HAZARD MAPPING FOR INFRASTRUCTURE PLANNING IN THE ARCTIC

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ABSTRACT

The Arctic is undergoing drastic change when viewed through the lens of climate science, economics, and politics. With billions of dollars in infrastructure and active critical missions in the Arctic, the United States (U.S.) Department of Defense (DoD) has substantial interest in the stability of the region. This research subsequently identified and mapped Arctic hazards on a military installation using modern and historical remote sensing data to provide a tool for communicating risk, prioritizing maintenance, and planning future infrastructure projects. The results demonstrate the application of hazard mapping for use in community planning decisions.

INTRODUCTION

The Arctic is a strategic priority for the U.S. DoD, and the dynamic changes of the environment are a threat garnering increased interest from decision-makers. The former Secretary of the Air Force, Barbara Barrett, stated “the Arctic is among the world’s most strategically significant regions – the keystone from which the U.S. Air and Space Forces exercise vigilance” [8]. In the 2020 DoD Arctic Strategy, a focus on infrastructure adaptation and security is highlighted as paramount to maintaining critical operations, but the strategy lacks specific steps to achieve these goals. With a constellation of critical bases across the Arctic and evidence of rapid environmental change, the need for a continual focus on hazard identification is evident. Since infrastructure in the Arctic is vulnerable to a unique environment and to changing climate conditions [6, 11, 18, 19], this research provides an approach decision-makers can use to create planning tools to adapt to the Arctic challenges today and in the future.

BACKGROUND

Regardless of location, the successful design and maintenance of infrastructure relies on an understanding of local hazards. This is especially true for the Arctic, which represents a particularly challenging environment to build and maintain infrastructure. These challenges include seasonal freeze and thaw cycles that lead to frost heaving, difficulty in surveying heterogeneous properties of soil with the addition of ice, possible excess water from impervious shallow ground, ice uplift, and extreme thermal stresses [14]. These challenges are a result of the hazards created by the existence of permafrost. Covering nearly a quarter of the land in the northern hemisphere, permafrost is a common feature of the Arctic landscape [20]. Sometimes called permanently frozen soil, permafrost represents soil that is frozen for more than two consecutive years; it is distinguished from seasonally frozen ground, which is frozen for less than two consecutive years [17]. Permafrost can range from bedrock to surface deposits and can differ substantially in particle size, water content, and ice features. The sensitivity of permafrost to human activities and temperature changes [16] further increases the risk of infrastructure damage.

The major hazards of interest in this study are the thawing of permafrost, frost action from excess surface water, and terrain slope. For the purposes of this research, a hazard refers to a natural process or feature that has the potential to cause physical damage to the environment, infrastructure, or people [1]. While not unique to the Arctic landscape, terrain slope contributes to the hazards experienced in the Arctic through its relationship to cryogenic processes and the downslope movement of material, as well as general slope stability considered in geotechnical and foundation engineering. Slope stability is a complex topic in geotechnical engineering; in general, though, a steeper slope has a greater chance of slope failure [4] and a greater chance of solifluction [7].

Infrastructure challenges plague the Arctic, which indicates that previous planning and design considerations may have been insufficient to cope with the fragile but destructive landscape. In addition, climate change is causing new hazards to occur [10]. While Arctic-wide surveys have identified risk to infrastructure from permafrost [6, 9, 10, 13, 19], the distribution of hazards on a community scale over many areas is generally undocumented. To tackle this problem, remote sensing data, relying heavily on historical aerial photography, and facility condition data were compared to explore the relationship between the spatial distribution of geotechnical hazards and existing facility damage.

Shown in Figure 1, the location of interest for this research is Thule Air Base, which is in Northwest Greenland and is the northernmost DoD installation. It houses critical infrastructure supporting space operations that is impacted by Arctic stability. Constructed on ice-rich permafrost that reaches to depths of 300 meters, the base's infrastructure has sustained widespread damage from cryogenic action over its 70-year history [3]. As new facilities are planned and maintenance of existing facilities is prioritized, assessing risks continues to be key to facility health and long-term mission success. These risk assessments can be improved by using hazard maps to visually represent the natural hazards related to permafrost degradation and facility health. Hazard maps thus integrate environmental observations into a simple decision-making tool used to manage the risks related to natural hazards [2].

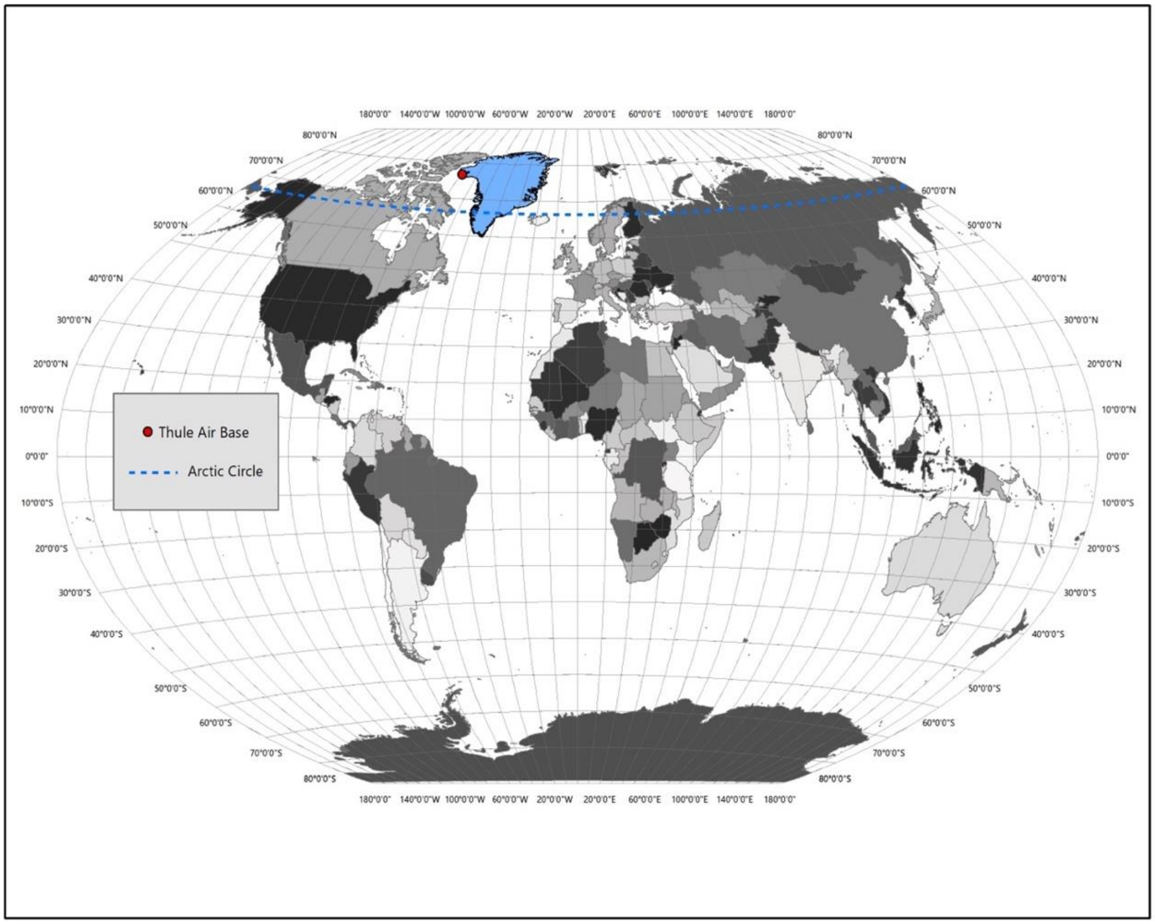

Figure 1. Thule Air Base's Relationship to Arctic Circle

METHODOLOGY

The creation and validation of a hazard map for Thule Air Base focused on three major hazards related to permafrost. Based on data availability and risk to facility health, the selected hazards were visible features that indicate cryogenic processes, surface hydrology and drainage, and surface slope. Visible features were identified as hazards based on the likelihood of thaw, the presence of fine grain soil, and the type of ice features beneath each feature. The next hazard, surface hydrology and specifically drainage accumulation, is impacted by the heat capacity of water (1 calorie per gram per degree centigrade). Liquid surface water can increase the vulnerability of permafrost to thaw by increasing the thermal conductivity of the ground, which causes a greater flow of heat to the permafrost [12, 17]. Another destructive property of water is expansion under freezing conditions. When water freezes, it expands by 9%; however, when saturated soil freezes, it can double in volume [7]. This expansion leads to frost heave, which can produce enough force to lift the foundations of buildings. Finally, slope is identified as a hazard due to its influence on slope stability and the movement of earth on slopes due to cryogenic processes [7].

Permafrost features can be identified through photogrammetry, which is the interpretation of photography for information. Using descriptions from permafrost experts and texts [5, 7], we scanned modern high-resolution images and historical reconnaissance photographs for features matching the descriptions of common visible landscape features of permafrost terrain. Hydrologic hazards and ground slope were identified using tools available in ESRI's ArcMap software. Permafrost features, ground slope, and hydrology hazards were represented separately in ArcMap and then combined to create a cumulative hazard map. The foundation conditions of facilities across the base were then determined using existing investigation reports, inspections, and facility maintenance data. Finally, the cumulative hazard map was compared to the calculated foundation health to explore the relationship between permafrost related hazards and infrastructure deterioration. This overall approach is shown in Figure 2. The hazard of each identified feature was evaluated using the scoring matrix shown in Table 1. Additionally, to validate the underlying assumption that Thule Air Base is experiencing warming temperatures and increased rainfall, simple linear regression of historical weather data was compared to regional climate projections based on a methodology from Lai and Dzombak [14].

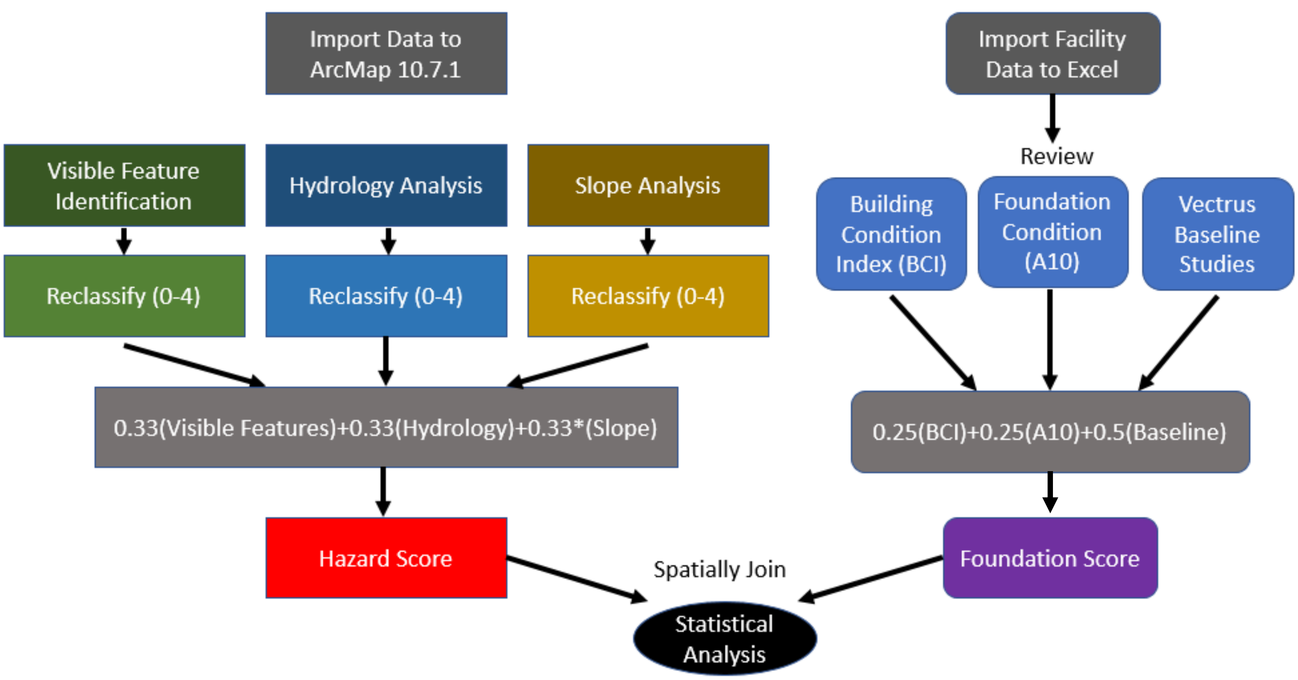

Figure 2. Methodology for Hazard Map Creation and Foundation Health Scoring

Table 1. Hazard Scoring

Feature	Raw ESRI Classification	Hazard Score
Very Low Drainage Accumulation	0-1000 cell accumulation	1
Low Drainage Accumulation	1000-5000 cell accumulation	2
Medium Drainage Accumulation	5000-10000 cell accumulation	3
High Drainage Accumulation	10000+ cell accumulation	4
Very Low Slope	0-12 degrees	1
Low Slope	13-25 degrees	2
Medium Slope	25-45 degrees	3
Steep Slope	45+ degrees	4
Solifluction	Visual	1
Ponding	Visual	2
Sorted Circles	Visual	3
Mounds	Visual	3
Ice Wedges	Visual	4

RESULTS

The results of climate trend analysis and hazard mapping for Thule Air Base, Greenland, both indicate current and developing hazards that must be incorporated in maintenance decisions and future community planning efforts. The results indicate increasing mean annual air temperatures and abundant geotechnical hazards related to cryogenic activity. Finally, the statistical analysis of hazard score and foundation health point to a possible relationship between these variables but requires further investigation.

Climate Trends

Shown in Figure 3, an analysis of historical weather data indicates that a statistically significant increase in mean annual air temperature (MAAT) has occurred over the last six decades. This is a further indication of the need to examine the risk associated with increased cryogenic action leading to possible facility damage.

DV	MAAT
IV	Year
Observations	67
R-Squared	0.295
Model	Ordinary Least Squares
Model P-Value	0.00000205
Equation	MAAT = 0.0382*(Year) - 86.6
Coefficient P-Value	0
Intercept P-Value	0

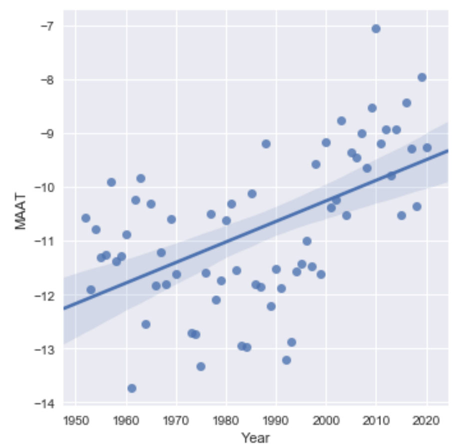

Figure 3. Model Outputs and Line of Best Fit for MAAT

Hazard Mapping

Using ESRI's ArcMap software, we analyzed aerial photographs and Light Detection and Ranging (LiDAR) data to identify hazards across the landscape of Thule Air Base. We used historical and modern aerial photography to identify over 450 visible cryogenic features. Figure 4 shows the five major categories of visible surface features we identified: ponding, solifluction, mounds, polygons, and sorted circles. From the locations and distribution of these features, as shown in Figure 5, we made a number of observations. Solifluction dominates the southern extent of the base, which suggests cryogenic action is causing the slope of South Mountain to move downward (i.e., northward). Mounds, typically created from saturated fine grain soils heaving and creating protrusions, are abundant at the base of North Mountain. Polygons are clustered around the coast in the industrial area of the base, and ponding is visible all across the valley and on the mountain sides, which suggests saturated soils and possible thawing permafrost. The high concentration of hazards on the coast and on the southern extent of the map ultimately indicates a need for serious investments to investigate the geotechnical properties of these areas. As an alternative, the area could be avoided all together if there is a low tolerance for risk or the budget does not allow for extensive earthwork. We also used LiDAR data to identify drainage and slope hazards. Many points of intersection between drainage and facilities are indicated in the analysis of the surface hydrology of the landscape. These intersections increase the risk of damage from water infiltration of the fill and subsequent heave and/or shrinkage. The results of mapping the surface slope, although simple in a standalone format, combine with the other hazards to inform the overall threat. This cumulative hazard is captured in Figure 6.

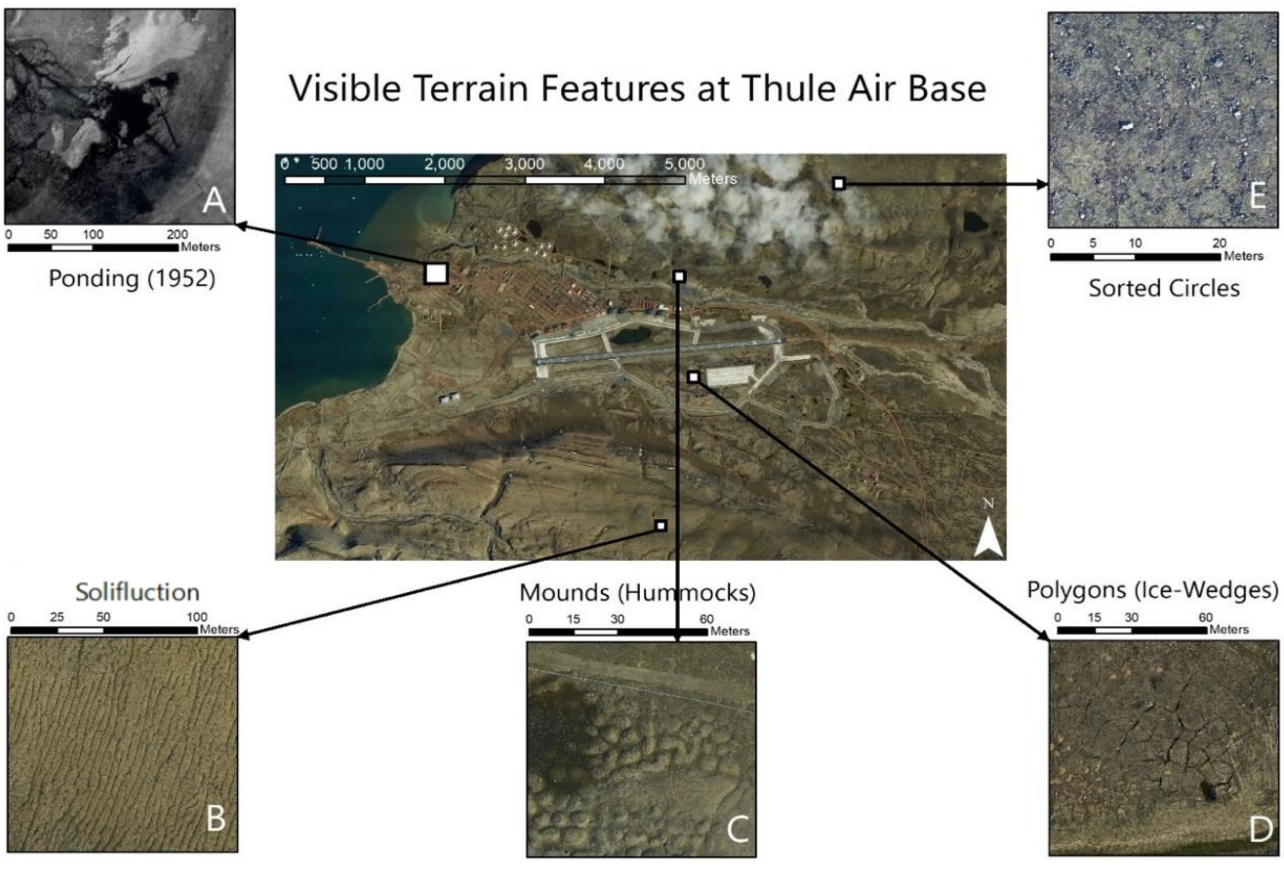

Figure 4. Major Features Identified from Imagery

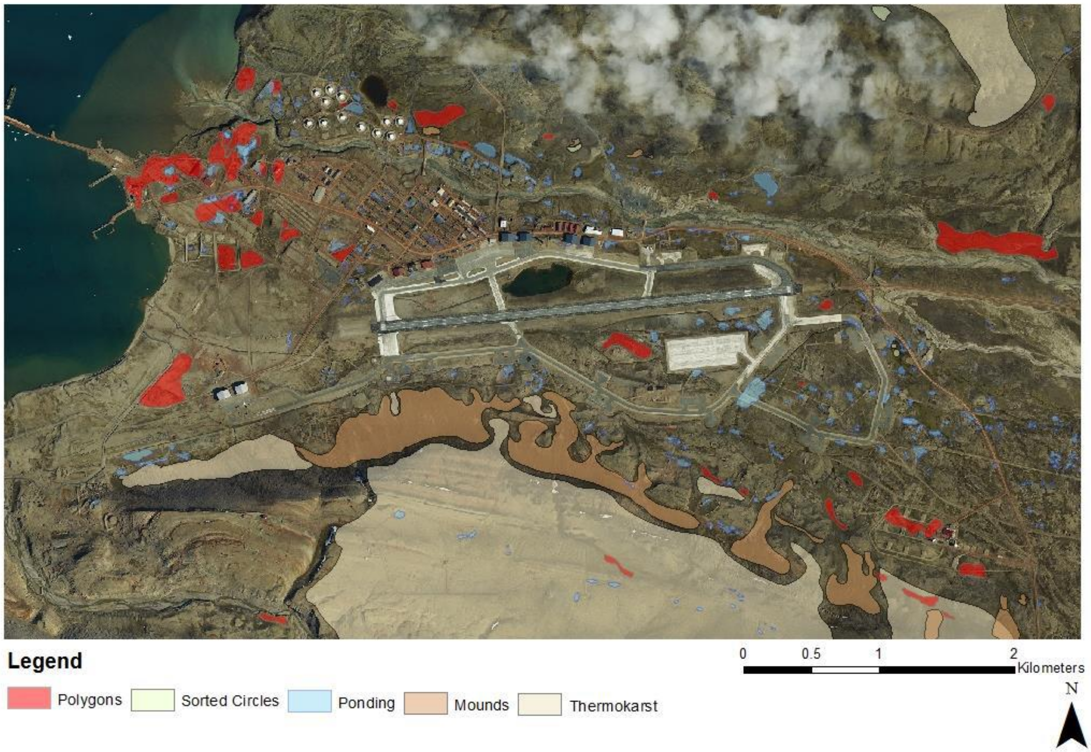

Figure 5. Locations of Visible Surface Features

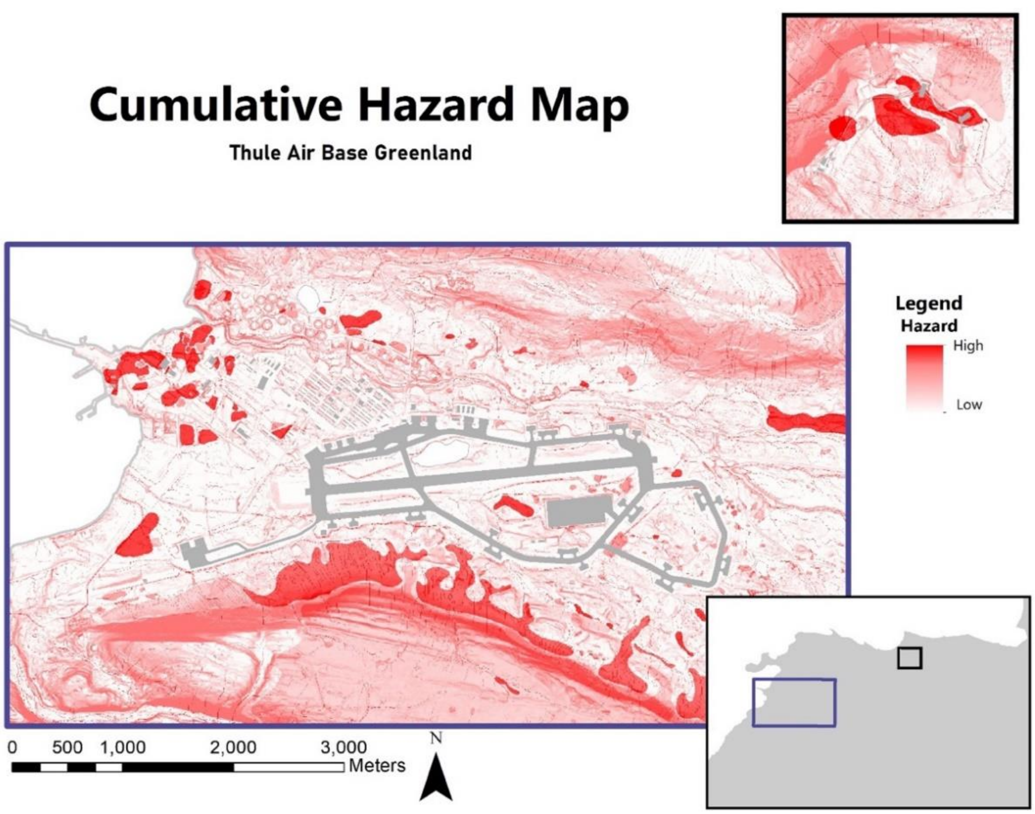

Figure 6. Cumulative Hazard Map Combining Visible Features, Drainage, and Slope

Hazard and Damage Relationship

The ability to predict future facility damage based on current hazards could be an important tool for decision-makers. A visual inspection of Figure 7, which maps cumulative hazard and facility damage, does not initially indicate a strong correlation. In fact, an ordinary least squares model using the cumulative hazard and the square root of the facility damage resulted in weak negative correlation coefficient of 0.048 (p-value of 0.014), suggesting that a higher hazard might be related to lower foundation condition scores. However, the weak nature of this relationship and the existence of autocorrelation warrants further exploration and suggests other variables may be affecting the relationship. Ultimately, the results suggest that geotechnical hazards, including permafrost, pose a threat to infrastructure and that a spatial relationship may exist between facility damage and geotechnical hazards; however, more research is needed to improve the ability to make decisions based on this relationship.

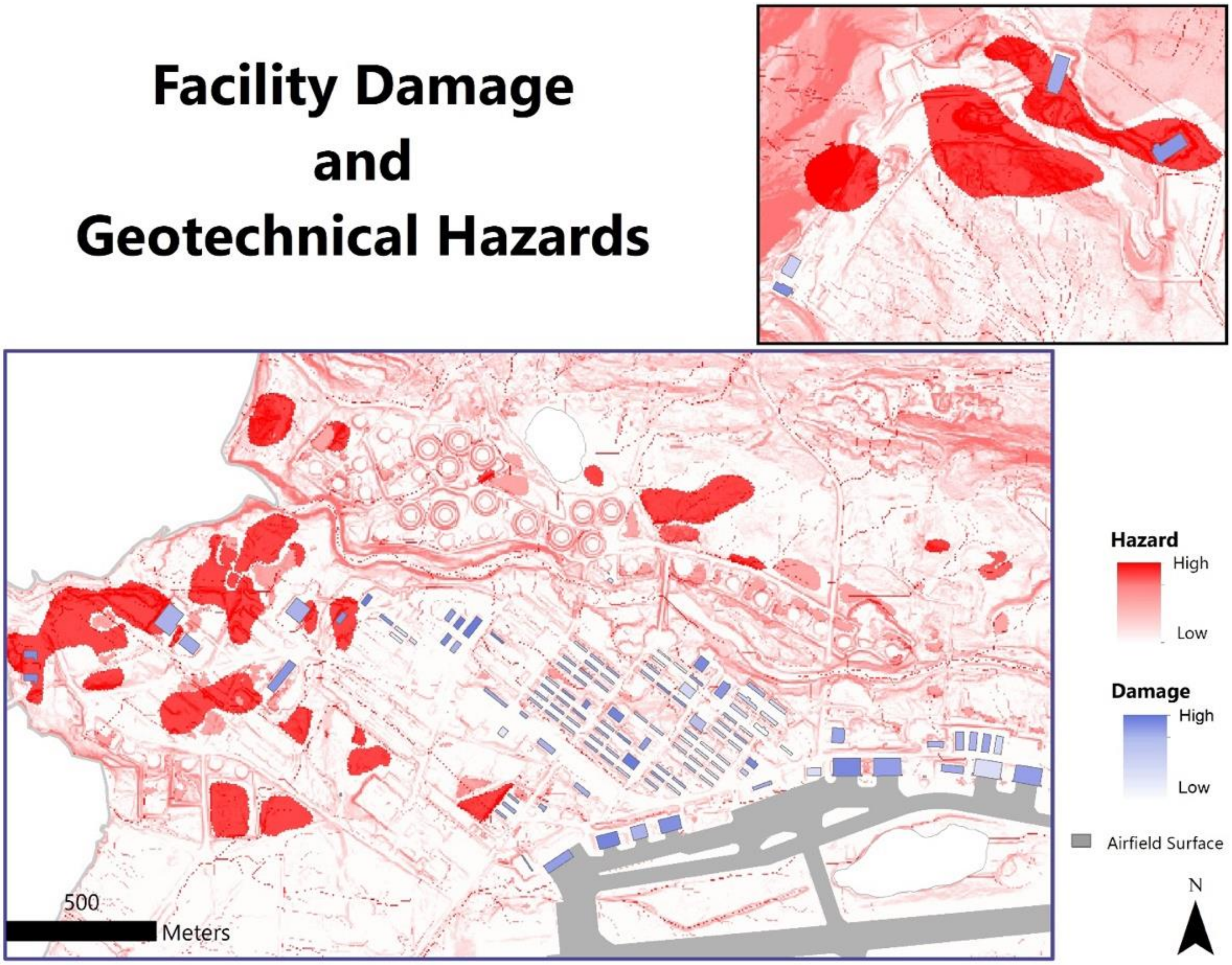

Figure 7. Facility Damage Scores and Cumulative Hazard

Significance of Historical Photography

A major realization from this research is the importance of high resolution aerial photogrpahy. To demonstrate the utility of these photos, an example historical photo is juxtaposed with its modern equivalent in Figure 8. With both modern and historical photos, the undisurbed surface can be studied and hazards can be identified; these hazards can be compared to existing damage of the facility to create a more accurate model. With the extensive earthwork needed to create large settlements such as Air Force bases, many of the visble permafrost features are hidden. Access to historical photopgrahy shows how the landscape has changed, regardless of human disturbances, which helps inform the risk of further changes.

Figure 8. Juxtaposition of Historical and Modern Photographs

CONCLUSION

The investigation of hazard mapping in the Arctic for infrastructure planning indicates a substantial need for an assessment across Arctic communities. There is serious risk to the infrastructure at Thule Air Base, but the use of hazard mapping as a decsion-making tool for community planners and engineers can improve the health of infrastructure systems. Many hazards present a threat to the longevity of infrastucture and the economic feasibility of future development of Arctic communities. The results of hazard mapping in this study demontrate the tools for community planners to communicate risk to decision-makers and inform future areas of study. The weak relationship established between hazards and foundation damage guides the way for future research to expand the data, explore more relationships, and involve experts in the analysis of threats. To be successful in the Arctic, serious attention must be paid to geotechnical investigations and community planning efforts. As the DoD addresses ways to adapt to climate change, it is prudent to invest in the investigations of historical and modern data to inform the spatial awareness of hazards and to continually update and improve decision-making tools.

DISCLAIMER: The views expressed in this article are those of the writers and do not reflect the official policy or position of the U.S. government, Department of Defense, U.S. Air Force, Air Force Institute of Technology, or U.S. Air Force Academy.

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