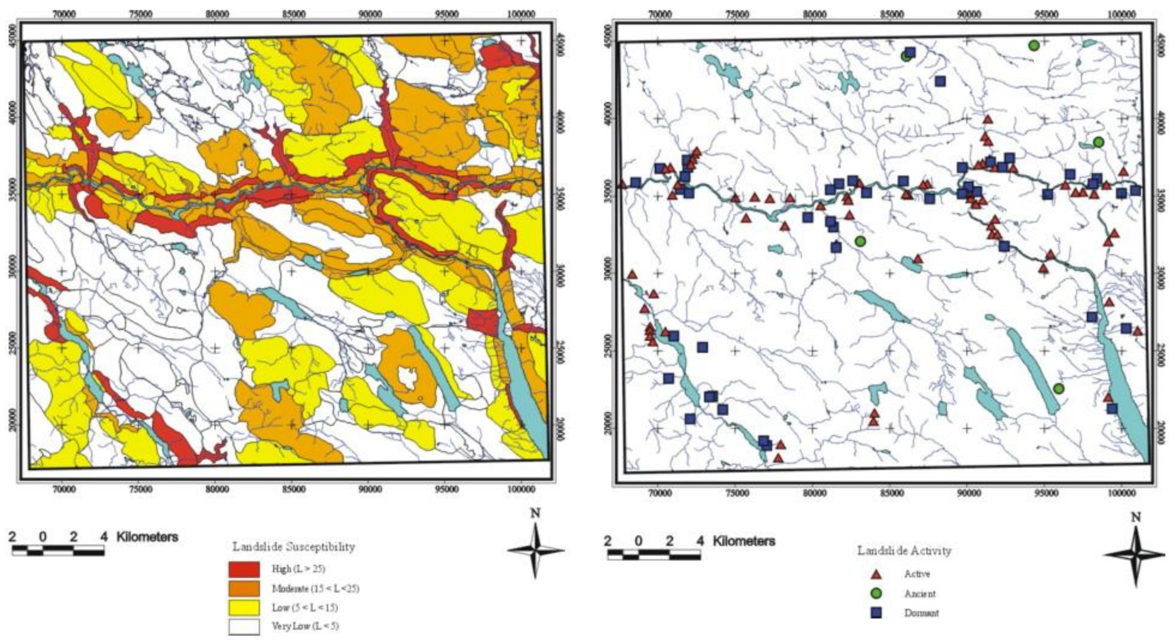


Figure 15. Example of landslide susceptibility (left panel) versus landslide inventory (right panel) mapping (Jackson et al. 2012)

Typically, the magnitude of a landslide can be measured in terms of the total displaced, or potentially displaced material with slide length being a proxy indicator (Jagielko et al. 2012). The concept of a "Safety Factor", expressed as the ratio of a slope's shear strength over its shear stress is used as a quantitative indicator that can be approximated with standard mechanical theory models and mapped with GIS datasets (Fell et al. 2008; Jagielko et al. 2012). That being said, visual analysis of air photos and topographic overlays are commonly used to map historical landslides and vulnerable areas, which are commonly used to identify potential ongoing ground movement hazard zones (Bell and Glade 2004; Fell et al. 2008; Guzzetti et al. 2012). Often statistical models of landslide susceptibility are prepared using many of the datasets and factors described in Section 4.3.2 in various combinations, depending on the specific context (e.g., see Couture and Riopel 2008; Jagielko et al. 2012).

4.3.4.2 Ground subsidence mapping models

Ground subsidence hazard modeling is based on similar geotechnical analysis used in landslide models (e.g., stable slope analysis, permafrost thaw, thermokarst movement, subsidence susceptibility based on terrain attributes). However, given that this class of geohazard occurs over longer periods of time as is not event-based, other methods are also used for mapping. Like with landslide mapping ground subsidence mapping is generally categorized into historical analysis of ground movement events and susceptibility.

Airborne LiDAR and satellite-based synthetic aperture radar (SAR) provide high-resolution measurements of elevation that can be compared over time to determine rates of subsidence (Stevens et al. 2012; RSI 2013; Gunther et al. 2015). Figure 16 provides an example of mapping derived from this type of analysis along HWY 3 in the Northwest Territories, north of Yellowknife from (Stevens et al. 2012). There are also less quantitative approaches to mapping subsidence and mass movement by analyzing changes on the landscape using field-based geomorphic landscape analysis to compare changes in the terrain over time.

Susceptibility mapping approaches are also commonly used, especially when mapping larger areas. For instance, (Hong et al. 2014) developed a Permafrost Settlement Hazard Index for mapping ground subsidence across Alaska. This index used the following 6 variables, which were also present in numerous other ground subsidence across Northern Canada studies reviewed in RSI (2013), and presented in Table 5:

- Ground ice
- Air temperature
- Soil texture
- Snow depth
- Vegetation
- Organic soils

Grandmont et al. (2012) also used a similar index, however, it is tailored to local-scale land use assessment in Northern regions and is comprised of surficial deposit type, drainage characteristics and slope factors, with each being assigned a different rating value from 1-10 (see Figure 16 for maps of these factors).

Table 5. Summary of factors comprising ground subsidence hazard mapping models in Northern Canadian projects (adapted from RSI 2013)

Study Area:	Salluit, Nunavik	Tasiujaq, Kangirsuk, Akulivik, Puvirnituq, Nunavik	Clyde River, Nunavut	Paulatuk & Ulukhatok, NWT	Mayo & Pelly Crossing, Yukon	Arviat, Whale Cove, and Kugluktuk, Nunavut	Mactung Mine, Yukon	MacKenzie Valley, NWT
surficial geology	X	x	x	x	x	x		x
ground ice	X		x		x			
slope / aspect	X	x			x	x	x	x
ground temperature	X				x			
soil salinity	X		x					
permafrost properties	X						x	x
air temperature	X							
drainage conditions		x						
historical flooding			x					
standing/ ponding water			x	x	x	x		
snow cover				x	x			
erosion					x			
vegetation								x

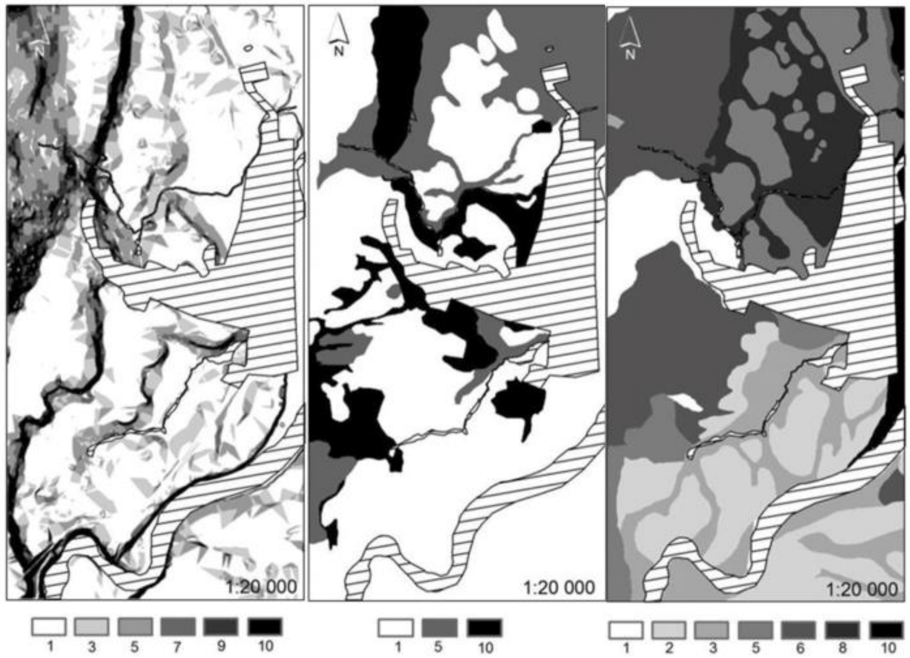


Figure 16. Mapping of the three factors using the 10-point rating system for each factor. Left panel is slope, centre is drainage rating and right panel is surficial deposit type (from Grandmont et al. 2012)

4.3.5 Summary of Considerations in Landslide and Ground Movement Hazard Mapping

- There are various kinds of ground movement that could be assessed, each having different triggers and contextual factors that would need to be incorporated into the mapping project;
- There is no universal approach for mapping ground movement and landslide hazards and the ideal approach depends on applications of the mapping, scale of interest, and available resources and datasets, among other considerations. However, bylaws and building codes do offer guidance in some jurisdictions regarding acceptable levels of potential for buildings to be exposed to landslides;
- All mapping projects will generally require an inventory of historical ground movement events as a starting point. This can be a fairly general or highly specific/detailed list of events and their properties, depending the project;
- As the scale of interest becomes smaller, assessments will be more quantitative and required fieldwork to obtain the necessary data for mapping;

- Susceptibility mapping is used to identify relative difference in ground movement hazards across a landscape and can involve various different factors combined in an empirical model.
- Highly quantitative ground movement hazard mapping, which estimates the intensity/size of ground movement events using geotechnical models is generally only viable on a highly local scale and requires substantial data.
- Key northern climate change-related considerations for landslides and ground movement include:
    - Changing permafrost conditions, including deepening of the active layer;
    - Changing intensities and extent of landscape-level disturbances like forest fires, which can make areas more susceptible to ground movement;
    - Changing precipitation regimes.

In Northern Canadian contexts, permafrost is a significant control on ground movement hazards, as changes in ground ice distribution and content can act as a trigger of ground movement. Permafrost degradation is explored in detail in Section 4.2 of this report.

4.4 FLOODING HAZARDS

Flood hazard mapping, particularly in local communities, involves many datasets that may be readily available from government sources, such as hydrometric flow data available from the Water Survey of Canada, river hydraulic information from engineering studies of bridges and river crossings, and watershed information (soils, topography, land-cover) that are available from municipal planning documents. It may be the case, however, that this information is either dated or does not cover sufficient area. While soil information is generally available from geotechnical studies and does not change frequently, new information on land-cover, river morphology, and water resource infrastructure may need to be surveyed. It may also be necessary to use remote sensing methods to gain an understanding of seasonal dynamics. Often climate information is readily available from existing sources. However, in northern settings, some work is typically required to ensure that the data are consistent and complete.

4.4.1 Hazard Overview and Definition

A flood can be best defined as an "overflow of water onto normally dry land… caused by rising water in an existing waterway, such as a river, stream, or drainage ditch [and] … ponding of water at or near the point where the rain fell" (National Weather Service 2010). Floods are defined as hazardous when they become a source of potential harm or damage (Church et al. 2012). Due to many complex interactions between meteorology, hydrology, the environment, and water management infrastructure/operations that can produce flooding, flood hazard characterization often involves first determining which of processes lead to flooding in a given area (FEMA 2009). Figure 17 and the following descriptions highlight the major causes of floods that are might be relevant to Northern Canadian communities, based on their driving physical processes (Church et al. 2012; Whitfield 2012):

- **Flash Flooding:** Elevated streamflows and water levels resulting in rivers overtopping their banks, causing flowing water to extend into floodplain areas. These elevated flood flows occur from a complex range of natural and anthropogenic watershed hydroclimatic processes, predominantly snowmelt and freshet and rainstorms (Marsh and Hey 1989). Flash flooding generally affects long reaches of a river or portions of a watershed(s), and can therefore be very widespread.
- **River Blockages (Ice Jams, Debris Jams, Beaver Dams, etc.):** Riverine flooding can be caused by the blockage of flow from a variety of sources, which results in river water overtopping its banks upstream of the hydraulic barrier. Sources of blockages include the mobilization and build-up of ice; debris build-up commonly against infrastructure such as bridge abutments; or more natural causes such as beaver dams (Church et al. 2012; Burrell et al.

2015). While flash flood events arise from watershed conditions and climate driven processes, a blockage typically causes floods to be much more isolated in their spatial extent and can occur under normal flow conditions, however river blockages may become more likely during flash floods. This is due to the fact that elevated flows can mobilize more debris upstream. Ice-related blockages are the most important type of blockages that could be considered for Northern Communities.

- **Overland Inundation:** Poor drainage and the presence of topographic depressions can create the conditions for surface water to pond, creating an in-land flooding hazard. Ponding is most common in low-lying areas and topographic depressions, and can be particularly relevant in urban areas, where impermeable surfaces cause more rainfall to flow as overland runoff (OPW of Ireland 2009; Kaźmierczak and Cavan 2011). Ponding is typically more of an issue when watershed conditions are saturated, which may result from large amounts of soil moisture due to preceding precipitation, snowmelt, and under conditions where storm intensities are greater than the drainage capacity of soils (Paniconi and Putti 2015).
- **Coastal Inundation:** Coastal areas in Northern Canada, primarily Arctic Coastal communities, are vulnerable to inundation by storm surges, tidal effects and sea-level rise during the open-water season (Marsh and Hey 1989; Hatcher and Forbes 2015). Many of the factors that influence overland flooding risks are important, particularly the topography and elevation of coastal areas relative to sea level.
- **Groundwater Flooding:** In areas where the water table is close to the ground surface, flooding can be a constant hazard. Groundwater flooding is a result of the hydrologic and hydrogeologic conditions of a watershed and can act to elevate streamflows and contribute to ponding (OPW of Ireland 2009; Whitfield 2012; de Moel et al. 2015; Patrick et al. 2015; Wade et al. 2015).
- **Water Infrastructure Failures:** Many forms of infrastructure are used in water management to help mitigate flood hazards, including dams and reservoirs, urban stormwater storage and conveyance systems, river spillways, and diversion channels (State of Queensland 2011). Although this infrastructure can be quite effective in protecting communities from flood hazards, they are designed to a specified threshold and can be overwhelmed or fail under extreme conditions. Releases of water from these systems can pose serious flood hazards in the case of dam breaks, or more constant threats in the case of ageing and failing urban stormwater management infrastructure (Shrubsole et al. 2003).

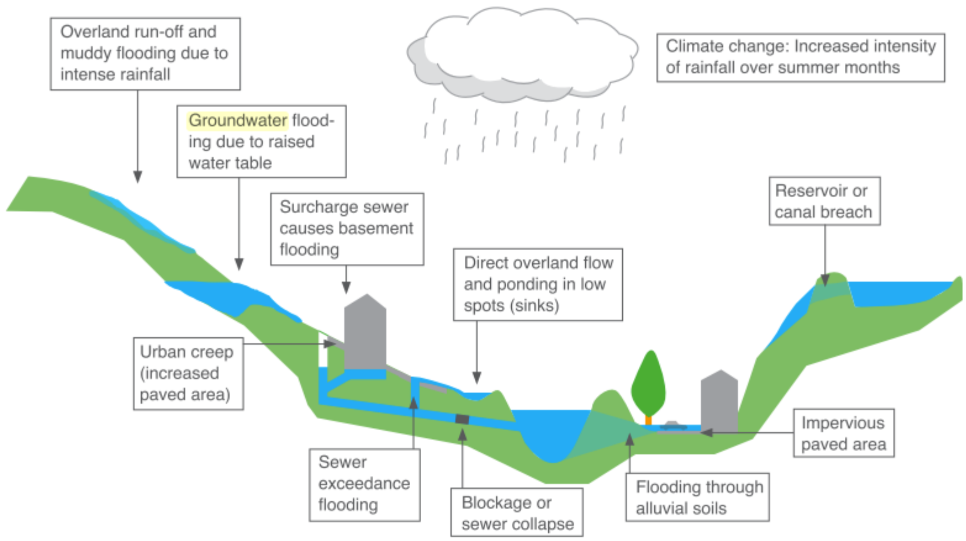


Figure 17. Cross-sectional diagram of a watershed highlighting numerous possible causes of flooding (from OPW of Ireland 2009)

From a damage perspective, the hazard severity is associated with the depth and velocity of flood waters and the duration they persist (Branch and Insurance 2001; Schneider and Schauer 2006; Spekkers et al. 2014). As such, flood hazards are typically characterized relative to these factors. Surface water flood hazards (i.e., all excluding groundwater flooding) events are typically expressed cartographically as the spatial extent of a flood of a specified scenario. In the case of flash and overland flooding this is typically the likelihood of occurrence of, or a historical flood event that represents, the flows or precipitation that are deemed to be hazardous (e.g., a 1% probability flood event; Hurricane Hazel), and which are tied to the event's intensity and duration (Burrell et al. 2015). For ice jams, which are an important risk for Northern Communities to consider, determining relationships between river stage and ice blockage from historical events is the recommended method for understanding potential effects, however some physically-based modeling may be necessary to characterize this flood hazard type in more detail (FEMA 2003; Burrell et al. 2015). Groundwater flooding is typically characterized using a GIS-based analysis incorporating layers of surficial geology and hydrologeogic characteristics (hydraulic conductivity, porosity, thickness), water table depth, surface topography and interactions/connectivity to surface water bodies (Buss; Hughes et al. 2011). Like surface water flooding, these are characterized using historical time series.

4.4.2 Climate Drivers of Flooding

The hydrologic regime, and thereby flooding patterns, within a watershed are highly related to its climatology. The influence of climate on hydrology is highly complex with many feedbacks, but some of the major effects are described as follows:

- Temperature affects the timing and extent of snowpack development and melt, evapotranspiration and the overall water balance and moisture conditions, which drive streamflow in northern watersheds;
- The timing, intensity and duration of precipitation events will affect streamflow, flood risk and almost all hydrologic processes in a watershed, including groundwater levels;
- Freeze-thaw cycles in Northern watersheds influence the likelihood of ice-jams in rivers, as well as permafrost conditions that affect soil infiltration and subsurface flow; and
- Landscape level effects of on average warmer air temperatures are changing permafrost conditions at such a rate and a such broad spatial scales that basin and/or sub-basin wide changes in hydrology are occurring, resulting in, e.g., changed base flows, etc.

From a flood hazard standpoint, alterations to the hydroclimatologic regime of watersheds result in changes to the extent, frequency, magnitude, duration, and timing of various kinds of flooding (Whitfield 2012). Studies pertaining specifically to northern Canada have suggested that the net result of climate change is a greater likelihood of more frequent flooding (GNWT & GOC 2010; Government of Yukon 2011; Adamowski et al. 2013; Government of Yukon 2013). This is due in large-part to projected increases in heavy rainfall for northern latitudes (Scoccimarro et al. 2013; Westra et al. 2014), less stable snowpack and overall wetter watershed conditions that promote flooding and more frequent (Pike et al. 2010a; Kundzewicz et al. 2014).

4.4.3 Datasets and Data Acquisition

Having a solid understanding of previous hydrologic or flood characterizations in a study area is a critical starting point for any flood hazard mapping study (Church et al. 2012).

Table 6 provides a summary of the key types of background information recommended by APEGBC for flood hazard assessments. Figure 18 provides a summary of the various variables and datasets for flood hazard mapping and some methodologies commonly used to obtain these.

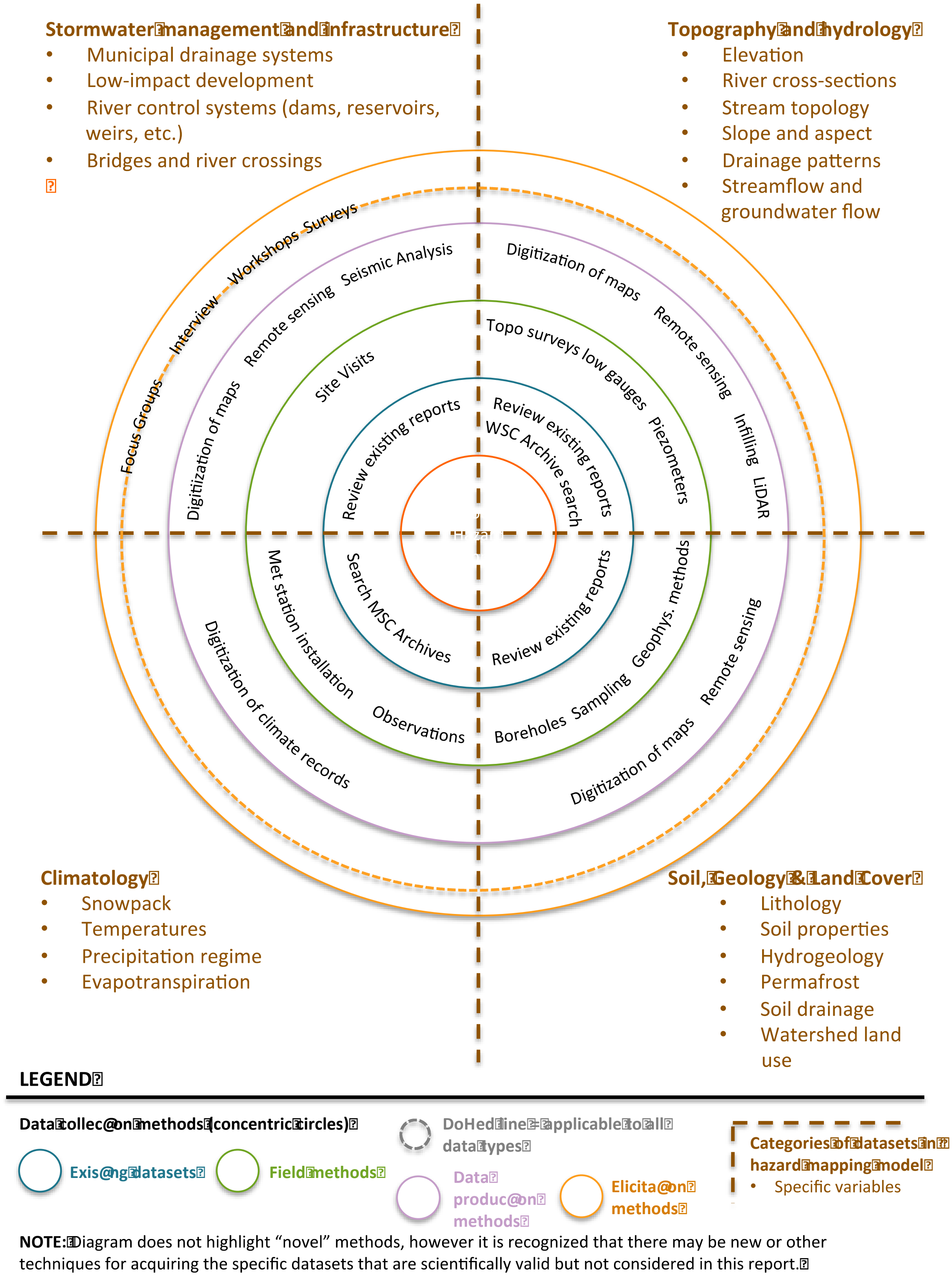


Figure 18. Summary of flood hazard mapping variables and common approaches for data collection

Among the most critical datasets that should be assessed during the gap analysis for all types of flood hazard mapping is good quality and high-resolution topographic information. It is also important to have a good quality dataset (usually a time series or “design event”) of the hydroclimatic conditions that lead to flooding. Fortunately, there are many publically available datasets that can be accessed for hydrologic analysis from the Water Survey of Canada, the Meteorological Service of Canada, NOAA, the Geological Survey of Canada, and the United States Geological Survey and many territorial government agencies. A selection of these publically accessible datasets is provided in

Table 6.

The specific datasets required as inputs for hydrologic and hydraulic analysis used within flood hazard mapping depend on the analysis techniques and tools to be used, however,

Table 7 summarizes the datasets that are generally required. As mentioned, many of these are available from public sources or through request to appropriate government agencies, however some fieldwork may be needed to infill data. During the gap analysis, it is recommended that the inputs needed in the analytical tools selected for flood hazard mapping be used as criteria for determining if additional field work is required or alternative analysis techniques need to be used to fill data gaps.

A lack of hydroclimatic datasets for a study area will be a significant restriction on the ability to map flood hazards and may require development of a longer-term field monitoring program. Fieldwork may also be required to support the biophysical approach to flood hazard delineation (Burrell et al. 2015) and to collect high-resolution topographic information using common surveying methods or airborne techniques. Fieldwork may also be required to collect highly localized data inputs for models, such as watercourse bathymetry and high-resolution topography needed in hydraulic analysis.

There is a long history of flood hazard mapping taking place under regulatory processes. This has often required the establishment of expert committees to guide the process of flood hazard mapping. These groups often provide input related to the flood events and hazard levels of interest, applicability of different modeling tools and datasets and areas of greatest uncertainty. Determining these parameters are critical components of the hydrotechnical process for flood hazard mapping and often elicitation of experts and local stakeholders is used.

Table 6. Types of data and information relevant to flood hazard mapping and valuable as background data (Adapted from Church et al., 2012)

Category	Specific Datasets
Previous Assessments	• flood hazard maps, terrain maps and climatological assessments • floodplain mapping and alluvial fan mapping • other resource inventory maps and reports previous flood assessment, geological, and geotechnical reports that address the study area • sedimentation records and reports • hydrogeology reports Basemap
Basemap Data	• large and small scale topographic and cadastral maps, LiDAR • channel, lake/ocean bathymetry • maps that show existing and proposed land use, infrastructure such as transportation routes, utilities, surface drainage, in-ground disposal of stormwater, and in-ground disposal of waste water and/or sewage • air photos of different years (historical to present) and scales • bedrock and surficial geology • in areas of logging: forest cover maps, forest development/stewardship plans, watershed assessments, past and proposed forest road construction and logging, and other relevant logging-related information.
Exposed Elements	• locations and characteristics of existing development, including residential and non-residential, and associated infrastructure locations and characteristics of proposed development (if relevant).
Historical Datasets	• evidence and history of flooding in the area (e.g. newspaper articles, oral histories, etc.) • locations and number of Water Survey of Canada gauges and Meteorological Service of Canada climate stations • streamflow and precipitation data gathered by municipalities, hydro utilities, government ministries, mining companies and others • evidence and history of wildfires and insect infestations in the area

Table 7. Summary of typical datasets required for flood hazard mapping using different tools

Analysis Process:	Hydrologic Anlaysis	Hydraulic Analysis
Coastal Flooding Inputs	• Offshore water levels • Windspeeds	• Geology • Topography • Offshore bathymetry • Shoreline protection structures
Riverine Flooding Inputs	• Historical streamflows (for probabilistic analysis and model validation) • Watershed conditions (soils and geologic parameters, land cover parameters, topography, hourly or daily climate) for streamflow generation modeling	• River and floodplain topographic cross-sections (high resolution, e.g., 1-m, preferable) • River crossings and structure information • Floodplain soil and land cover for roughness coefficient calcs.
Overland Flooding Inputs		• Detailed topography • Locations and design of structures • Drainage infrastructure network
Infrastructure Flooding Inputs	• See type of flooding infrastructure is designed for.	• Structure design thresholds • Estimates of structure inflows and outflows, based on relevant hydroclimatic variables (streamflows, precipitation, wave heights)
Groundwater Flooding Inputs	• Surface recharge • Geology and soils and their flow parameters • Subsurface layer elevations and surface topography	• N/A

4.4.4 Data Standardization and Organization

Flood hazard mapping information, both inputs and outputs, are typically organized in a transparent and readily accessible repository, as this information is often part of provincial/territorial and/or municipal regulatory requirements. Ideally, all input and output datasets should be stored in a database for easy access and updating. The Australian National Flood Information Program, which is a public-facing portal of flood information for site-specific areas, provides one such example. This, like many other examples, standardizes the data formats and types of information that consultants and government agencies produce. Broader water information management tools, such as ArcHydro, provide useful frameworks for the organization of flood hazard mapping input and output datasets.

4.4.5 **Flood Hazard Mapping Models**

As previously described, the approaches, including models and datasets used for mapping flood hazards are highly dependent on the type of hazard to be mapped. Different tools are needed to capture the physical processes associated with each flood hazard type. Burrell et al. (2015) reviewed approaches for ice-driven flood assessment and as part of this work identified four broadly applicable approaches to all flood hazard mapping, as follows:

- **The biophysical approach:** This approach is best suited to preliminary investigations and involves identifying low-lying areas susceptible to poor drainage or adjacent to rivers using topographic, geologic and ecological information.
- **Past flood extent:** High-water marks of historical events provide a very useful indication of the extent of flooding in a given watershed and can be used as an indication of the overall flood hazard in an area.
- **Flood Envelope Approach:** This is similar to the “past flood extent” approach, however it applies a statistical approach to relating historical observations of streamflow and environmental variables to topography and flood extents.
- **Hydrotechnical Approach:** Testing of different watershed and hydrologic conditions using modeling tools to delineate the extent of various flood scenarios (i.e., design flood or storm).

Within each of these approaches, there are a number of more specific techniques and tools that can be used, however it is beyond the scope of this report to review all possible ones. As such, this section will highlight key approaches that emphasize understanding climate change effects on flooding that are applicable to Northern Communities.

4.4.5.1 Regulatory Mapping Approaches

Historically in Canada, a significant amount of flood hazard mapping was completed through the Federal Disaster Reduction Program (FDRP), which saw different jurisdictions adopt slightly different criteria, but similar overall approaches for mapping the extent of floods (Shrubsole et al. 2003; Burrell et al. 2015). Most of the flood hazard mapping in Canada has followed the hydrotechnical approach, with responsible agencies adding additional freeboard distances. In some cases where limited data or resources have prevented a detailed hydrotechnical approach from being implemented, flood hazards are specified as an specified distance from a water body (MMM Group 2014). Standardized flood mapping programs also exist nationally around the world, with key guidance relevant to Northern Communities being the U.S. (FEMA 2009), the UK (Wicks and Lovell 2011; Environment Agency 2013), and Sweden (SAWA 2010; Naslund-Landenmark 2015), and Finland (Silander et al. 2012) which follow the EU's directive on flood risk management.

Within the jurisdictions described above (including Canada), hydrotechnical methods that involve hydrologic and hydraulic analysis are the dominant method of mapping for most types of flooding, with the exception being groundwater flooding which uses a GIS-based model to identify overlapping areas of vulnerability to high water tables. This approach for groundwater flooding aligns closely with "biophysical" method described in Burrell et al. (2015).

4.4.5.2 The Hydrotechnical Approach

Hydrotechnical approaches are also used for modeling the effects of ice-jams and infrastructure failure (e.g., dam breaks). Collection and analysis of historical flood information is however a crucial starting-point for all the analysis in flood hazard mapping. This information will be used to determine the types of flood hazards relevant to a study area, establish probabilities and hydrologic parameters for defining floods, and validate hydrologic and hydraulic analysis/models (see Section 4.4.3 for more information on datasets).

Figure 19 provides a conceptual model of a typical approach to flood hazard mapping. The first step is to identify and characterize the flood hazards relevant to a study area, including an inventory of historical events, associated impacts, and trends in the frequency and intensity/magnitude of flood events. Increasingly, this analysis includes an assessment of potential changes in the climatological drivers of flood associated with climate change (e.g., changes in extreme precipitation, spring freshet, etc). Land use change can also be included. At this stage, the datasets needed for subsequent analyses are typically collected and base-maps are prepared (e.g., topography, soils, land-cover, surface-water network, etc.). The next step is to develop and apply the applicable hydrologic models or analyses to determine the flows (riverine and infrastructure flooding), water levels and wind conditions (coastal and infrastructure flooding), watershed runoff and ponding (overland and infrastructure flooding), and groundwater levels (groundwater flooding) associated with flooding. This analysis involves understanding the local frequency, commonly referred to as "return-period", of different hydroclimatic conditions that cause flooding. It is also during this stage that specific events, or flood scenarios, of interest are modeled (e.g., the effect of climate change on flooding). Hydrologic modeling is also needed to translate climate drivers of flooding into the appropriate hydrologic variables. Key uses of hydrologic modeling include the following:

- The combined effect of winds and water levels to produce shore-bound wave heights;
- Precipitation events need to be translated to runoff and streamflow for riverine and overland flooding; and
- Various hydroloclimatic conditions can be fed into groundwater models to determine water table elevations under those various scenarios action and coastal flooding.

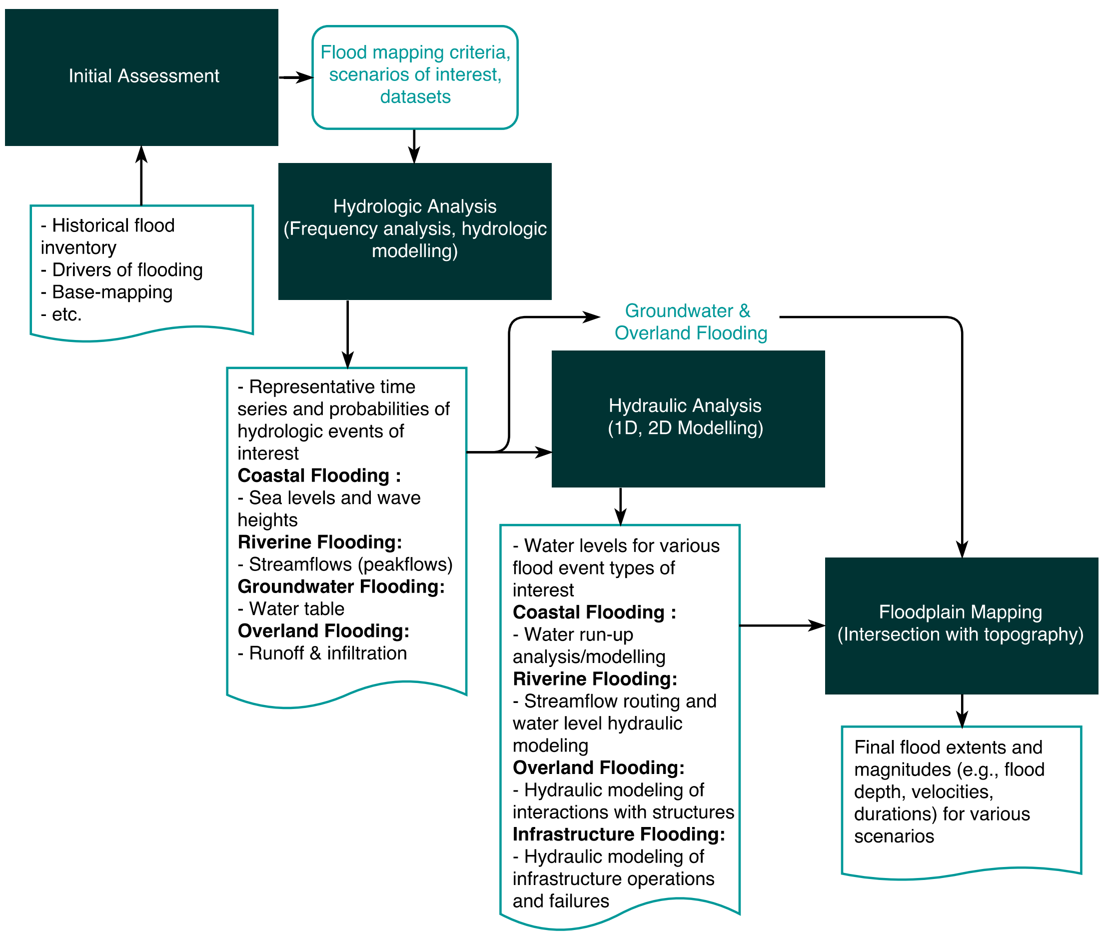


Figure 19. Summary of a typical hydrotechnical approach to flood hazard mapping (Adapted from: FEMA 2009; Wicks and Lovell 2011; Silander et al. 2012; Bowering et al. 2013; MMM Group 2014; Burrell et al. 2015; Naslund-Landenmark 2015; Patrick et al. 2015)

For riverine and infrastructure-based flooding, and in some cases overland and coastal flooding, specified hydrologic scenarios (e.g., wave heights, streamflows, runoff) are used in hydraulic analysis to determine actual water levels resulting from hydroloclimatological drivers. Hydraulic analysis can be one or two dimensional in nature, and usually involves a pre-created modeling package[2]. Hydraulic models are also used to test the effects of infrastructure failures, as water management assets are represented in hydraulic models. Hydraulic modeling is used in overland flooding primarily in urban areas to understand interactions between buildings and how runoff, however in many cases, hydrologic model results can directly identify areas where water ponds. For coastal flooding, hydraulic analysis is used to translate wave heights into onshore inundation estimates, called wave run-up analysis. Coastal protection infrastructure is also modeled using hydraulic analysis.

The final step in flood hazard analysis is to intersect those flood elevations with base-map data to determine the extent of flooding and identify exposed assets and populations.

It should be noted that the potential applicability of a robust hydrotechnical approach is limited by data availability and the resources needed to develop, test and run simulations with modeling tools. The hydrotechnical method is best suited to riverine and coastal flooding, while inland flooding (i.e., ponding) usually does not require hydraulic modeling to identify areas susceptible to flooding on a landscape (Wicks and Lovell 2011). All infrastructure-related flooding, including dam-breaks, overwhelmed urban stormwater management systems and rural drainage networks require hydraulic analysis (Dressler 1954; US Army Corps of Engineers 1995; Schmitt et al. 2004; Gironás et al. 2010).

The selection of specific tool(s) for flood hazard mapping will generally depend on the availability of data and project resources, primarily when there is an interest in considering climate change effects. This is primarily because models are required to translate future climate conditions into the relevant hydrologic variable at the local-scale, and development of such modelling tools can be costly, time-consuming and data-intensive. Data requirements are discussed in detail in Section 4.4.3.

[2] A list of hydraulic models approved for use by the U.S Federal Emergency Management Agency (FEMA) can be found at the following URL" http://www.fema.gov/hydraulic-numerical-models-meeting-minimum-requirement-national-flood-insurance-program

4.4.6 Summary of Considerations in Flood Hazard Mapping

- Prior to mapping, ensure a good understanding of historical and potential future flood regimes, including the types of flooding, seasonality, magnitude of different events, and key locations of interest where assets and populations are or may be situated. Biophysical assessments may be useful at this point.
- The hydrotechnical approach is the dominant form of flood hazard mapping and requires specifying certain events that are deemed important to map. This is done using historical events and frequency/trend analysis.
- Select analytical tools and methods that align with the scale, flood types and available data.
- Hydrologic modeling will be necessary if interested in mapping future flood hazards influenced by climate change.
- Key climate change-related factors which may affect flood dynamics in the North and will need to be considered in flood hazard mapping include:
    - Permafrost thaw;
    - Snowpack conditions;
    - River ice conditions;
    - Evapotranspiration and soil moisture; and
    - Rainfall regimes

Reviewer Checks:

Has the project proponent clearly described their planned methods for collecting data?

Is there a clearly explained link between the data collection and hazard modelling?

Is it clear how objectives will be met using the proposed combination of data and hazard modelling?

5 STEP 4: FINAL PRODUCTION AND PUBLICATION

Unlike typical academic pursuits, or professional documents provided to experts such as engineers or geologists, hazard maps typically target a more general audience. The academic rigor of maps can be retained, but details such as the scale, specific types of hazards considered, visualization and communication of the information, and level of detail required can all be changed to suit a particular end use. For example, if a mapping initiative was focused on flood hazards within a city because the end user was a municipality, then high-resolution information (5-10 m cross sections) would be useful. However, if the end user is interested in knowing which cities along a river are at greater risk of flood, a much coarser flood hazard mapping model would be more appropriate.

As well, the completed hazard maps should be provided in formats that are compatible and suit the end-user (Sheppard et al. 2011). There are many ways to produce compatible hazard maps to suit the end-users' needs. One example to ensure effective use of the maps would be for the mapping practitioners and the end-users to establish a working relationship. This will help instill confidence in the maps and clarify how they can be interpreted and used by the end-user (Champalle et al. 2013), as credibility and relevance of information are important criteria for many end-users (Cash et al. 2002; Eriksen and Kelly 2007).

Other pragmatic considerations revolve more around suitable mediums for delivering the maps. The project team should determine whether the end user has the software required to open digital copies of the map, as well as the knowledge to use that software. If not, then the format of the map should be varied (e.g., providing multiple layers of a map in individual .pdfs rather than a single geodatabase file). Similarly, if paper copies of the map are being produced, consideration should be given to the size of the map and general production quality (including quality of paper, legibility of fonts, and resolution of printing). These small details are extremely important in determining whether a hazard map, regardless of its technical robustness, will be used and adopted as a tool by the intended audience, or disregarded.

5.1 SINGLE VERSUS COMPOSITE HAZARD RANKING

As described in earlier sections, there are many models available to estimate the hazard posed by individual processes including floods, landslides, coastal erosion, and permafrost thaw. The resulting hazard map may consider multiple hazard-inducing *factors* for a single hazard type, or they may "composite" hazard, representing the combined potential for negative consequences as the result of either multiple hazard *types* (Champalle et al 2012). Examples of northern, multi-hazard risk ranking include maps developed for seven different Yukon communities, Pelly Crossing among them (Figure 20).

Figure 20 Composite hazard risk map for Pelly Crossing, Yukon, reflecting degrees of hazard from floods, permafrost degradation, and landslides.

An example of a single hazard, multi-*factor* map, and supporting information, focused on the community of Salluit, Northern Quebec is shown in Figure 21. The risk rankings presented on this map are based specifically on the potential for building foundation failure as the result of land movement related to permafrost thaw across the community.

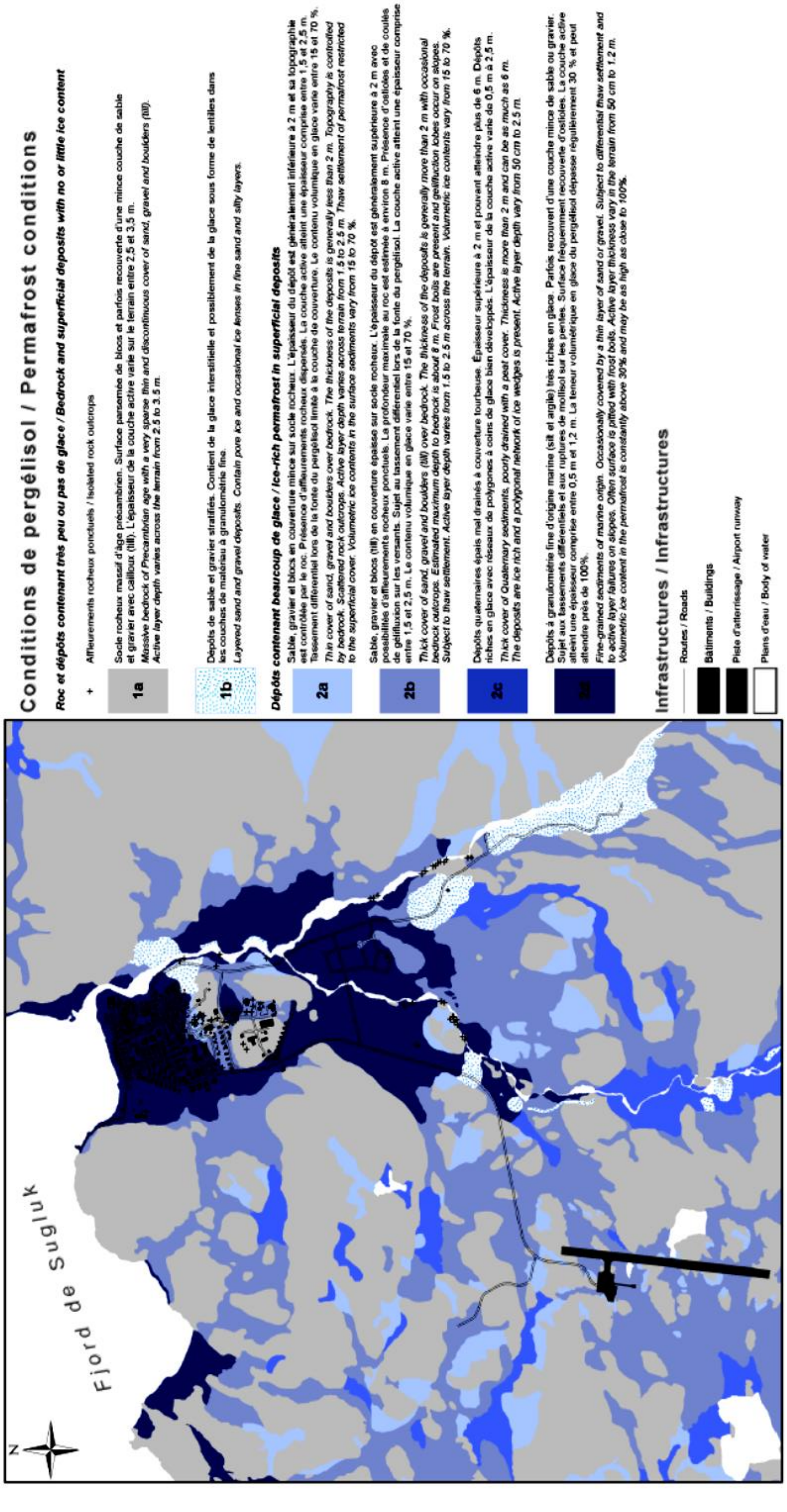


Figure 21. Six categories of permafrost terrain relative to land movement hazard risk in Salluit (from Allard et al., 2010).

Based on principles and steps described in Cova (1999), CSA (2011), ICLEI (2010), Kappes et al. (2012) and Public Safety Canada (2012), there are four overarching steps to complete a composite hazard ranking: determination of spatial scales and types of hazards, development of likelihood scoring framework, mapping of individual hazard, and aggregation of individual hazard scores.

In order for multiple hazards to be expressed consistently a common scale of analysis that applies to all the hazards in question needs to be established. This may be a uniform grid or mask of polygons to allow for this comparison and aggregation of different hazards for a given location. Each hazard will be analyzed and aggregated or disaggregated to this scale and it is important to consider the effect of this processing on the accuracy. Alternatively, there may be a common "basic unit" that links hazard types such as surficial geology polygons. This could be a shared base unit for permafrost, coastal erosion, and landslide hazards. Another point to consider is that it may be difficult to compare event-based hazards (e.g., floods), with longer-term changes (permafrost degradation), as the likelihoods are determined very differently.

It is necessary to have a consistent way of reporting likelihoods across different hazard types. This will generally involve normalizing different probability scales for various hazards to a uniform scale. In the process of normalizing probability scores from different hazards to the same scale, it is possible that some likelihoods may be become disproportioned. For example, landslides may range from 1:100 to 1:2000-year return period event, where floods may range from 1:10-1:100. In this example the flood events may appear insignificant compared to landslides.

Once a uniform spatial unit and the frameworks for scoring likelihood have been identified, each hazard can be ranked using the hazard models described in earlier sections. Different methods will be required for each hazard, and each method will have a different amount of confidence associated with it. As such, it is important to note from the levels of confidence associated with each hazard map.

Numerous individual hazard scores can be aggregated for a given spatial unit as long as the scores are comparable. When this is done, typically in a GIS platform, it may be necessary to factor the information confidence into the scoring, by weighing each hazard's score differently.

5.2 CONVEYING THE DESIRED MESSAGE

Several matters are important when producing hazard maps. The way hazards are being perceived by the public in a region must be acknowledged, the target audience should be identified, and accurate cartography and visualization techniques must be used (Lahr and Kooistra, 2009). The map practitioner is responsible for conveying the message in the most effective way. To do this, it is important to consider the target audience and to tailor use of symbols and mapping conventions to suit the interests and technical knowledge of that audience. For example, when the polygon or units composing the hazard zones are large and data is averaged, whole regions may seem affected by a hazard whereas a high risk may only occur at one or two localities when displayed on a finer grid (Lahr and Kooistra, 2009). Similarly, while it may be possible to portray many types of data simultaneously (e.g., geologic units, contours, hazard levels, and key features), it may confuse the end user if they are unaccustomed to this level of detail in a map. Also, it may not be necessary to include some details if the intended user is already highly familiar with the mapped area.

Colours and symbols are also significant as they are used to distinguish between features on a map. Maps made for communication with the public need to meet other requirements than hazard maps intended solely for scientific analysis and explorative purposes. As a result, standard mapping protocols, such as those used for geologic mapping may need to be relaxed, simplified or discarded in communication to the public. These details are often retained in the GIS used to underpin the public maps. When used for communication, further considerations must be taken regarding cartographic techniques as they can easily lead to misinterpretation and provoke unnecessary worry (Lahr and Kooistra, 2009). For example, in many northern communities, a combination of hazards (permafrost, flooding, landslide, etc.) would qualify as unacceptably high for more populous southern locations. However, when there are no alternatives, it is more important to give end users a ranking of relative hazard rather than absolute hazard. In other words, it is unhelpful to rank an entire community as high hazard. Rather, it is more helpful to demonstrate that there are areas that are higher, and other areas that are lower hazard. The meaning of these rankings can be explained in presentations and reports. It is the responsibility of the map practitioners to communicate the project results, including the hazard maps, appropriately in order to avoid misinterpretation.

5.3 GOOD PRACTICES IN COMMUNICATION

While this section comes late in this report, success in communication is greatest when the intended users are engaged early and often in a hazard mapping project. Maintaining respectful and productive relationships with northern communities is vital to the production of useful and relevant hazard maps (Berkes et al. 2007; Engler et al. 2013). This is true regardless of whether the researcher is using elicitation methods as part of the approach to mapping. Visiting researchers are often most successful when they respect the culture of the region and try to integrate northern knowledge, knowing that this will contribute significantly to the outcome of the project (Alexander et al. 2011). This is an aspect that should be considered because increasing emphasis is being placed on northern hazard mapping, as resource development is expanded and northern communities grow.

In order for hazard mapping to be of maximum use for decision-making, the intended users of the map should be determined at the start of the mapping process and its applicability should be understood (Lahr and Kooistra, 2009; Kirchhoff et al. 2013a). Because hazard maps can serve as a basis for spatial planning, local hazard assessment, emergency planning, and technical protection measures, it is often very beneficial to include end users from these areas in order to plan and tailor end products in such a way as to maximize their usability (Hagemeier-Klose and

Wagner, 2009). This can be achieved many ways, but community meetings should be considered at several stages of the project (at least two meetings, one at the beginning and one at the end, for a short term project). Other activities could include focus groups, interviews, mapping workshops, school visits, field training, hiring field assistants, etc.

In practice, descriptions of the applied methods, and the supporting data can be difficult to "simplify" to the point where they can be easily consumed by all end users. However, regardless of the technical detail, all data and descriptions of methods should be made available to interested users.

Broader awareness of the mapping initiative within the community of end-users can influence whether the hazard map is then put to practical use by local planners, administrators, design engineers, or others. Regardless of the map characteristics above and the expertise of the end user, the importance of clearly communicating on the maps any potential limitations to their use (e.g., in planning or design) cannot be understated (Champalle et al. 2013).

Reviewer Check:

Has the proposal you are evaluating accounted for the intended end use of the map?

Has the project team described plans to tailor the map to meet requirements of end users?

Will the project team write a plain language description of the methods?

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