Remote Sensing-Based Indices for Arctic Community Planning

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Abstract

Building in Arctic environments presents unique challenges due to hazards such as permafrost degradation, steep slopes, and hydrological risks. This paper presents an accessible framework for generating informative maps tailored for non-expert users involved in the early stages of Arctic community planning. We introduce three indices: Permafrost Stability, Slope, and wetness—derived from satellite remote sensing and digital elevation data. The Permafrost Stability Index leverages Sentinel-1 SAR data to quantify ground subsidence and identify zones of instability, using a percentile-based aggregation over multi-year records. The Slope Index assesses construction suitability by classifying terrain steepness, while the Wetness Index utilizes topographic wetness to highlight areas prone to water accumulation.

1 Overview

Many environmental factors must be taken into account when choosing building sites in Arctic communities. Geographical indices are useful tools to assist decision making; however, accessibility and availability are major obstacles for end users using this type of data (1). The intent of this project is to provide accessible useful geographical indices to assist non-experts in the initial phases of community planning. These maps are not intended to replace full geotechnical evaluations of potential sites.

We chose 3 different indices to start with: Permafrost Stability, Slope, and Wetness. Permafrost stability is our main focus as it presents a critical environmental challenge with widespread implications for ecosystems, infrastructure stability, and global climate systems. As temperatures rise, permafrost degradation leads to ground destabilization, threatening vital infrastructure such as roads, pipelines, and buildings and releasing greenhouse gases like methane, a potent driver of climate change. Slope is a measure of how much effort will be needed to level the building area. Wetness is a measure of where water is likely to collect based on topology.

2 Index Calculations

2.1 Permafrost Index

The permafrost index is intended to identify sites where the ground is displaced over the year due to the active layer thawing/refreezing. This can have a significant impact on any infrastructure in that area (2). To measure this we use ground subsidence over the summer as a proxy for overall permafrost stability (3). To calculate ground subsidence we use a process outlined in (3) and (4) to convert Sentinel-1 SAR data to ground displacement. The steps we follow to determine displacement over a given summer are as follows:

1. For our target area, use surficial geology data from (5) data and manual inspection of satellite imagery to determine locations of several bedrock outcrops in the region. These can then be used for corrections later as stable reference points.

2. Download Sentinel-1 SLC data for the target area and summer from the Alaska Satellite Facility (6).

3. Use Alaska Satellite Facilities HyP3 cloud platform to process 12 day image pairs into displacements over that period (7). This process includes interferogram creation, phase unwrapping, geocoding, and dropping low coherence values.
4. For each displacement pair, sample it at each previously identified bedrock point and generate a linear spline from the results.
5. Apply a correction to the displacement values by subtracting the generated spline.
6. Sum up the corrected displacement pairs for each 12 day period to get total displacement over the summer.

Once we have data for each year we generate the Permafrost Stability Index as follows:

1. For each year, aggregate it with the previous 2 years by taking the 20th percentile value. Since we are measuring subsidence, the displacement values are negative, meaning that this is actually the 80th percentile in terms of largest displacements.
   - This method was chosen as we want to identify spots even if they only have significant displacement in a single year, but we also want to filter out outliers.
2. Bin each value according to thresholds from (8).
   - Low = less than 1 cm of displacement over the summer.
   - Medium = 1-3 cm of displacement over the summer.
   - High = greater than 3 cm of displacement over the summer.

For preliminary validation we use a method similar to (9) by comparing the calculated displacements to the surficial geology from (5). We take the calculated displacements and calculate an average for each type of surficial geology, then we verify some specific geology types have low displacement and others have high. Low displacements should occur over bedrock and other rocky areas, as well as areas like the alluvial fan at the mouth of the Duval River. High displacements occur in ice rich areas like the Till Blanket. We can't fully validate the index through this method, but it gives us a way to tune our pipeline.

The final index has a resolution of 40x40m.

2.2 Slope Index

The Slope Index is intended to identify areas that are flat enough to build on easily. We use a digital elevation map from (10) and use that to calculate slope for each pixel. The initial DEM map is 1x1m, but we downsample the resulting slope to 10x10m to reduce resource requirements. We then bin the slope values according to thresholds from (11).

- Low = less than 20% slope
- Medium = 20% to 40% slope
- High = greater than 40% slope

The DEM we use to generate slope includes the elevations for the structures in Pangnirtung, this causes some artifacts around existing buildings that can be ignored.

2.3 Wetness Index

The Wetness Index is intended to identify areas where water will likely collect based on topology. We use the same digital elevation map as the slope index (10). We then calculate Topographic Wetness Index (TWI) at 1x1m and then downsample to 10x10m to reduce resource requirements. TWI is designed to find areas that are likely to collect water based on slope and the upstream catchment area (12). It's important to note that TWI is solely based on topography and does not factor in things like rain fall or snow melt. It also does not factor in underground drainage. We then bin the resulting values, the thresholds were chosen based on manual inspection and likely will need to be adjusted for other areas.

- Low = TWI less than 8
- Medium = TWI between 8 and 9.5
- High = TWI greater than 9.5

The DEM we use to generate slope includes the elevations for the structures in Pangnirtung, this causes some artifacts around existing buildings.

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