EXPLORATORY ANALYSIS FOR LOCATION OF AN ALL-SEASON ACCESS CORRIDOR THROUGH NORTHWEST TERRITORIES' SLAVE GEOLOGICAL PROVINCE FOR NATURAL RESOURCE MINING TRANSPORTATION USING LEAST COST ANALYSIS

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Abstract

This paper examines the preliminary development plan for the Slave Geological Province Access Corridor project, and evaluates the identified criteria and constraints referring to economic, environmental and social sustainability. The corridor project was first introduced in the 1970's, and in March 2019 progress was made when the Federal government granted $3.4 million towards preliminary work for the all-season corridor, with an additional $2.7 million contributed from other environmental agencies and developers to assist in the preliminary construction of the all-season corridor (CBC News, 2019). Due to the unpredictability of seasonal roads, especially in a time of global climate change and weather extremes, an all-season road is significantly more reliable and will provide benefits to the economy and mining industry of the Northwest Territories. The land is rich in natural resources and creating an all-season road would greatly increase accessibility to northern Canada, directly improving livelihood and future exploration. This paper proposes potential methods for creating a least cost path suitability using geographical information systems via examination of economic, environmental and social factors at various levels. This methodology produced six pathways using six cost surfaces. More detailed criteria layers produced complex heterogeneous cost surfaces that hold a heavy influence in creating barriers in the cost surface layer. Broad, more course data created cost surfaces will continuous cost cells, where cell costs were not as sporadically mixed. The pathways produced in this report are not intended for actual use; rather the methodology, models and scripts should be used as framework for the proposal of the Slave Geological Corridor.

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Terms

Permafrost: land that has been permanently frozen for at least two years. Permafrost is found in varying degrees; sporadic permafrost, extensive permafrost and continuous permafrost.

Slave Geological Province (SGP): a geologic province surrounding Slave Lake. A geologic province is an area defined by its similarity in geomorphic attributes and features.

Slave Geological Province Transportation Corridor (SGPTC): all-season transportation passageway through the Slave Geological Province.

Multi-Criteria Evaluation (MCE) (MCA Multi-Criteria Analysis): an analysis that involves evaluating multiple criteria in comparison to each other to determine optimality.

Least Cost Pathway (LCP): an analysis uses a raster cost surface to create a linkage of cells that acquire the least cost possible

Seasonal roads: ice roads or winter roads. These are roads that operate for approximately three months of the year. They are constructed on frozen, sturdy features such as permafrost ground, rivers and lakes. They require a constant temperature of sub-zero in order to be properly functional

Introduction

In the northern regions of Canada, there exists an abundance of natural resources including rare earth elements such as diamond, zinc, gold and copper (Hall, 2012). The vast amount of untouched assets has created a large market for resource extraction (Slave Geological Province Transportation Corridor, 1999). However, these northern areas contain a sparse road network in view of the largely dispersed population. This is a major limiting factor to resource extraction because it restricts routing access to resource mines and shipping ports. Without proper transportation networking, work quality, fuel haulage and extraction are impeded. This means larger transport trucks and construction vehicles cannot access the remote area easily. The advantages associated with developed transportation systems such as those in populous cities are not experienced in remote areas because of the low population and low demand. As a result, an all-season roadway has not been a priority until relatively recent realization of climate change effects and future consequences.

The natural climate of northern latitudes plays an integral role in the arctic transportation network (Barrette, 2018). The cool and icy climate restricts construction processes due to the melt and thaw of earth's surficial geology in warmer seasons. Permanent infrastructure can become warped due to the freeze-thaw cycle if not insulated properly (Qingbai et al., 2002). Seasonal roads built on solid frozen features during winter months have constructed as a possible short term solution. Seasonal roads increase accessibility in the cool season but provide limited access in the warmer season. Consequently, an all-season road is favorable in order to gain reliable and sustainable access to resource-rich extraction areas. In consideration of environmental, engineering and social criteria, a proposed all-season corridor can be constructed through a multi-criteria and least cost path way analysis using geographical information system (GIS) technologies. An optimal pathway can be determined by the following criteria: low environmental impact, minimal maintenance and engineering costs, and improvement of social livelihood and future wellbeing.

The purpose of this paper is to examine route alternatives for the development of the Slave Geological Province Access Corridor project. The idea is to explore different options to providing year-round access to Slave Geological Province's three main diamond mines - Snap Lake, Ekati and Diavik - to the capital, Yellowknife, in order to more reliably extract and export natural resources and transport fuel. With thoughtful, considerate planning and development, the road will ideally connect to an all-season road in Nunavut to inevitably link all major natural resource mines and shipping ports.

Background

Expansion of the arctic road network in consideration of natural resource exploration was first proposed in the 1970's by the Department of Indian Affairs and Northern Development (Slave Geological Province Transportation Corridor, 1999). This new corridor was intended to help develop and enhance the mining industry by expanding employment and contributing to economic exports. Potential roadway alternatives were examined, however, the impedance of the underdeveloped transportation system and inadequate alternatives pushed for the consequential need for an all-season road. In the 1990's focus shifted back toward construction plans for new transportation corridors to enhance economic development. This would connect all three territories including the road network from Northern Yukon to Yellowknife, and greatly improve connectivity. In 1998 the Government of the Northwest Territories dedicated sufficient funds and support for four new roads, one being the Slave Geological Province Transportation Corridor. Plans for construction and routing remained conceptual for the next couple decades. Due to drastic change in climate, lack of economic funds and resources, the plans did not develop further into a constructional phase.

In March 2019 the Canadian Government announced that they plan to contribute $3.4 million for preliminary research for an all-season corridor through the Slave Geological Province. Other monetary contributions are gathered from the Canadian Northern Economic Development Agency (CanNor) with an investment of $2.7 million and the territorial government granting $678,000. The overall budget for initial construction cost is estimated at $1 billion (Canadian Broadcasting Corporation, 2019). Similar to the initial proposal in the 1970's, this road hopes to create access to resource and mineral rich area to increase GDP and connectivity in northern Canada. The new all-season, two-lane gravel road is estimated to be a total of 413 km long, constructed in two phases, the first phase spanning from Yellowknife to the Nunavut-Northwest Territories border. The plans for this pathway have been minimally developed since the original proposal. Before new plans can be drafted CanNor, the Government of the Northwest Territories and other industry partners are investing a total of approximately $3 million dollars on mapping and aerial surveying which was not as readily available during the initial phasing in the 1970's and onward. The change in landscape, ecoregions and temperature due to global climate change means that the proposed all-season road may no longer be feasible. An exploratory study of the new concerns with the initial construction phase and the hypothetical draft of the pathway are the premise and foundation for this study.

Purpose and Objectives

The main purpose of this project is to identify a potential least cost corridor to access resources in northern Canada, subsequently contributing to the territories and federal economy. The methodology and basis of this report is drawn from *Multi-criteria evaluation and least cost path analysis for an arctic all-weather road* (Atkinson et al., 2005). This paper examines factors for proposition of an all-season route through Nunavut using suitability and least cost pathway analysis. The framework is adapted and reworked to fit the criteria for a similar study to determine p[potential location for an all-season route through the Slave Geological Province. In order to achieve this goal, several objectives are sought after.

Objective one: Identify influencing factors that impact the construction of the road, analyzed through a social, economic (engineering) and environmental lens.

Objective two: Through literature and past research determine proper weighting influences for cost surfaces to prepare for a cost pathway, several surfaces will be made to analyze different relationships between the three factor categories (social, economy and environment)

Objective three: Least cost pathways are derived from the cost surfaces. Additive costs are assigned based on cell value of the path. The paths are then compared to the current seasonal winter road and the proposed all-season road.

Through these objectives multiple least cost pathways will be created, each created with different weightings. The outputs show the dependency and influence that factors have on the routing outcome. Overall, these objectives will achieve the main purpose of identifying the least cost corridor with suggested methodology and workflow to aid in the construction of the slave geological corridor and examine how different methods result in varying corridor paths.

Literature and Research Review

This section is intended to provide a brief understanding of the concepts and studies used to create the methodology and workflow in this report.

Mining Industry

Canada's monetary capital is based off of a staple economy, meaning that raw natural materials are harvested and extracted from the land and then exported elsewhere for manufacturing (Fitzpatrick, 2007). Historically, Canada has exported furs, lumber, agricultural products, metals, and minerals, which is the fundamental foundation supporting Canada's economic growth (Hall, 2012). With much of southern Canada being developed and highly populated, resource extraction in this region has either met its maximum value of depletion, or the land has been developed for other industries and is not usable. This has resulted in a push for exploration further north to less populated areas untouched by colonization and modern infrastructure (Fitzpatrick, 2007). A discovery of plentiful natural resources in northern Canada has led to a shift in Canada's mining industry, one being the diamond industry.

Canada's first diamond mine, Ekati, opened in 1998 in the Northwest Territories (NWT) located 310 km north-east of Yellowknife (Hall, 2012). A spike in Canada's Gross Domestic Product (GDP) and new employment opportunities in the NWT due to mining operations was a beneficial aspect to Canada's economy. Canada quickly became the third largest producer of diamonds assembling crates worth $2.8 billion dollars contributing to over 20 percent of the Northwest Territories' GDP (Fitzpatrick, 2007). Two other diamond mines, Diavik and Snap lake opened in 2003 and 2008 respectively (Hall, 2012). These three mines created 3000 new jobs for NWT residence (Impact Economics Canada, 2019). However, due to the sparse population and distance between the populous cities and mine locations, transportation can be a limiting factor to expanding employment opportunities. The road network favors the southern portion of the territory centering on the capital city, and does not extend to northern regions where the majority of the mining sites are located. The three mines rely on seasonal roads to transport employees, fuel and resources to and from the extraction site to the city centers and shipping ports. Because the seasonal roads hinge on a consistent sub-zero temperature, in warmer seasons these roads are non-operational and isolate communities (Barrette, 2018). Not only are these roads used for mining transportation, they are used to transport other shipments such as food, building materials, machinery and fuel. By creating access for fuel and construction materials all year round the overall cost of the mine operations will not outweigh the benefits. Especially with an increase in warming global temperature and unpredictable future of the ice road transportation network the cost of construction may soon be too costly to operate.

Arctic Climate and Infrastructure

Local weather in NWT is changing as global climates shift. From 1958 to 2012 the territories average annual temperature has increased by 4 degrees Celsius, with an average yearly temperature of negative 5.7 degrees Celsius in 2012 (Government of the Northwest Territories, 2012). In 2018, the average yearly temperature increased to negative 4.1 degrees Celsius (Statistics Canada, 2019; Time and Date Weather, 2019). The warmer summer months, reaching as warm as 20 degrees Celsius, and the cold winter months, which can plummet to negative 40 degrees Celsius, create a freeze-thaw cycle of permafrost and ice cover.

The thaw and freeze cycle of permafrost creates a sensitive and permeable foundation that is not favorable for construction (Barrette, 2018). A soft surface can cause warping in the infrastructure and future complications and repairs. This can be an issue for permanent construction of transportation networks in arctic climates. Therefore, serious consideration and planning must be viable for all infrastructures that is intended to be accessible all year round.

A solution to improve routing is the construction of seasonal ice roads. These are temporary roads created from ice pavement across frozen grounds using compacted snow and ice (Stephenson et al., 2011). The initial building cost is low, because the material (snow, ice) is abundant and costs approximately $20 million dollars a year to construct and maintain (Impact Economics Canada, 2019). Seasonal roads must be reconstructed annually and are only active for four to six months of the year because the temperature must stay below zero degrees Celsius in order for the ice roads to be of use. Northern latitudes endure restrictive transportation and shipping due to the harsh weather conditions (Stephenson et al., 2011). The impact of weather on travel is becoming more restraining with the rise of extreme weather events, such as rapid freeze-thaw cycles, flash precipitation and heat waves. Geohazards such as thaw subsidence and active layer failure are accompanied by climate change and warming (Fortier et al., 2010). Permafrost degradation and subsidence vulnerability can hold heavy impacts to the framework of buildings and roads. Constructing on subsidence soils increases infrastructure maintenance costs, and poses a safety threat.

Permafrost Construction

As stated previously, active permafrost layers are one of the major challenges when constructing infrastructure in arctic regions. For example the Qinghai-Tibet Highway in China is built on mountainous terrain that encompasses more than 70 km of permafrost (Wang et al., 2009). The permafrost in this region is a consequence of altitude rather than high latitudes, though most characteristics are similar (Li et al., 2000). Just like in the Canadian Arctic, the permafrost has responded quickly to warming climates and raised average temperatures, consequently increasing melt rates. Due to the high rate of permafrost thickness and area change, extensive maintenance and rebuilding has occurred over the past two decades (Wang et al., 2000). To combat this issue, tests were conducted on the road embankment. The research found that areas with insulation layers reduced the maximum season thaw depth; however this could cause a positive feedback loop in the warmer months causing higher rates of melt creating a 'thaw-sandwich', where heat is trapped between the seasonally frozen layer and the permafrost table (Qingbai et al., 2002). Therefore, an insulated base of 15-20 centimeters constructed of gravel is recommended to receive that highest average benefit, without inducing a warming loop in the summer months and has an estimated useful life of 8-12 years (Wang et al., 2009).

Similarly complications occurred in the arctic Inuik-Tuktoyktuk highway in northern Canada (Ormiston & Sheldon, 2019). In 2017 a segment of the arctic highway stretching from Inuvik to Tuktoyaktuk was opened for use. This highway opened the door for many cross arctic transit opportunities, granted that the highway created connections from coast to coast. The operation of the all-season highway has experienced increased maintenance fees due to melt in permafrost and embankment erosion (figure 1). The arctic region is highly influenced by global climate changing, due to rapid permafrost melt (Prowse et al., 2001). Permafrost construction must be thought out delicately and foresee differences in soil characteristics during warm and cool periods (Prowse et al., 2009). One of the major contributors is slope instability due to permafrost thawing. Extensive deformation of infrastructure heaves and embankment cracking are some of the side effects of improper foundations in the arctic highway (Piamsalee, 2019). Leading to extended maintenance costs and rebuilding. Historically, environmental factors such as permafrost were not presented as a concern for construction (Prowse et al., 2009). But with amplified climate changes, melting, instability and unpredictability of permafrost is a major influencer for arctic infrastructure planning.

Figure 1: Landslide and erosion of road embankment along the Dempster Highway (Ormiston & Sheldon, 2019)

Portions of the permafrost table located on slopes with clayey soils result in a poor foundation stability (figure 2) (Qingbai et al., 2002). Clay is sensitive to freeze-thaw cycles and therefore requires higher maintenance either to create road cuts or future maintenance to fix cracking and unstable road. The base and embankment of the road construction in a permafrost prone area is one of the most important factors in order to lower future maintenance costs and risks.

Figure 2: Uneven permafrost melting causing road damage, Tibet (National Snow and Ice Data Centre, 2013)

Consistency of permafrost is one of the most challenging aspects of building permanent infrastructure in northern Canada. Ecosystems and permafrost continuity change and retreat north as climate change continues. Due to the high sensitivity of permafrost to temperature change, it is best that these areas are avoided if at all possible. Even with pre-planning and innovative technologies, such as introducing new insulation like with the Qinghai-Tibet Highway, the rapid change in climate is incalculable. This unpredictability coupled with high frequency of extreme weather events make it difficult to prevent and prepare for these disasters.

Road Construction Criteria

Engineering, environmental and social cost factors need to be analyzed before construction can begin. The three factored categories can be applied as lenses to capture both the benefits and costs imposed on the construction process. Environmental criteria encompass areas that need to be avoided or protected due to their ecological significance or sensitivity (Atkinson et al., 2005). Engineering criteria examines and aims to limit the actual construction cost and future maintenance. Social criteria are aspects that concern themselves with the social welfare of the population, and consideration for future livelihood. Finding balance between these lenses has the potential to create a road that is monetarily efficient, environmentally conscious and beneficial for future populations.

Slope

Straight roads that do not climb steep slopes or curve at sharp angles provide routes with optimal travel (Seppala, 1999). Steep slopes may require road cuts, meaning that mountains and hills are cut through in order to build the road (figure 3). Road cuts create sharp up-right angles which can collect snow drift and disrupt groundwater drainage, and in turn cause icing problems. Cutting through slopes also disrupts animal habitats and vegetation (Goode et al., 2012). Slopes greater than 22 degrees can be dangerous for transport trucks and heavy machinery. Due to their large weight, it requires a vast amount of energy for the truck to propel itself up a slope (Seppala, 1999). The heavy weight can also be difficult for the truck to stop or slow down when travelling down the steeper slope causing safety concerns for the driver. Slopes less than 22 degrees and greater than 5 degrees are reasonable for construction, as road cuts are not always necessary for these slopes, and heavier vehicles are able to ascend and descend without imposing implications. Flatter slopes, less than 5 degrees are optimal, because there is less material going into the construction opposed to construction costs of road cuts or bridges, and reduces the risk of heavy braking when descending downhill.

Figure 3: Road cut along Trans-Canada Highway, Kicking Horse, and British Columbia

Surface Material and Geology

Engineering geology on frozen soils is one of the principal factors that must be considered in arctic regions before construction commences (Qingbai et al., 2002). Transport trucks and cargo are no doubtablely bigger and therefore heavier than normal vehicles, especially when carrying construction materials or mined rocks and minerals. A stable base is essential for successful route construction, which can often be challenging in cooler environments that tend to have a portion of frozen ground cover (Seppala, 1999). The surface material and surface geology determine how permeable and porous the area is, and therefore how reliable and durable the surface is for construction. Surface material consists of sediment and material that had been transported, reworked or deposited from its origin to a new location from glacial melt, river or wind (Natural Resources Canada, 2019). Surficial geology refers to the makeup and origin of the surface including soil composition. Solid bedrock creates a suitable and sound base for road construction due to its sturdy structure (Qingbai et al., 2002). Bedrock is dense and impermeable, meaning that it is difficult for water to seep into and expand in subzero temperatures creating gaps during melt seasons. On the contrary, landforms such as drumlins are deposits of clay and silt from glacial till. This material is frost sensitive and therefore should be avoided because it is so easily influenced by seasonal changes in temperature (Seppala, 1999). Clay and silt are porous covers that easily allow water and moisture to transverse through. Pockets of water in the soil freeze and expand creating an uneven and unpredictable surface through the freeze-thaw cycle.

Permafrost

The thickness and continuity of permafrost plays a role in how sensitive the ground is for development (Wolfe, 2000). Although continuous permafrost is optimal for seasonal roads, all-season roads require a surface that is not as easily influenced by the freeze-thaw cycle. It is inferred that as global climate change continues and global temperatures increases the freeze season will become shorter and milder and the warm season will become longer and warmer (Ormiston & Sheldon, 2019). This means areas with vast amounts of permafrost will be highly activated by the cycle change, while areas with less frozen ground will not be as deeply impaired (Qingbai et al., 2002). Consequently, construction should commence on areas with little to no permafrost present to avoid risk of warping and uneven ground due to melt. Sensitive soils and permafrost are the most influential criteria considered in this analysis. With melt and thaw cycles, the permafrost changes thickness and area, creating an unpredictable foundation for infrastructure (Fortier et al., 2011). As stated previously, increased frequency of extreme weather events and climate change can lead to higher temperatures and large melts. Building on areas that are known to be fully covered with permafrost would be too costly due to the constant need for seasonal maintenance from freeze and thaw. As well, several case studies examining an all-season road in a heavily permafrost area in Qinghai China, found that building on heavy ice areas created a positive feedback loop. The equilibrium of water and ice was off balanced due to the insulation of the pavement asphalt (Qingbai et al., 2002). This factor plays a major role in the construction process and heavily permafrost areas should be avoided.

Figure 4: Permafrost erosion due to hyper melt Tuktoyaktuk, Northwest Territories (Piche, 2017)

Proximity to Waterways

Protection of water features and group water are important criteria for construction and permitting of any infrastructure. Water crossings such as bridges and culverts can impede fish and other aquatic wildlife from migrating and passing up and down stream (Gibson et al., 2011). In addition, it is costlier to build over lakes and streams with bridge passageways. Therefore, crossing over bodies of water should be avoided if possible as to not interfere with natural habitat of aquatic species. Constructing infrastructure in close proximity to waterways can destroy and hinder aquatic ecosystems and animal habitat from pollution run-off directly into the body of water or seep into the underlying water table and contaminate groundwater (Patrick et al., 2002; Sibley et al., 2008). Building in close proximity to the stream bank can affect bank stability and erosion. In order to protect these areas from pollution, ecosystem imbalance and erosion the road should not be built within a 400-meter radius around features. Building further from the water features is most suitable because further distance decreases the chance of pollution, runoff and other costs.

Proximity Wetlands

Similar to water features, construction should not occur within close proximity to wetlands. Wetlands make up a unique ecosystem containing hydric soil and aquatic plant vegetation, and merges aquatic and terrestrial habitats (Zelder & Kercher, 2005). Wetland ecosystems provide many beneficial services, including carbon sequestration, flood management and natural water purification (Vila & Bernal, 2018). All of these benefits are becoming increasingly more important with global climate change (Erwin, 2008). Construction within wetlands, or within close proximity can infringe on the productivity of these services, and destroy animal habitat and vegetation.

Flora and Fauna

The new corridor should not destroy any known populous flora or fauna habitats. For example, denning sites, borrows, endangered species, or species with other known concerns (Patrick et al., 2002; Goode et al., 2012). Vegetation and animal species rely on different aspects of the arctic landscape for shelter, source of food and water. As stated previously, bodies of water are importance source of drinking water for land mammals and to catch prey, as well as an important habitat for aquatic animals and fish.

Denning mammals such as grizzly bears, wolves, ground squirrels and foxes depend on esker tillage to construct habitats (McLaughlin et al., 2002). Denning animals also prefer moderate south or west facing slopes between 20 and 25 degrees to create dens. Similarly, shrubby vegetation prefers south facing slopes which are favorable for shrubbery growth in arctic climate (Choler, 2005). Therefore, steep south facing slopes should be avoided for construction as to not disrupt vegetation growth and denning sites.

Vegetation growth is sensitive to temperature and solar radiation. Where incoming solar radiation is high this usually indicates high ground surface temperature and increase in oxygenation and stimulate vegetation growth (Young et al., 1997). Higher change creates greater cycling of nutrients for arctic plant growth and is more susceptible to the freeze-thaw cycle and therefore is costlier. Seasonal temperatures that stay relatively indifferent do not experience a great thaw or freeze, these areas also are not as influenced by incoming solar radiation. Normalized Vegetation Index and surface temperature have a positive correlation (Raynolds et al., 2008). As surface temperature increases the productivity of arctic vegetation also increases. These areas should be avoided, because vegetation encourages stability of slope and stream banks, oxygen exchange and contributes to ecosystem resilience.

Figure 5: Wolf pup in Esker escarpment in the Central Arctic NWT

(Government of the Northwest Territories, 2019)

Proximity to Natural Resources

Proximity to known natural resources with potential for mining extraction sites is a beneficial factor for road construction. A pathway that connects to other plentiful extractable resources will be beneficial for future mining leases. For future mining leases it will be more easily accessible to reach these areas from the all-season road, therefore enticing active permits and operations. Overall, more active mines will be beneficial contributing to revenue and creating employment opportunities. Another benefit to constructing the roadway in close proximity to natural resources is that some sources can aid and supplement construction materials (Atkinson et al., 2005; Seppala, 1999; Krajick and Snati, 2002). Rather than purchasing and importing construction materials, contractors can make use of natural elements that are available in the area.

For example, eskers are created from gravel and sand, both permeable substances but sturdy carrying capacity, and therefore have the ability to create a road base that is not overly sensitive to frost (Seppala, 1999). As stated previously, it is costly to build up and over esker slopes, building on the banks of the Esker creates a structural sound road base. However, it is important to mind the environmental effects of constructing in close proximity to eskers such as infringing on animal habitats building burrows in the hill side, and replenishable groundwater filtration source that gravel pits provide (McLaughlin et al., 2002). The use of esker granular material for infrastructure therefore poses a problem for environmental conservation. In this case the benefits of building in close proximity impose too many threats to environmental well-being and therefore the cost outweighs the benefit. On the contrary the underlying bedrock and geology can provide a sound base for construction if the material is impermeable and non-sensitive to seasonal change, such as bedrock and glacial tillage.

Multi-Criteria Analysis and Least Cost Path Routing

To calculate spatial relationships between required criteria and constraints the methodology of a least cost pathway is suggested to produce results. A cost surface created from a multi-criteria analysis (MCA) is created to derive relative costs. This method examines trade-offs of criteria attributes based on multi-object optimization theory (Carver, 1991). Where both constrains and criteria factors are defined as decision problems with various objectives by applying a unit of measurement to create consistency of overall comparison. An MCA incorporates decision making and standardization of prices to reflect specific needs and preferences pertaining to the objective at hand (Jankowski & Richard, 1994).

There are several methods to determine how each criterion will be included and influence the resulting cost surface. One common way to do this is to use the 'voting' method, this is where a single comparison of A and B, A and C, A and D...n are compared one at a time (table 1) (Laarhoven, 1983). Whichever factor is more important than the other wins the 'vote' (Bonnycastle et al., 2014). Once all individual factors are voted the votes are tallied and divided by total votes to assign weights. One complication to this approach is that it assumes that all factors must win at least one vote. This hones in on each individual factor and does not allow any other outside influences to sway the vote.

Table 1: Voting Comparison

Factor	**A**	**B**	**C**	**D**
A	X	A	C	D
B		X	B	D
C			X	C
D				X

Another method is to assign a membership function, also known as Saaty's pairwise comparison. This works by assigning a value on a 1 to 9 scale to each layer (Laarhoven, 1983). The values are described in table 2. This method ranks the layers in comparison to one another, as to which layer is most important and which is the least important (Abildtrup et al., 2006). With this method the weights can be more specific rather than a full vote as in the way of the voting method, they can be assigned a partial weight based on a scale.

Table 2: Saaty's Fuzzy Logic (Pairwise Comparison)

Fuzzy Number	Scale	Triangular-Fuzzy Number(TFN)	Reciprocal of TFN
1	Equally Important	1, 1, 3	1/3, 1, 1
3	Weakly Important	1, 3, 5	1/5, 1/3, 1
5	Essentially Important	3, 5, 7	1/7, 1/5, 1/3
7	Absolutely Important	7, 9, 9	1/9, 1/9, 1/7
2, 4, 6, 8	Intermediate value between two adjacent judgments		

A hybrid weighting system of the two methods is a pairwise ranking system (Bonnycastle et al., 2014). Voting still occurs but they are voted on a scale of 1 through 3. Where 1 indicates a tie, 3 is a high win and 2 is a low win, the reciprocals behave similarly. Where 1/3 is a high loss and 1/2 is a low loss. This method incorporates in-depth comparison of Saaty's pairwise comparison but keeps the simplicity of the voting method by restricting options. This method includes the simplicity of the voting method with the high level of detail from the pairwise comparison. The weights determined by the ranking system are used to weight the criteria for the MCA cost surface.

The cost surface created through the MCA is the basis for the cost pathway identification. Each criterion adds a cost to each individual cell value, therefore averaging the cell cost from all criteria gives an overall surface cost. The cost pathway uses a single best path from the starting location to the desired destination (Esri Cost Path, 2016). By analyzing each cells cost the pathway moves to the cheapest surrounding cell in the direction of the specified destination.

Study Area

The study area encompasses approximately 91,000 km2 of the eastern Northwest Territories. Yellowknife is located in the southwest of the study area, Slave Lake along the south side, and Nunavut borders the north east (figure 6). This area is rich in natural resources and contains over 20 active mining leases, including three operating diamond mines; Snap Lake, Diavek and Ekaiti (figure 7). The population of the NWT is approximately 44 thousand, with over half of the population residing in the Mackenzie Valley area, predominantly Yellowknife with a population of approximately 20 thousand (Statistics Canada, 2018). Yellowknife was established as a gold mining center in the mid 1900’s and officially became the territory's capital in 1967 (Anderson, 2019). Due to the concentration of the mining industry in the Mackenzie Valley area, the majority of the population resides in the Valley, and consequently the road network is most established in this region. Outside of the city center, the transportation network is sparse consisting of seasonal winter roads therefore restricting access during warmer seasons.

Figure 6: Snap Lake, Diavik and Ekati Diamond Mines

(CBC, Government of the Northwest Territories, The Globe and Mail)

More than half of the Northwest Territories' residence are Aboriginal people (the Dene, Inuit/Inuvialuit and Metis). The remaining population can be described as distant relatives of European settlers and explorers from the late 1800's, or other more recent immigrants (Anderson, 2019). More than 16% of the workforce is employed in resource extraction and mining fields of work. With total mineral production totaling at over $2 billion, it is the leading economic income for the territory. Mining exploration is followed by energy generation (oil fields) and agriculture, relating to hunting, fishing, and trapping which is still considered one of the greatest resources for the Aboriginal people in the region. Although there are vast amounts of resources to generate revenue and create job opportunities, the NWT has one of the highest unemployment rates at 11%. One of the greatest barriers in creating more jobs in the booming mining and energy industry is the access to the areas where resources are plentiful.

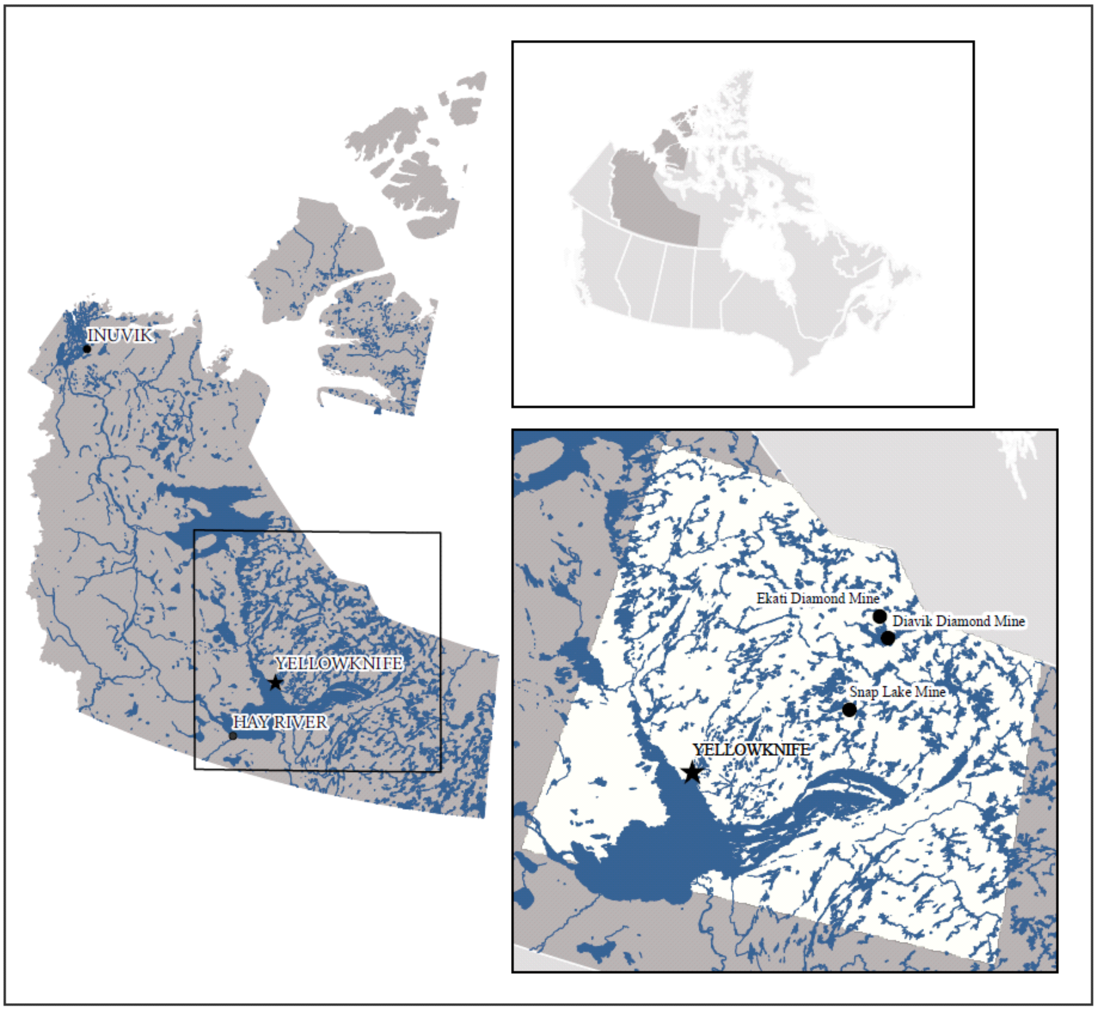


Figure 7: Study area encompassing the three diamond mines (Produced on July 2 2019)

Data and Software

Datasets were gathered from different portals and databases and reprojected and clipped to fit the study area (appendix A). The data were collected from reliable sources, and include metadata for historical and creation information. The majority of the spatial data is compiled from the Government of the Northwest Territories data portal, and Geogratis (Natural Resources Canada, Government of Canada), and some statistical and attribute data is gathered from Statistics Canada and the Government of the Northwest Territories.

ArcMap 10.6.1 (ArcGIS Desktop) and ArcGIS Pro 2.3.0 are the main software used to perform analysis. Utilizing a variety of licenses, such as Spatial Analysts and 3D Analyst, and toolboxes; Data Management, Analysis, Conversion, Spatial Analyst and Geocoding.

Pyscriter and IDLE are used to create the python programing portion of the project. The python scripts call on ArcPy module to incorporate Arc tools in an automated process.

Methods

This section outlines the steps taken to achieve the final goal of a least cost pathway. Including preprocessing to prepare the data for reclassifying into cost values, followed by summing criteria surfaces to create a cost surface, varying weights to achieve different surfaces and ultimately deriving six different least cost pathways from the resulting cost surfaces.

General Preprocessing

Preprocessing involves preparing data for the primary analysis. The first step of the preprocessing is to clip and project layers. All layers are reprojected from their original projection into Lambert Conformal Conic. It is important that all layers have the same projection and underlying datum so that when further analysis is performed areas on one layer are true to that of another. The projection also helps with visually displaying the data based on location and type of analysis. The clipping boundary used is the subset of the Northwest Territories, encompassing an area in the east from Yellowknife to Nunavut. The area encompasses the three main mines and surrounding areas to account for buffering edge effects. By reducing the extent of the data layers and clipping to the bounding extent, this reduces processing time by only analyzing the area that is important to the study. Some layers may need further specific preprocessing steps in order to prepare the layer for suitability and reclassification and some preprocessing may need to be performed before the reprojecting and clipping can occur. These specific processes are described in more detail within each criteria layer.

All raster layers produced are masked to the study area boundary and given a cell size of 20m. Due to the large area, a smaller cell size would require extra processing time and larger cell sizes may stray from important details. All shapefiles produced are output into a file geodatabase in order to organize data efficiently into feature classes. Rasters are not stored in a raster catalog, as most tools cannot take these datasets as input, or may produce errors in results when raster catalogs are used for tool input. Alternatively, raster are produced as TIFF files, because they are most commonly accepted by all tools in ESRI's Arc Suite.

The reclassified rasters are based on a 1 to 9 scale. This medium ranged scale was selected to allow enough variability between factors, but without overcomplicating assignment decisions. One is least costly and therefore most suitable, and nine holds the most cost and should be avoided if possible. Any areas that are prohibited will be assigned NoData. NoData ensures that these areas will not be included in the overall cost surface raster, regardless of other criteria layers.

Criteria Layer: Slope

The 30 individual DEMs are combined using the mosaic to new raster tool. This creates a seamless digital surface raster of the entire study area. The mosaicked raster is projected and clipped to the study area. The slope tool uses the DEM as input and produces an output of the slope in degrees. The slope layer is then ready to be reclassified by the reclassify tool. As stated in the literature review, low lying slopes are favorable for road construction, and therefore lower lying slopes are deemed least costly and higher slopes unsuitable (table 3) creating the reclassified layer displayed in figure 8.

Table 3: Slope reclassification

Slope (Degree)	Reclass Value
<5	1
5-22	3
>22	9

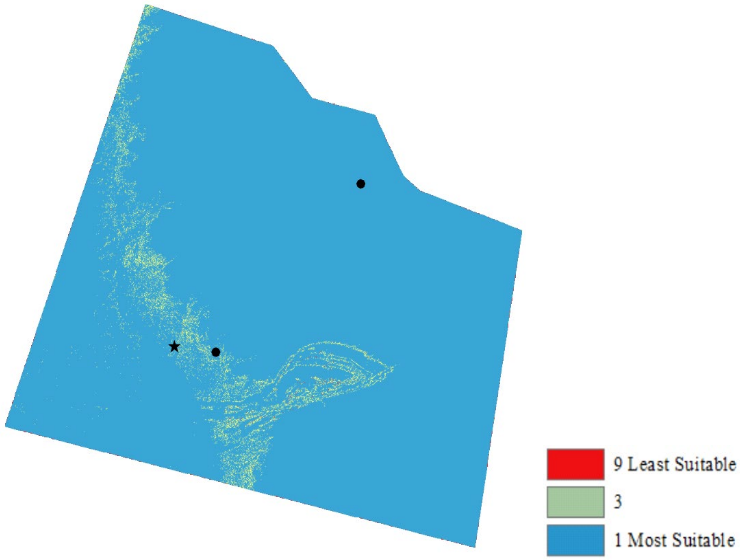


Figure 8: Slope reclassification

Criteria Layer: Surface Material

The surface material layer is derived from the ecological region shapefile. The surface material attribute holds value describing the general surface material of the region. This layer was reclassified based on how well the surface material would perform with road construction depending on if it added value, such as rock or gravel, or was detrimental, such as ice permafrost or organic material. The reclassification is described in table 4.

Table 4: Surface Material Reclassification

Attribute Value	Description	Reclass Value
Ice and Snow (IC)	Glacial ice and permanent snow	9
Organic Soil (OR)	Contains >30% organic matter	9
Rock(RO)	Rock and gravel	1
Mineral Soil (SO)	Mineral particles, containing <30% organic matter	5

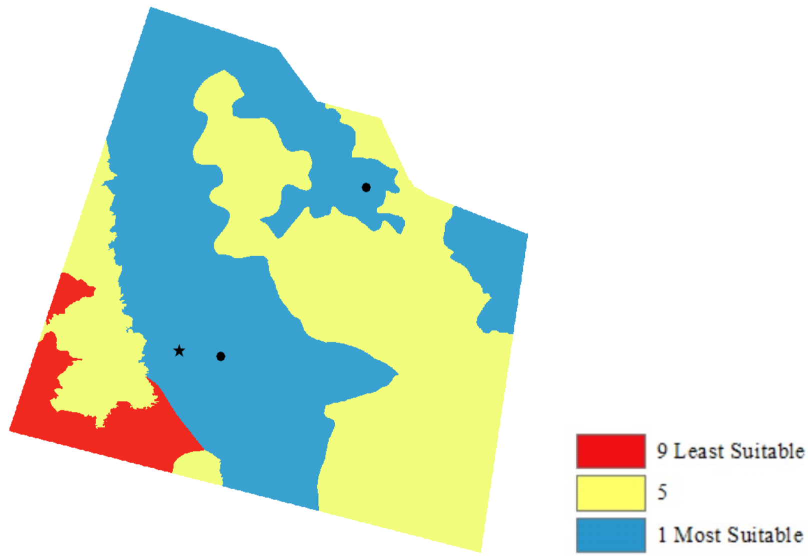


Figure 9: Surface Material Reclassification

Criteria Layer: Surface Geology

Similar to surface material, surface geology is derived from the Ecological Region layer using the attribute data. The surface geology refers to the geological makeup of the region, and are reclassified based on the benefit and cost provided to road construction. Minding that rock and gravel are most suitable for a sturdy base, and softer materials such as sand and organic matter are more porous and unfavorable. The reclassified values are presented in table 5.

Table 5: Surface Geology Reclassification

Attribute Value	Description	Reclass Value
R	Rock with minor quaternary deposits including unweathered and weathered rock	1
Tvb	Till veneer and blanket complex (thin till)	3
Tb	Till blanket, thick and continuous till	5
O	Organic deposits (peat, muck, inorganic sediments) bogs, fens and swamps masking underlying surface materials	9

fC	Colluvial Fines: Sand and Gravel, derived from substrate weakly consolidated shale and siltstone substrate, highly weather tills	7
A	Alluvial deposits, stratified silt, sand, clay and gravel. Floodplain, delta and fan deposits, including glaciofluvial deposits	8
Gx	Glaciofluvial complex, sand and gravel, till and rock	5

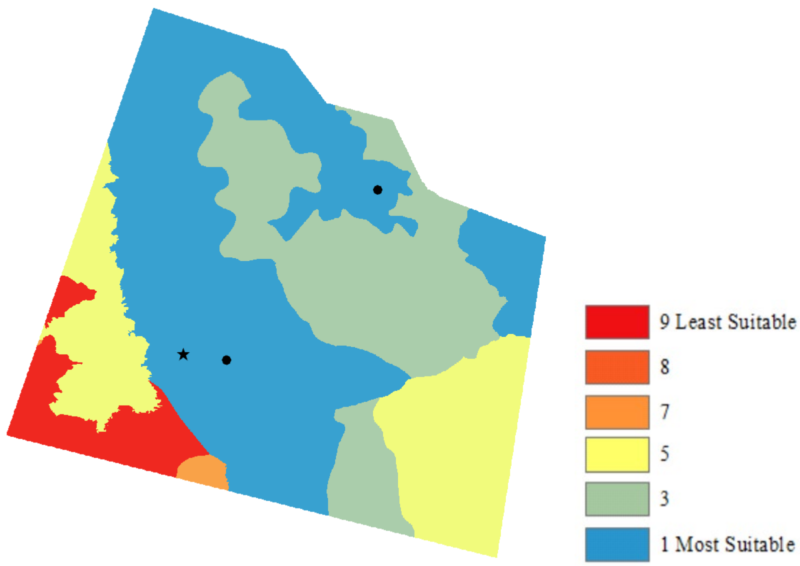


Figure 10: Surface Geology Reclassification

Criteria Layer: Permafrost

The permafrost sensitivity layer is derived from the permafrost contingency shapefile obtained from the Government of the Northwest Territories data portal. The polygon shapefile was transformed into a raster using the polygon to raster tool. The raster is then reclassed using the reclassify tool on the permafrost field value which holds the type of permafrost thickness and its connectivity; the old and new values are described in table 6.

Table 6: Permafrost Reclassification

Field Value	Coverage	Reclass Value
No permafrost	0%-10%	1
Sporadic permafrost	10%-50%	3
Extensive permafrost	50%-90%	7
Continuous permafrost	90%-100%	9

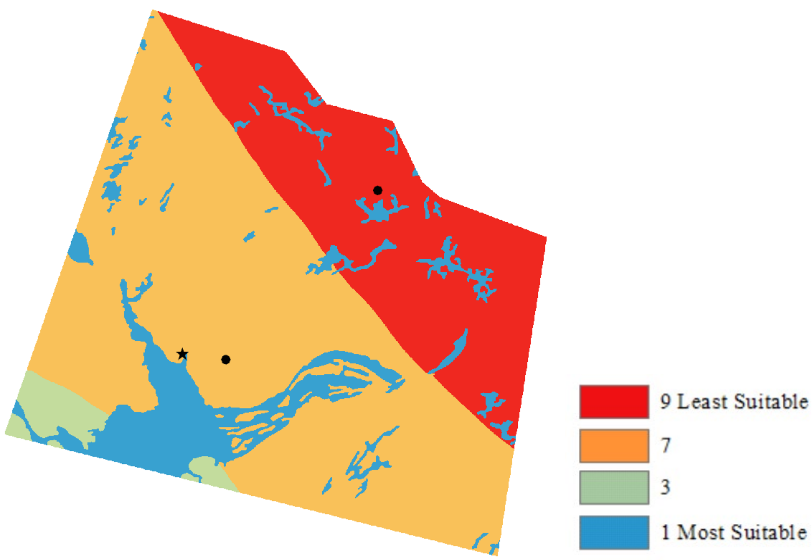


Figure 11: Permafrost Reclassification

Criteria Layer: Watercourse

The Euclidean distance tool is used to buffer the watercourse layer, which produces a distance raster of separation away from each feature. The raster is reclassified based on the distance, where closer to the watercourse are unsuitable and areas further away are acceptable (table 7).

Table 7: Watercourse Reclassification

Distance from watercourse	Reclass Value
0-1m	NoData
1-400m	9
400m-1500m	5
>1500m	1

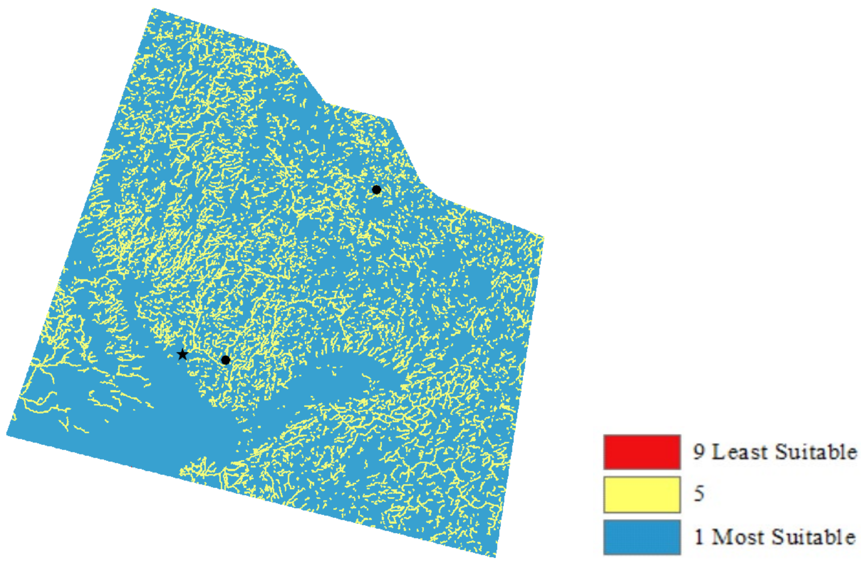


Figure 12: Watercourse Reclassification

Criteria Layer: Waterbodies

Mimicking the process of watercourse classification, the waterbodies layer is input in the Euclidean distance tool to create a distance raster. Closer proximity to the water body serves higher cost than further distance from the water source. The reclassification is summarized in table 8.

Table 8: Waterbody reclassification

Distance from waterbody	Reclass Value
0-1m	NoData
1-400m	9
400m-1000m	7
1000m-1500m	5
1500m-2000m	3
>2000m	1

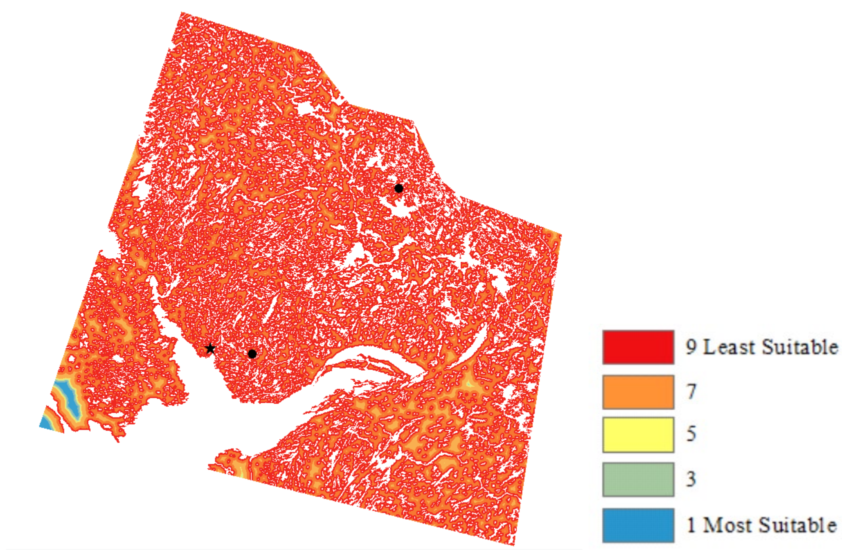


Figure 13: Waterbody reclassification

Criteria Layer: Wetland

Wetlands should be avoided if possible, and buffered to ensure that runoff contamination does not damage the ecosystem. The wetland polygon layer is used as input in the Euclidean distance tool; the produced raster is then reclassified using the weightings in table 9.

Table 9: Wetland reclassification

Distance from Wetland	Reclass Value
0-1m	NoData
1-400m	9
400m-1000m	7
1000m-1500m	5
1500m-2000m	3
>2000m	1

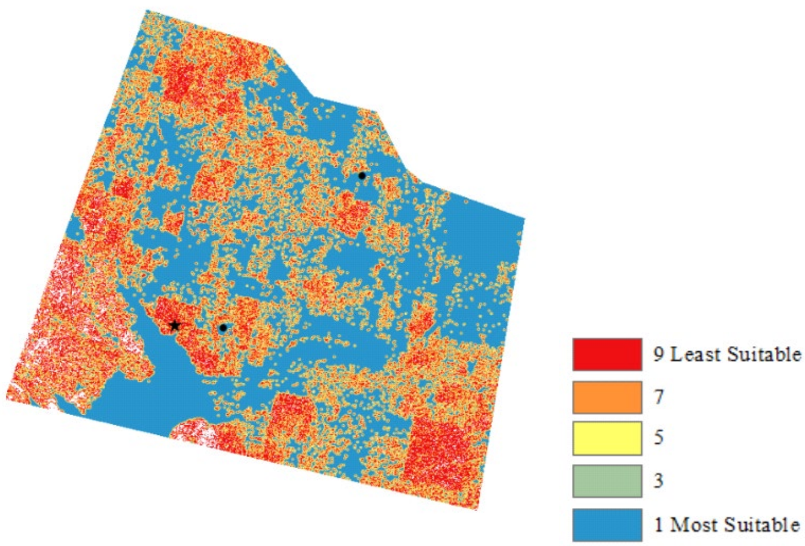


Figure 14: Wetland reclassification

Criteria Layer: Eskers

Eskers provide a habitat for burrowing animals and some vegetation and therefore are avoided if possible. The esker polygon layer is input into the Euclidean distance tool to determine distance from esker features. The output raster is reclassified with the reclassify tool, with values shown in table 10. These values determine that construction will not occur on the esker, or in close proximity to disturb habitats from construction or noise pollution.

Table 10: Esker reclassification

Distance from Eskers	Reclass Value
0-1m	NoData
1-400m	9
400m-1500m	5
>1500m	1

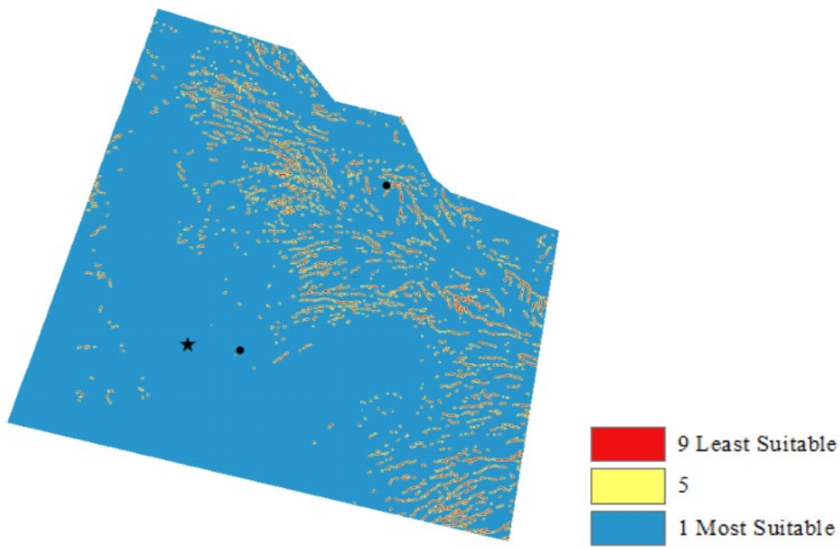


Figure 15: Esker reclassification

Criteria Layer: Surface Temperature

A combination of surface temperature and incoming solar radiation are derived from the ecological region layer. Surface temperature and incoming solar radiation can be indicators of vegetation growth. As stated previously seasonal temperature change and incoming solar radiation are connected to vegetation productivity. Areas of little change and low solar radiation are favorable because they theoretically produce less vegetation. Areas of high change in temperature and incoming solar radiation foster plant growth due to increased cycle of nutrients. The reclassification is summarized in table 11.

Table 11: Surface temperature reclassification

Surface Temperature Change (degrees between seasonal high and seasonal low)	Change in Incoming Solar radiation (megajoules per square meter per day)	Reclass Value
0	22	1
16	22	3
30	22.5	7
39	23	9

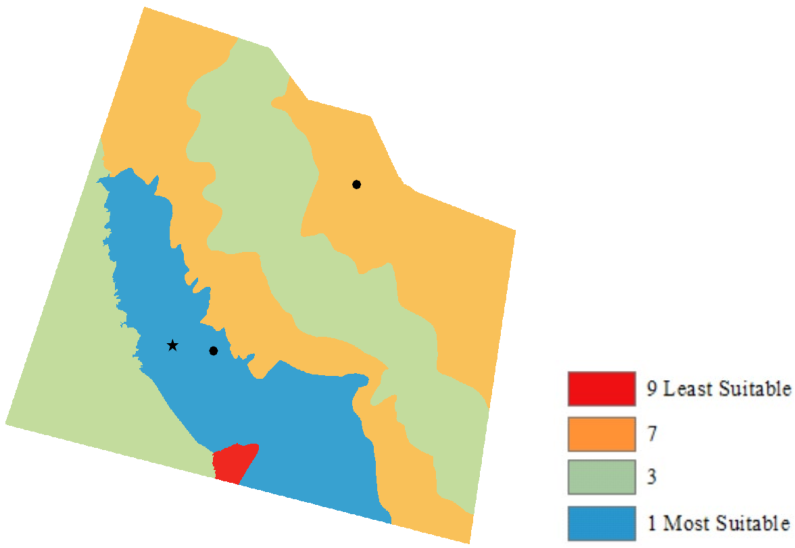


Figure 16: Surface temperature reclassification

Criteria Layer: Aspect

The aspect of an area can help predict the vegetation growth patterns. Low shrubs and arctic vegetation tend to grow in west facing slopes, as well animals tend to make their dens facing south. To create the layer, the mosaicked DEM is used as input in the Aspect tool. The resulting raster displays the area based on which direction slopes are facing. The majority of the surface is flat with slopes in the southern portion. This raster is reclassified with the reclassify tool, values are summarized in table 12.

Table 12: Aspect Reclassification

Aspect	Reclass Value
Flat	1
North	2
North East	3
North West	4
East	5
West	6
South East	7
South West	8
South	9

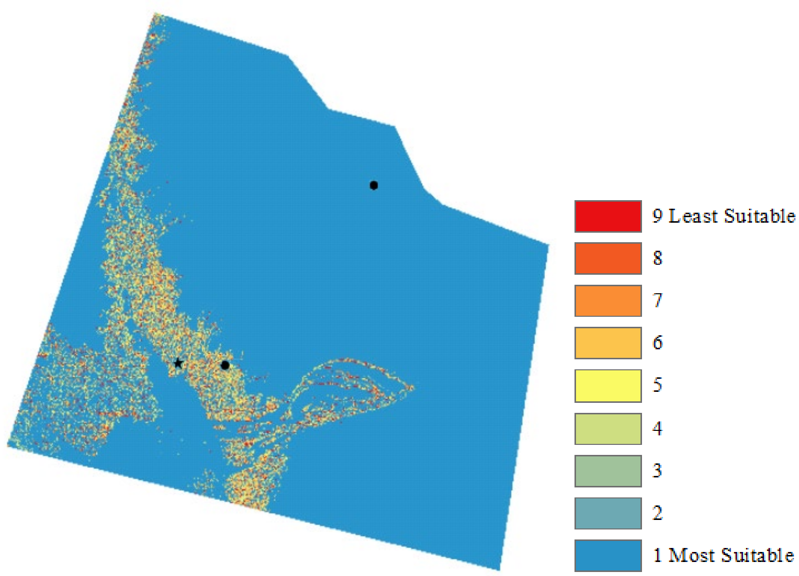


Figure 17: Aspect Reclassification

Criteria Layer: Natural Resources

The natural resource layer is created from the mining leases and mining resources layers. The point file was input into the kernel density tool to create an interpolated surface. Each point is counted and higher concentration of points in proximity to one another creates a higher kernel density, where points are not in close proximity this creates a lower kernel density. This new raster surface suggests that higher point count indicates higher amount of known natural resources, and potential for future mining leases. The kernel density raster was reclassified to reflect higher density as more suitable for future construction, and absence of natural resources is unfavorable. The reclassification was set split using equal intervals to create 9 new classes (table 13).

Table 13: Natural Resource Reclassification

Mine Density (standardized)	Reclass Value
<23	9
23-46	8
46-70	7
70-93	6
93-116	5
116-139	4
139-162	3
162-186	2
186-209	1

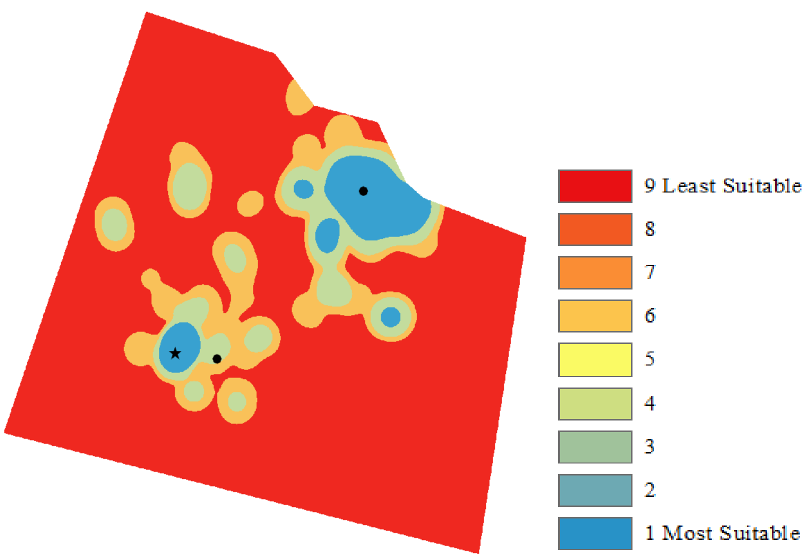


Figure 18: Natural Resource Reclassification

Criteria Layer: Distance to active mines

As stated in the premise of this research, the task is to construct a road in close proximity to the three active mines in the slave geological province. The three mines are extracted from the mining point file and used as input into the Euclidean distance tool to create a distance raster from the point locations. The raster was reclassified to create distance buffers from the location, summarized in table 14.

Table 14: Distance to Active Mines Reclassification

Distance from mine	Reclass value
<10km	1
10-20km	2
20-30km	3
30-40km	4
40-50km	5
50-60km	6
60-70km	7
70-80km	8
>80km	9

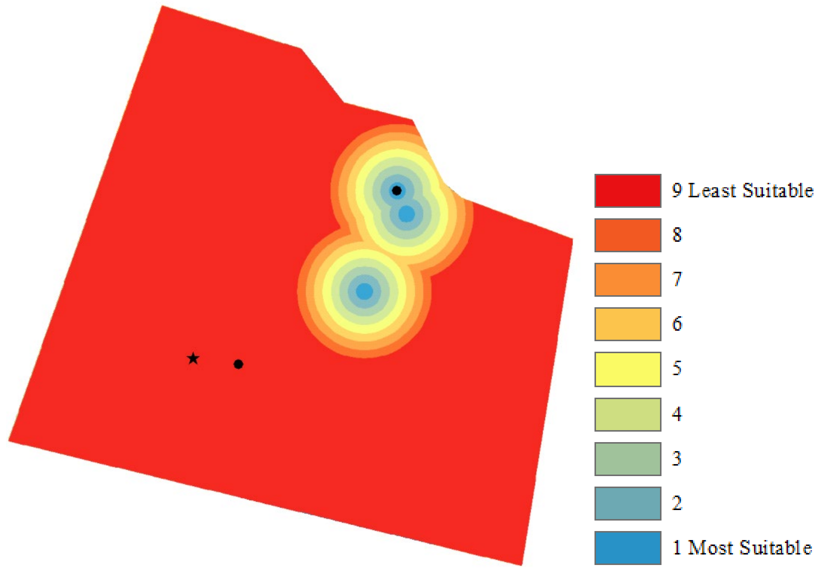


Figure 19: Distance to Active Mines Reclassification

Weighted Criteria

Once all individual layers are weighted, they are segregated into three suggestive lenses: engineering (economic), environmental and social. A fourth lens is created to fulfil the objective of creating the pathway in close proximity to the three operating diamond mines. Criteria are categorized into lenses so that the cost can be objectified solely from that particular lens. This simplifies the cost, so that there is minimal conflict when assigning cost values. The engineering lens includes: slope, surface material, surface geology and permanent ice. Due to the high construction value of building on steeper slopes, or having to cut through steeper terrain slope is included in this category. Surficial material can be beneficial or costly for example sturdy surfaces such as rock can be used for construction, therefore reducing the amount of material needed to be imported into the construction site. On the other hand, softer, porous materials such as organic matter or layers influenced by permanent ice are unstable for road construction and therefore more costly. Surface geology behaves similarly to surface material, except that it pertains to the geological makeup of the surface. Rocks and glacial till that can create a sound structured base for construction are more beneficial than building on softer surface. Organic and porous sands are heavily influenced by water freeze and thaw cycle and detrimental to construction foundation. The permafrost layer is the fourth criteria considered in the engineering surface. Extensive and continuous permafrost are generally more perceptible to seasonal changes in melt due to the thickness layer. Thinner and more sporadic layers are less likely to influence the construction base of the road because the effect from freeze-thaw cycle is minimized.

The environmental lens includes watercourses, waterbodies, wetlands, eskers, temperature and aspect. The watercourse layer is included under the environmental category in order to protect aquatic habitats for flora and fauna. Runoff from construction and road pollution can influence ecosystem equilibrium. Similarly, water bodies provide habitat, source of water and food for animals and aquatic life. The embankment surrounding water bodies creates an import ecosystem for some vegetation and stability, and is also important to have this buffered distance to not entice with embankment erosion. Wetlands also provide a unique bridging ecosystem of terrestrial and aquatic species. Eskers assist in habitat and denning sites for many mammals. Temperature and incoming solar radiation can be indicators of vegetation growth and soil stability. Avoiding areas of greater temperature change and high vegetation is preferable to not destroy and impact flora growth. Aspect of slope can also be an indicator of vegetation growth and animal denning sites. South and west facing slopes are favorable and should be avoided if possible to not interfere with animal habitats.

The social lens consists of only one layer which is the proximity to natural resources. The proximity is a social factor because it considers the future operation of mining and natural resource exploration, and creation of jobs in the future.

The last surface is directly related to the main objective; to build the corridor in close proximity to the three operating mines. The last lens is solely the distance layer from the three mines, to ensure that the proximity of the locations are considered and influence the course of the corridor construction.

A pairwise comparison analysis is conducted to create local weights for both the environmental and engineering factor layers. The social and mine distance layers only contain one factor each and therefore the local and global weights are the same. A pairwise comparison is determined by comparing factors from one to another. The four layers for engineering criteria and the six layers for environmental criteria are weighted using the pairwise ranking method with a 1 through 3 weighting scheme. 1 indicates equal weighting, 2 is slightly more significant, and 3 is highly more significant. The reciprocals behave in the same manner, where ½ is slightly less significant, and ⅓ is highly less significant. These weights are summarized for the engineering and environmental criteria in table 15 and 16.

Table 15: Engineering Ranked Weightings

Factors	Pairwise Results				Individual Weights*				Summed Weights**	Total weights***
	Slope	Material	Geology	Permafrost	Slope	Material	Geology	Permafrost		
Slope	1.00	0.50	0.50	0.33	0.05	0.11	0.11	0.14	0.41	**0.10**
Material	2.00	1.00	1.00	0.50	0.27	0.22	0.22	0.21	0.93	**0.23**
Geology	2.00	1.00	1.00	0.50	0.27	0.22	0.22	0.21	0.93	**0.23**
Permafrost	3.00	2.00	2.00	1.00	0.41	0.44	0.44	0.43	1.73	**0.43**
Total	**7.33**	**4.50**	**4.50**	**2.33**	**1.00**	**1.00**	**1.00**	**1.00**		**1.00**

Table 16: Environmental Ranked Weightings

Factors	Pairwise Results						Individual Weights*						Summed Weights**	Total Weights***
	Stream	Lake	Aspect	Eskers	Temp	Wetland	Stream	Lake	Aspect	Eskers	Temp	Wetland		
Stream	1.00	1.00	3.00	1.00	3.00	0.50	0.18	0.17	0.23	0.17	0.21	0.15	1.12	**0.19**
Lake	1.00	1.00	3.00	1.00	3.00	0.50	0.17	0.17	0.23	0.17	0.21	0.15	1.13	**0.18**
Aspect	0.33	0.33	1.00	0.50	1.00	0.33	0.05	0.05	0.07	0.08	0.07	0.10	0.45	**0.07**
Eskers	1.00	1.00	2.00	1.00	3.00	0.50	0.17	0.17	0.15	0.17	0.21	0.15	1.05	**0.17**
Temp	0.33	0.33	1.00	0.33	1.00	0.33	0.06	0.05	0.07	0.05	0.07	0.11	0.43	**0.07**
Wetland	2.00	2.00	3.00	2.00	3.00	1.00	0.35	0.35	0.23	0.34	0.21	0.31	1.81	**0.30**
Total	**5.67**	**5.67**	**13.00**	**5.83**	**14.00**	**3.17**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**		**1.00**

*Individual weights derived by dividing pairwise rank by factor total

**summed weights sum individual weights for each factor

***total weights are summed weight divided by four to get individual totaling weight

For the categories that have more than one input, engineering and environmental, the weighted sum tool is used to create surfaces that combine the criteria rasters based on their pairwise weighting (figure 20 and 21). Once the weighted surfaces have been created for all four layers with their local weights, the layers are used to create cost surface using global weighting variations. This process is conducted as a scripting tool and described in the following section.

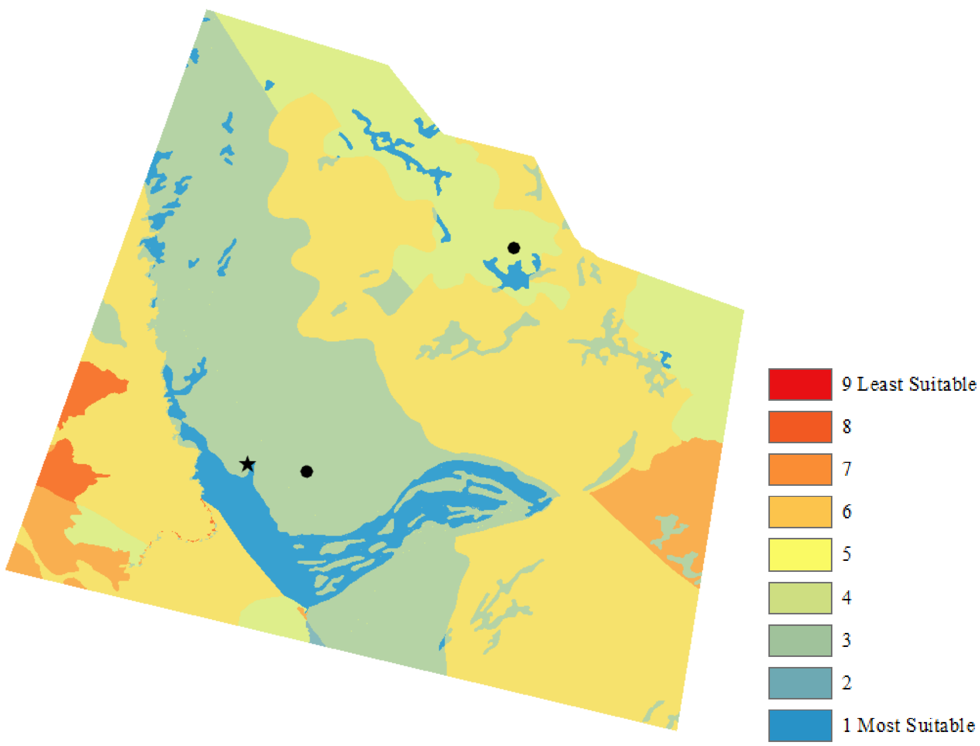


Figure 20: Engineering Weighted Surface

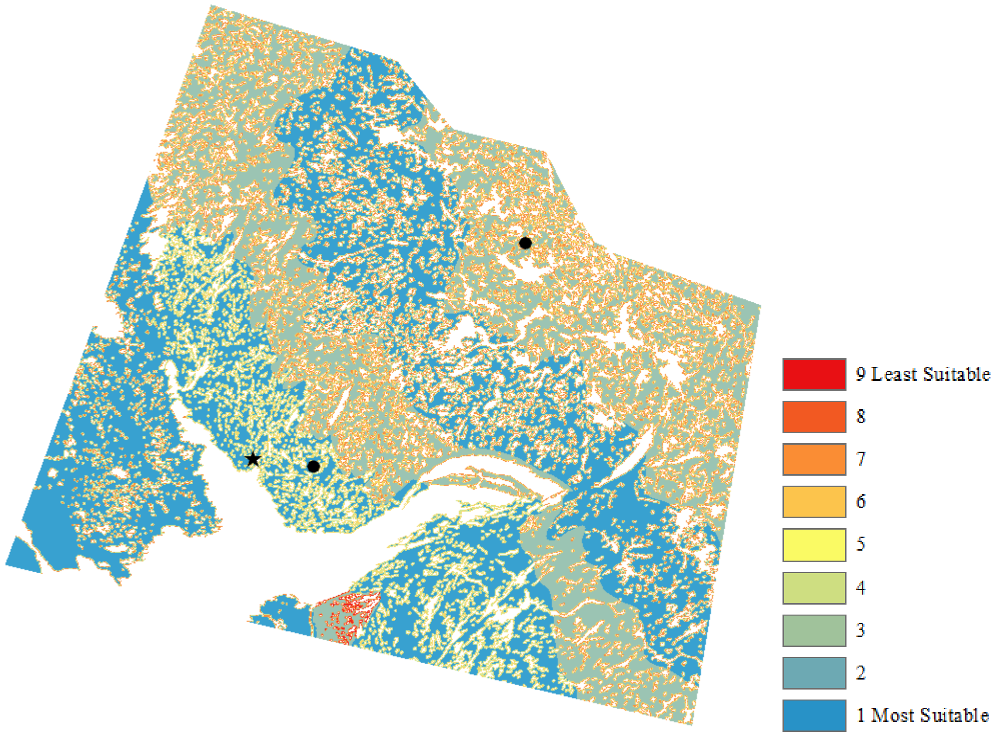


Figure 21: Environmental Weighted Surface

Python Scripting and Automation

Three scripts are created to automate the process of weighted sum, cost-distance, and cost path. The purpose of the script is to make the analysis more efficient and allow for quick changes to be made to the process. The same process is performed six times iterating over several files, therefore rather than the user manually selecting the tools and input parameters for each individual iteration, the parameters can be preset. Another benefit is that the intermediate steps produced in the process are stored in memory, this saves processing space and time when running complex scripts, because a saved output does not have to be produced for each step.

Instead of hardcoding the inputs, which makes the script less dynamic, the script calls on a text file which holds all of the input values. By using a text file to hold the input paths and values the outputs and inputs can easily be changed without interfering with the core script. The text file is saved as a comma separated value (CSV) file. Each value is separated by a comma, and each row represents a new set of inputs. These tools are presented in appendix B.

Weighted Sum

The weighted sum tool is used to add the categorized criteria layers to create a raster surface using global weights for the criteria. The four categories are re-ranked to produces 6 different surfaces. The summary of the weight assigned to each lens is described in table 17. The proximity to the three active mines is always rated at 30%, because this is a consistent objective. Engineering, environmental and social layers are cycled through importance weightings to display different surfaces based on what criteria is deemed more important. The variation in weighting will be useful for future development to understand how factors influence the proposed road.

Table 17: Global Surface Weights

Surface Iteration	Criteria	Weight
Surface One	Mine Location	30
	Engineering	15
	Environmental	25
	Social	30
Surface Two	Mine Location	30
	Engineering	25
	Environmental	15
	Social	30
Surface Three	Mine Location	30
	Engineering	30
	Environmental	25
	Social	15
Surface Four	Mine Location	30
	Engineering	30
	Environmental	15
	Social	25

Surface Five	Mine Location	30
	Engineering	25
	Environmental	30
	Social	15
Surface Six	Mine Location	30
	Engineering	15
	Environmental	30
	Social	25

A python script is created to iterate over the input surface files and weights to produce the six different weighted surfaces and call on a CSV file for input and output locations (appendix B). This script automates the weighted sum process by the individual cost surfaces of the mining locations, environmental, engineering and social criteria. The weighted sum tool uses the WSTable object as input. The parameters for this object are the input raster that is being weighed (ex. engineering, environmental and social surface rasters), the field in the raster that holds the cost value, and the weight to be assigned to the raster. The parameters are read from a text file and saved to the output location also specified in the text file creating the final cost surfaces.

Cost Distance

Now the cost surfaces have been created, they are ready to be used as input for the cost distance tool. Similar to the weighted sum method, the cost distance tool is created as a python script to iterate over the parameters and locations in a text file (Appendix xx). This tool only calls on three parameters from the text file; the location of the starting point file, which is the ending point of the all-season road which travels from Yellowknife towards Slave Lake, the location of the cost surface produced in the weighted sum script, and the output location and name of the backlink raster. An optional parameter is the maximum distance, which defines the threshold of the accumulative cost cannot exceed, this is not necessary for this analysis because it may skew results by having a restrictive distance barrier. The output is a backlink raster which contains the direction of identification from neighboring cells to signify to which cell the path will pass to. The product is then saved using the save function, the name and location are specified in the text file. This saved product is a surface containing cost values to travel from the starting point.

Cost Path

The cost path tool is the core tool in the third script. There are five parameters specified from the text file. The input destination is the point of the destination where the path ends. The cost distance input raster is generated from the output of the second script. The cost backlink input raster is also created from the second script. The path type can be specified as each cell, each zone or single best. Single best is used for this analysis because the path is derived from the minimum cost from the source cell, where each cell treats cells independently of each other and each zone uses zones to create pathways. The last parameter is the field destination parameter which is the field used to obtain values for the destination locations. Any field can be used for this step, FID is used in this instance. The product is saved using the specified location in the text file. The six different pathways are generated from the previous weighted surfaces, cost direction and back link rasters.

Results and Discussion

Six different least cost pathways were produced based on the different weightings of each of the factor layers. Surface one and two follow almost identical pathways. This is likely in view of the heavily weighted social lens for both surfaces. The social lens also includes the diamond mines as natural resource deposits and therefore acts as extra weight in combination with the mine proximity lens. This pulls path one and path two east, closer in the direction of the diamond mines. This is likely why these two paths resemble different route and turns than the other four generated pathways. Also when examining the cost surfaces produced for these pathways, they are very similar (Appendix C). The bullseye like effect of the social lens in visible within the surface. The social lens surface is the least complicated of all the surfaces and does not hold much detail, therefore the contribution from this lens creates the circular bullseye on the final cost surfaces but does not add significant value elsewhere due to its simplicity.

On the contrary path three and five have the social lens weighed in at only 15%. These routes follow a path further west off the other four paths- further away from the mining sites. The social lens does not have as much weight therefore these pathways are more heavily influenced by the engineering and environmental lens.

Path five and six both have the environmental lens weighted at 30%. These pathways strongly avoid water features. The surface generated for these two paths resembles the surface pattern of the environmental lens surface, where areas of low suitability run in a north-east south-west direction following the pattern of the eskers. As well there is a pattern of single cell lines resembling the water courses. The surfaces created with high impact from the environmental surface serve a distinct complex look because the environmental lens took into consideration so many different layers consisting of polylines and polygons collected at different scales. The water courses, water bodies, and eskers are all very detailed layers therefore their contribution to the environmental layer adds lots of small details to the final cost surface. On the other hand, the engineering lens consisted of polygon layers that covered large regions, up to 1000 km squared. These areas overlapped greatly therefore the areas of distinct cost overlapped for the majority of all four criteria layers. This vague, coarse detail in the criteria layer therefore created the engineering lens with little detail and a single cost covering thousands of contingent cells, opposed to the environmental lens where the cost is quite mixed.

The six generated paths do not fall in relation to the proposed all-season road and the seasonal road. The seasonal road is drawn towards frozen features such as water courses, water bodies and continuous permafrost due to the need for consistent ice and snow during the winter months. The all-season route prohibits in the MCA generated scenarios because they would acquire higher maintenance costs and unpredictable stability.

The proposed all-season road also avoids these frozen features and yet is still different from the six generated paths. The proposed all-season road may have considered other criteria not proposed in this analysis therefore altering the costs associated. For example, there could have been more social factors considered such as leases and land claims, archeological and historical sites. The data used to generate the proposed all-season corridor most likely used more detailed data. As discussed previously, the environmental criteria created a more complex surface than the engineering criteria, this is due to the level of detail of each criteria layer which makes for a more complex pathway because there are a larger number of areas of avoidance therefore creating more options for the route to take. It is assumed that a similar action was performed for the proposed all season road; that the data was collected at a larger more detailed scale allowing a more complex route. Resolution and scale of data can drastically change the cost surface and value of each cell, consequently altering the resulting cost path.

For example, surficial geology should be a primary factor for determining routing through permafrost and temperature sensitive geological areas. Table 18compares the six generated paths to the proposed all-season corridor using the surficial geology layer. A mask of each path was taken of the geology to determine the percentage of coverage. The coverage for both rock and till blanket are nearly identical for all of the pathways and the proposed route. This leads to an assumption that the surficial geology layer used to create the proposed route was much more detailed pertaining to area coverage as well as categories of geological cover. Because geological coverage holds such a high presence in the creation of arctic infrastructure it is likely that a highly detailed layer was used to create the all-season route so that a true cost was captured.

Table 18: Surface Geology Comparison

Route	R cells	Surface Coverage	Tvb cells	Surface Coverage
Surface 1	9816	58.7%	6895	41.3%

Surface 2	9707	57.8%	7090	42.2%
Surface 3	10156	61.6%	6340	38.4%
Surface 4	9778	58.7%	6881	41.3%
Surface 5	9774	60.6%	6357	39.4%
Surface 6	9774	60.4%	6403	39.6%
All-Season	15674	60.8%	10091	39.2%

The generated paths are compared to the previous seasonal ice road and the proposed all-season route on the same map in figure 22. The roads produced from this analysis are not intended to be a replica of the previously proposed road, rather an exploratory analysis to exercise different possibilities and criteria. All of the all-season roads, including the six from the analysis and the one generated by the government are much shorter than the seasonal road. This is due to the criteria of the seasonal road to be built on water features and frozen ground, where all-season roads strongly avoid these aspects. The routes generated in this research project follow a straighter path than the government proposed road. The six also fall more closely to Diavik and Snap Lake. Possible reasons that the six generated pathways vary drastically from the proposed all-season road could be due to inclusion and exclusion of different criteria, or different costs associated to each feature. Aboriginal and private land claims were not included in this study, and could be a contributing factor as to why the proposed path is not as linear as the six generated pathways. As well archeological and historical significance was not a contributing factor. Another reason for variation could be the surface geology and surface material. The proposed pathway may have been derived from more specific data and influence how the path avoids different features and landforms.

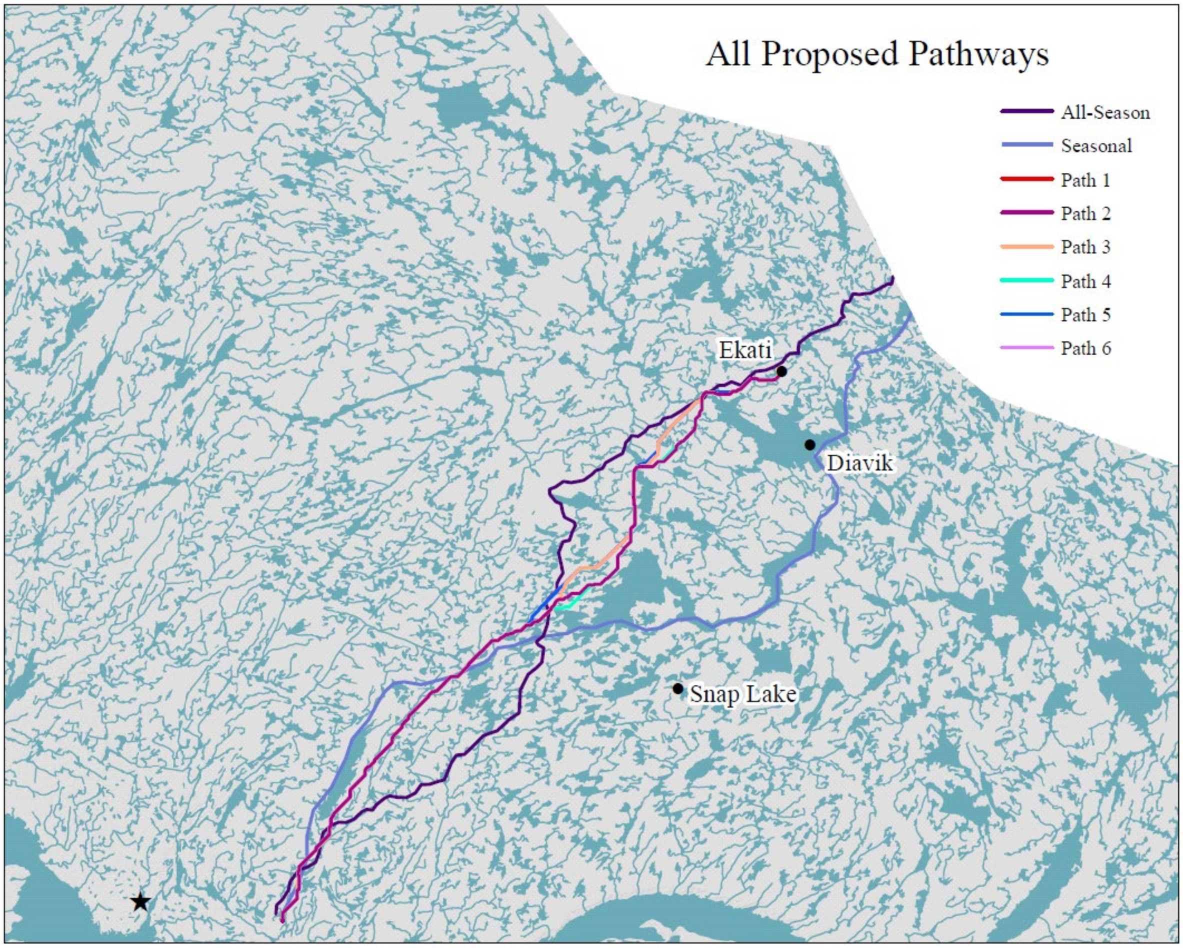


Figure 22: Route Comparison of All Proposed Roads

Limitation

There are some issues that arise with the scale at which the data was collected. Inconsistency of scale collection limits the study accuracy. Some data are aggregated at a small scale, which cover regions and others are point specific data detailing exact locations. When converting these input layers into rasters, all raster outputs were created at 20 by 20-meter cell size, for consistency. Some polygon features such as surface material and temperature are generalized and cover large areas up to 1000 km squared. The detail in data collected at small scale can be vague and generalized. However, data such as the watercourse shapefile are collected at a larger scale and can therefore be more accurate in detailing stream curves and bends. When converting small and large scale features to raster data that was rendered at a large scale may have been able to provide more accuracy for specific cells. for example the engineering layer consisted of broad criteria hence creating a very homogeneous cost surface, on the contrary the environmental criteria was much more detailed creating a heterogeneous mix of costs for the surface. The least cost pathway process is derived from each cell's cost; therefore it is sensitive to any change in cell value. a more complex and detailed surface may create small little barrieres with stream-like links of suitable cells for the path to follow. A less complex, less detailed surface does not create as many little obstacles, therefore the route is more direct. A slight change in cost surface can cause the resulting path to take a completely different course. For example the water courses and water bodies were collected at a large scale, therefore are fairly detailed by showing tight turns and bends and small bay inlets. This level of detail allows the cost raster surface to also reflect this level of detail, to the scale of the cell size at 20 by 20 meters. For

The extent of the study area limits the data types that were used in this study. Some of the data was retrieved from the Government of the Northwest Territories; therefore, the extent of the dataset only covered the one territory and does not cross the border into Nunavut. If the data were to cross over into Nunavut, some of the data layers that are NWT specific would not have corresponding cover for Nunavut. There are separate datasets of Nunavut that have similar data coverage as the Northwest Territories portal, however if the data was collected at a different scale, at a different time of year, or with different methods that could skew the results. Therefore, it was decided that consistency among data layers is optimal. The chosen study area would not extend into the adjacent territory resulting in data that are created in the same instance. If this study were to be conducted again it would be in the user's best interest to locate data that covers into the boarder of Nunavut so that edge effects from buffered criteria and other interpolated layers are included in the analysis.

The methodology of using an 8-cell search window limits how the path can move. There are three general search windows used in different GIS platforms; rook, queen and knight (figure 23). The rook window only has four options when travelling from cell to cell moving at 90 degree angles. The queen's move creates a few more options, with 8-cell options at 45 degree intervals. The knight's move offers the most variety with 16 different cells at 22.5 degrees. This means that the pathway can 'jump' over an adjacent cell and move to a cornered cell, if that cell costs less. This creates more moving and mimics real-life travel opportunities which may be cheaper overall. For future studies different cell size options should be conducted to compare resulting paths and costs. The knight's move is available through the open source program QGIS and GRASS. However, this software is not as widely used as Esri's GIS suite and therefore user manuals and help pages are not as well developed as some of Esri's tutorials and helping guidelines.

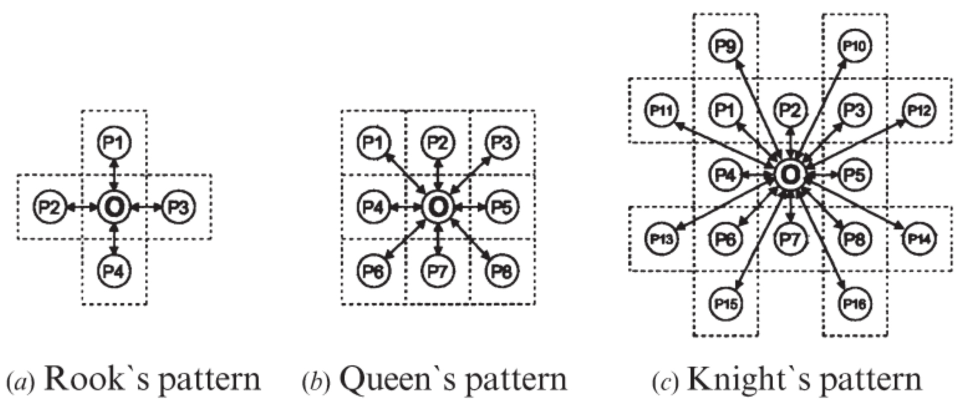


Figure 23: Window Size and Pattern (Yu et al., 2001)

For future projects, each layer should be considered for each lens category, so that cross category factors can be included. For example, in this analysis slope was included under the engineering cost surface however it could have just as easily been counted in the environmental layer. Steep slope construction can encourage erosion process by uprooting vegetation and rocks creating an unstable ground. As well, denning animals prefer higher steeper slopes to create their den sites. Another example are the watercourse and waterbodies layers. These are calculated in the environmental layer; however they could have been included in the engineering or social layers. Building bridges and passes add extra cost, require different material, and will need different maintenance and attention therefore incurring to the engineering cost. Contamination of ground water sources could be included with the social and future well-being of the population. In remote areas, clean water sources are essential therefore groundwater contamination could be detrimental to the population's water source.

for future studies the incorporation of remote sensing software and satellite imagery should be included. For example utilizing the normalized difference vegetation index (NDVI) and normalized difference snow index (NDSI). NDVI can be used to detect vegetation, this would have been useful to indicate which areas contained strong amounts of vegetation so that why could be avoided if possible. This data would have been useful in conjunction with the temperature data to indicate patterns of vegetation growth. Similarly, NDSI indicates areas of snow, and could be used to differentiate between snow and cloud cover in remotely sensed images. This could have been useful to use for a historic comparison of snow cover from present and past images of the region to indicate areas of high melt.

More layers could also be included in the social layer. Other factors such as proximity to larger populations, land claims and leases, historical and archeological sites, ports, or other infrastructure could have been considered. However due to the majority of the population settling in the southern portion this may have skewed results, or have no real impact on the overall pathway other than increasing the length. Being consistent with number of criteria would be beneficial to the overall validity of the project to ensure that each lens was strong enough to be accounted for the overall global weighting.

For future studies, the study area should be refined to include a smaller portion of the Northwest Territories to speed up processing time. A large portion of the study area was not needed for the analysis and therefore should be reduced. However, there should still be a substantial buffer to account for edge effects.

Conclusion

The benefit of constructing an all-season road in the slave geological province is highly beneficial to the livelihood and mining industry in the Northwest Territories. By examining different factor's costs and benefits pertaining to engineering cost, environmental impact and social sustainability, a viable route can be constructed. The outcome of this project produced six pathways, each influenced by a combination of different lenses. The scale at which the data was collected and the aggregation of lenses are large determining factors in the final production of the route. Complex surfaces with high level of detail, such as the environmental lens created many barricades of unsuitability, causing the route to travel along links of multi costs. The engineering layer was much more homogenous and generalized; the unsuitable and suitable cells alike cover large areas therefore creating a less complex pathway for the least cost corridor.

Further research should be conducted to ensure that the best methods are practiced, and all viable layers are analyzed for criteria and constraints. The main priority is to prepare for future uncertainties, which can be difficult when the climate and seasonal change are accelerating at incalculable rates. It is best to err on the side of caution and organize route plans that will not be as easily influenced by changing temperatures. Such as mindfulness of surficial material and geology since the makeup of the surface is the leading factor to construction failure in arctic permafrost regions due to its sensitivity to changing climate.

Appendices

APPENDIX A

Data Library and Summary

Name	Source	Type	Scale	Description
Canadian Permafrost Thickness, Geological Survey of Canada	Geogratis Natural Resources Canada	Polygon Shapefile	1: 100 000	Contains attributes of permafrost thickness and consistency
Waterbody	Geogratis Natural Resources Canada	Polygon Shapefile	1: 50 000	Lake and other water bodies
Watercourse	Geogratis Natural Resources Canada	Polyline Shapefile	1: 50 000	Streams, rivers and linear waterways
Wetlands	Geogratis Natural Resources Canada	Polygon Shapefile	1: 50 000	Arctic wetland locations
Eskers	Geogratis Natural Resources Canada	Polyline Shapefile	1:50 000	Linear esker features
Road Segment	Geogratis Natural Resources Canada	Polyline Shapefile	1:50 000	Linear road features, including seasonal and permanent road types
EcoRegions	Northwest Territories Government Data Portal	Polygon Shapefile	1:100 000	Classifies regions by ecological features such as surficial geology and surface material composition

Mining Leases	Geogratis Natural Resources Canada	Polygon Shapefile	1:50 000	Location for current and historical mining leases (active and inactive)
Mining Resource Locations	Natural Resources Canada	Excel containing x,y location	N/A	Mining locations provided for all currently active resources locations in an excel spreadsheet turned into point shapefile using the XY table tool
Digital Elevation Models	Geogratis Natural Resources Canada	DEM Raster	0.00002 meter cell size	Tiles: 86F, 86G, 86H, 76E, 76F, 76G, 86C, 86B, 86A, 76D, 76C, 76B, 85N 85O 85P 75M, 75N, 75O, 85K, 85J, 85I, 75L, 75K, 75J, 85F, 85G, 85H, 75E, 75F, 75G
Boundary	Feature created through ArcGIS	Polygon Shapefile	1:150 000	Encompasses the three mining sites, and surrounding area. Nunavut is not included in the boundary in order to keep other data layers consistent.

APPENDIX B

Script for weighted sum tool

```
##Created by Katrina Mavrou for MSA MRP at Ryerson University

# this script performs the task of creating weighted surfaces.
# By calling on file names and weights from a text (CSV) file
# the script iterates through the text file generating
# output surfaces for each line of text.

# import necessary modules and extensions
import arcpy
from arcpy import env
import arcpy.sa
from arcpy.sa import *
import csv

#check out spatial analyst extension
arcpy.CheckOutExtension("Spatial")

#set output to overwrite to reduce memory storage
```

```
arcpy.env.overwriteOutput=True

#set coordinate system to correspond to map preferences
arcpy.env.outputCoordinateSysytem=arcpy.SpatialReference("Canada Albers Equal Area Conic")

#set cell size to correspond to map preferences
arcpy.env.cellSize=20

#name variables to be called within script
ws="S:/MRPLS/Rasters" #workspace to receive and deposit rasters
weightfile="S:/MRPLS/weights.txt" #text file to receive input as text

#open and read CSV file
with open (weightfile, 'rb') as f:
  reader=csv.reader(f)
  csv_data=list(reader)

# create list for data to new stored in memory
atdata={}

# iterate over text file calling on each variable separated by a comma
for row in csv_data:
  #name variables for each item in CSV
  mine=row[0]
  mineweight=row[1]
  env=row[2]
  envweight=row[3]
  eng=row[4]
  engweight=row[5]
  soc=row[6]
  socweight=row[7]
  outfile=row[8]
  #input variables to weighted sum tool

outWeightedSum=WeightedSum(WSTable([[mine,"VALUE",mineweight],[env,"VALUE",envweight],
[eng,"VALUE",engweight],[soc,"VALUE",socweight]]))
  #save final output surfaces
  outWeightedSum.save(outfile)

#close CSV reader and file
F.close
```

Script for cost distance tool

```
##Created by Katrina Mavrou for MSA MRP at Ryerson University

# this script performs the task of creating cost distance surfaces.
# By calling on file names and weights from a text (CSV) file
# the script iterates through the text file generating
# output surfaces for each line of text.

# import necessary modules and extensions
import arcpy
from arcpy import env
from arcpy.sa import *
import csv
import os
import arcpy.sa

#check out spatial analyst extension
arcpy.CheckOutExtension("Spatial")

#set output to overwrite to reduce memory storage
arcpy.env.overwriteOutput=True

#set coordinate system to correspond to map preferences
arcpy.env.outputCoordinateSysytem=arcpy.SpatialReference("Canada Albers Equal Area Conic")

#set cell size to correspond to map preferences
arcpy.env.cellSize=20
#name variables to be called within script
arcpy.env.workspace="S:/MRPLS/Rasters/output" #workspace to receive and deposit rasters
costfile="Distfile" #text file to receive input as text

#open and read CSV file
with open(costfile, 'rb') as  cf:
  reader=csv.reader(cf)
  csv_data=list(reader)

# iterate over text file calling on each variable separated by a comma
insource="S:/MRPLS/StartPoint.shp" # variable for start location
for row in csv_data:
  costrast=row[0]
  backrast=row[1]
```

```
    outfile=row[2]
    #input variables into cost distance tool
    outCostDist=CostDistance(insource, costrast,"",backrast)
     #save output
     outCostDist.save(outfile)

#close CSV reader and file
cf.close
```

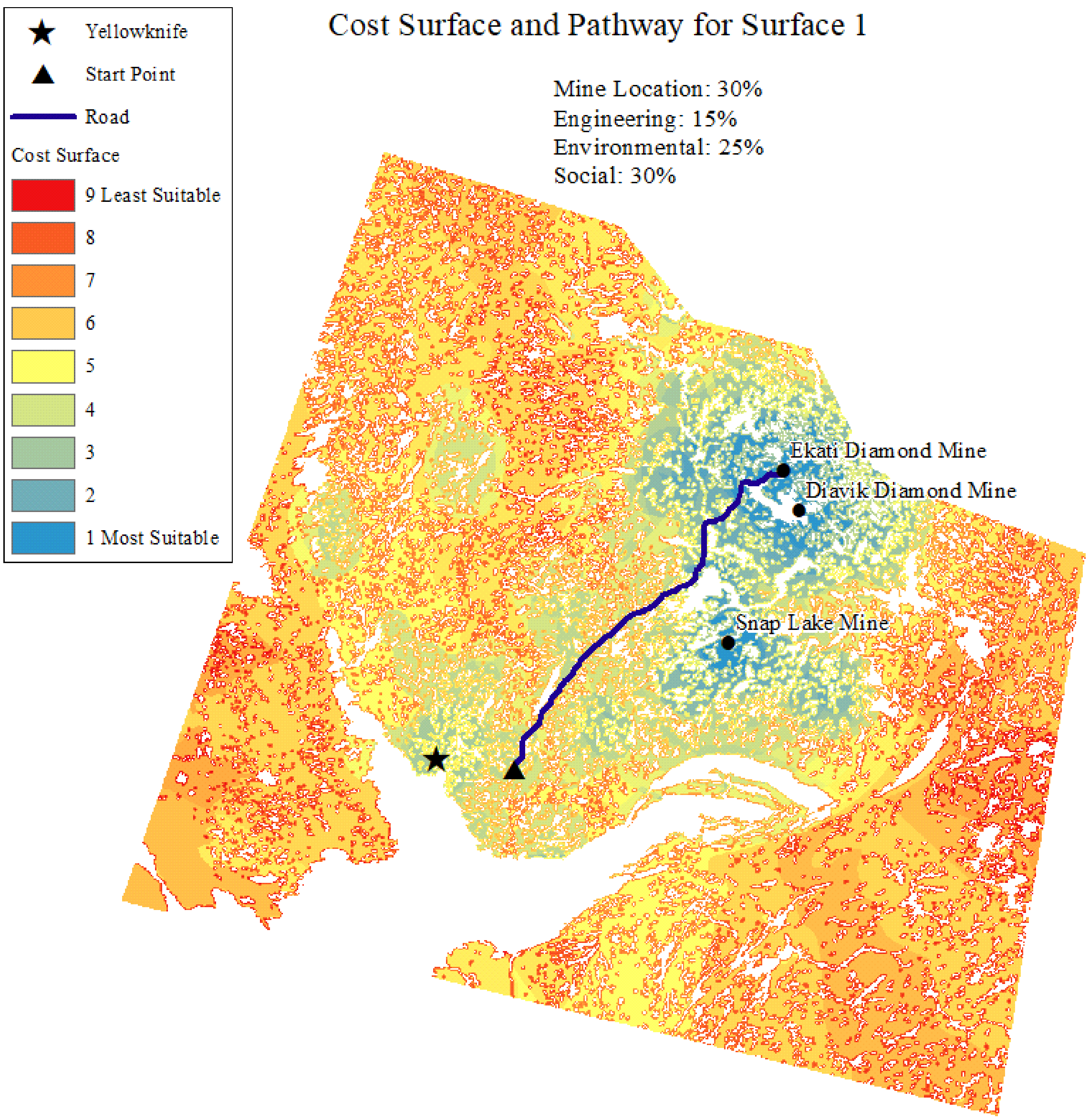
Script for cost path tool

```
##Created by Katrina Mavrou for MSA MRP at Ryerson University

# this script performs the task of creating a least cost pathway.
# By calling on file names from a text (CSV) file
# the script iterates through the text file generating
# output surfaces for each line of text.

# import necessary modules and extensions

import arcpy
from arcpy import env
import arcpy.sa
from arcpy.sa import *
import csv
#check out spatial analyst extension
arcpy.CheckOutExtension("Spatial")

#set output to overwrite to reduce memory storage
arcpy.env.overwriteOutput=True

#set coordinate system to correspond to map preferences
arcpy.env.outputCoordinateSysytem=arcpy.SpatialReference("Canada Albers Equal Area Conic")

#set cell size to correspond to map preferences
arcpy.env.cellSize=20

#name variables to be called within script
arcpy.env.workspace="S:/MRPLS/Rasters/output"
pathfile="S:/MRPLS/pathdata.txt"

#open and read CSV file
with open (pathfile, 'rb') as pf:
```

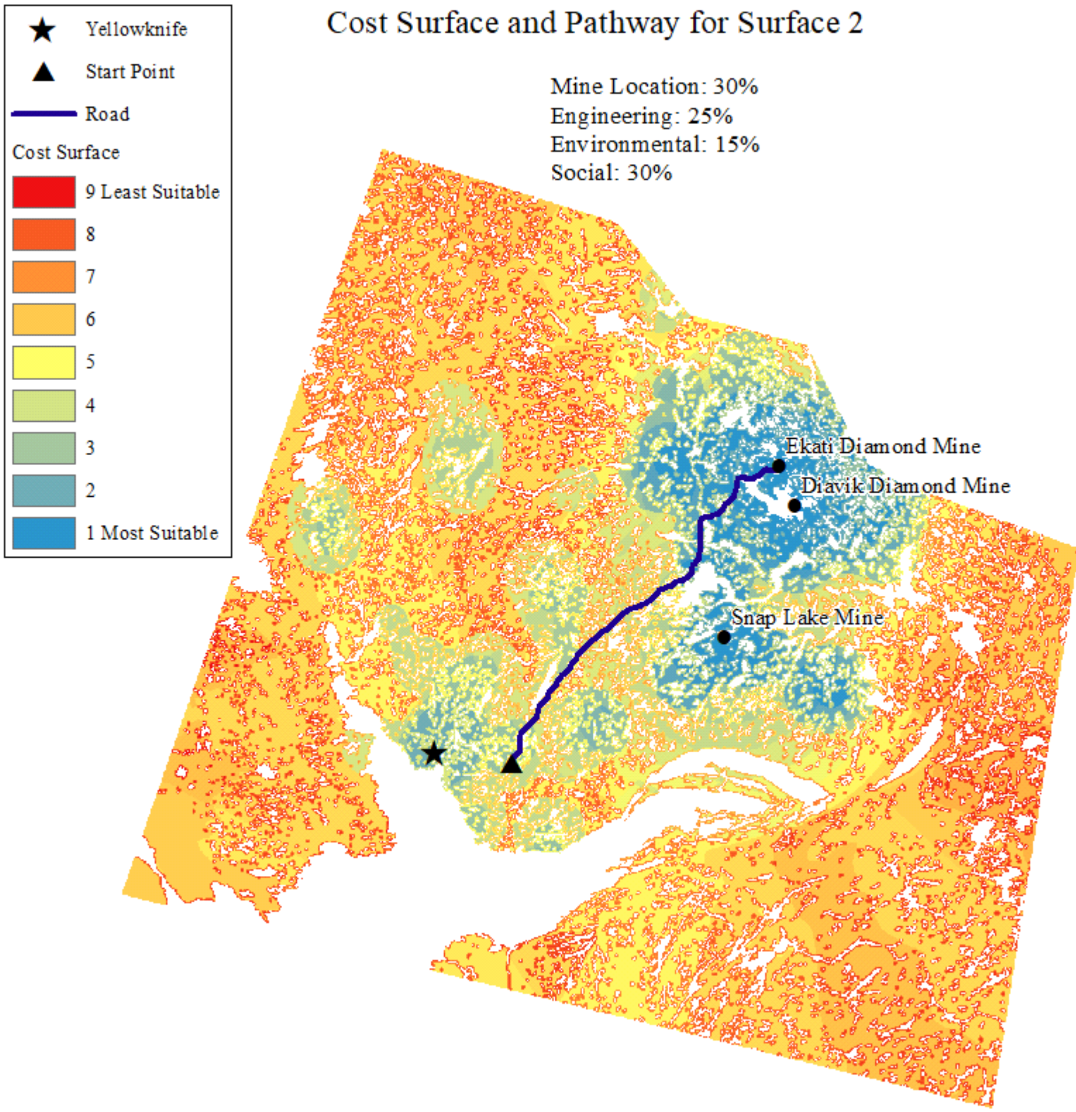
```
    reader=csv.reader(pf)
    csv_data=list(reader)

#set constant variable for the path endpoint
endpoint="S:/MRPLS/ekatimine.shp"

# iterate over text file calling on each variable separated by a comma
for row in csv_data:
    #name variables for each item in CSV
    costrast=row[0]
    costback=[1]
    #input variables into cost path tool
    outCostPath=CostPath(endpoint,costrast,costback,"BEST SINGLE")
    #save output
    outCostPath.save(outfile)
#close CSV reader and file
pf.close
```

APPENDIX C

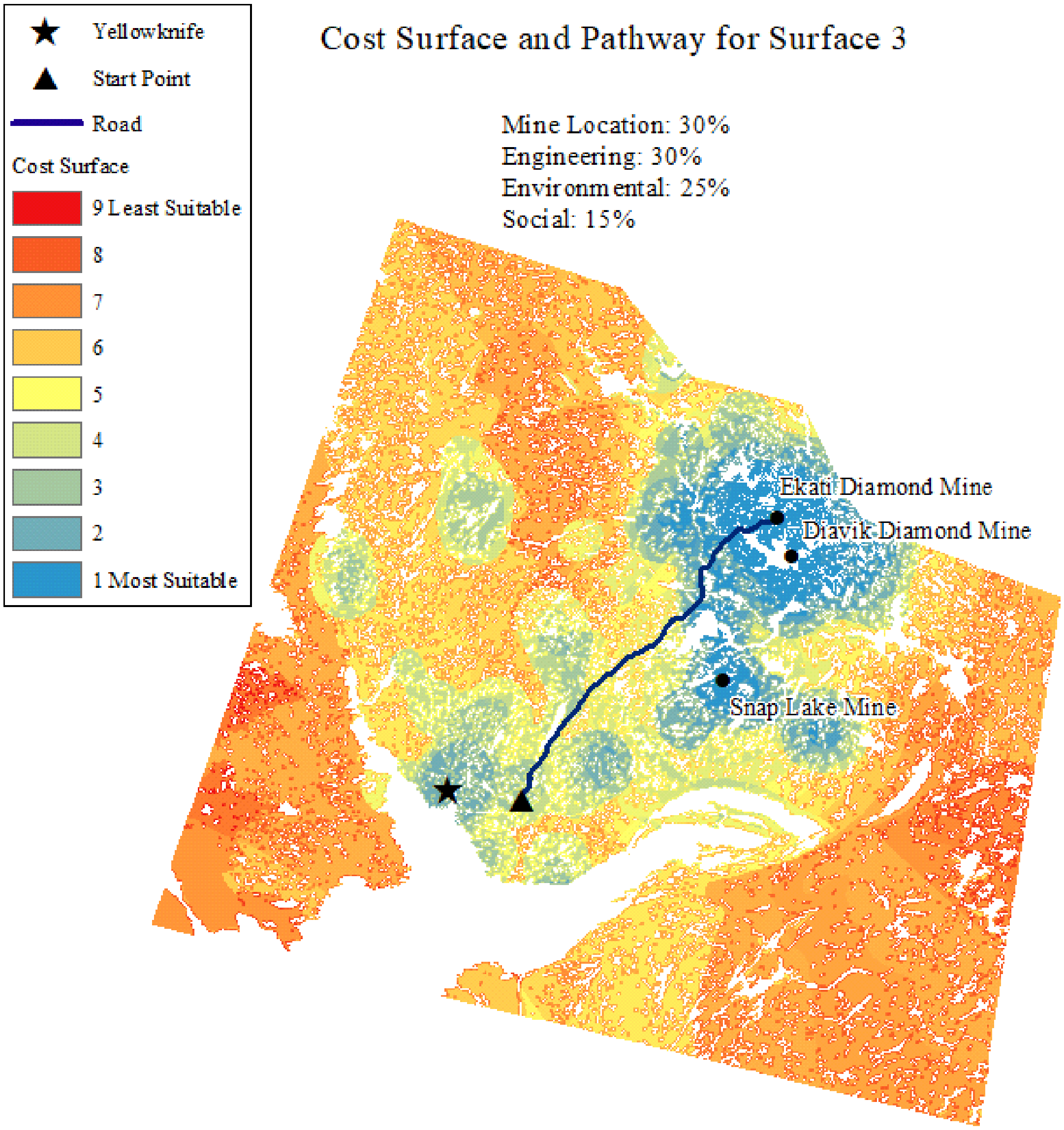
Cost surface and pathway for surface 1



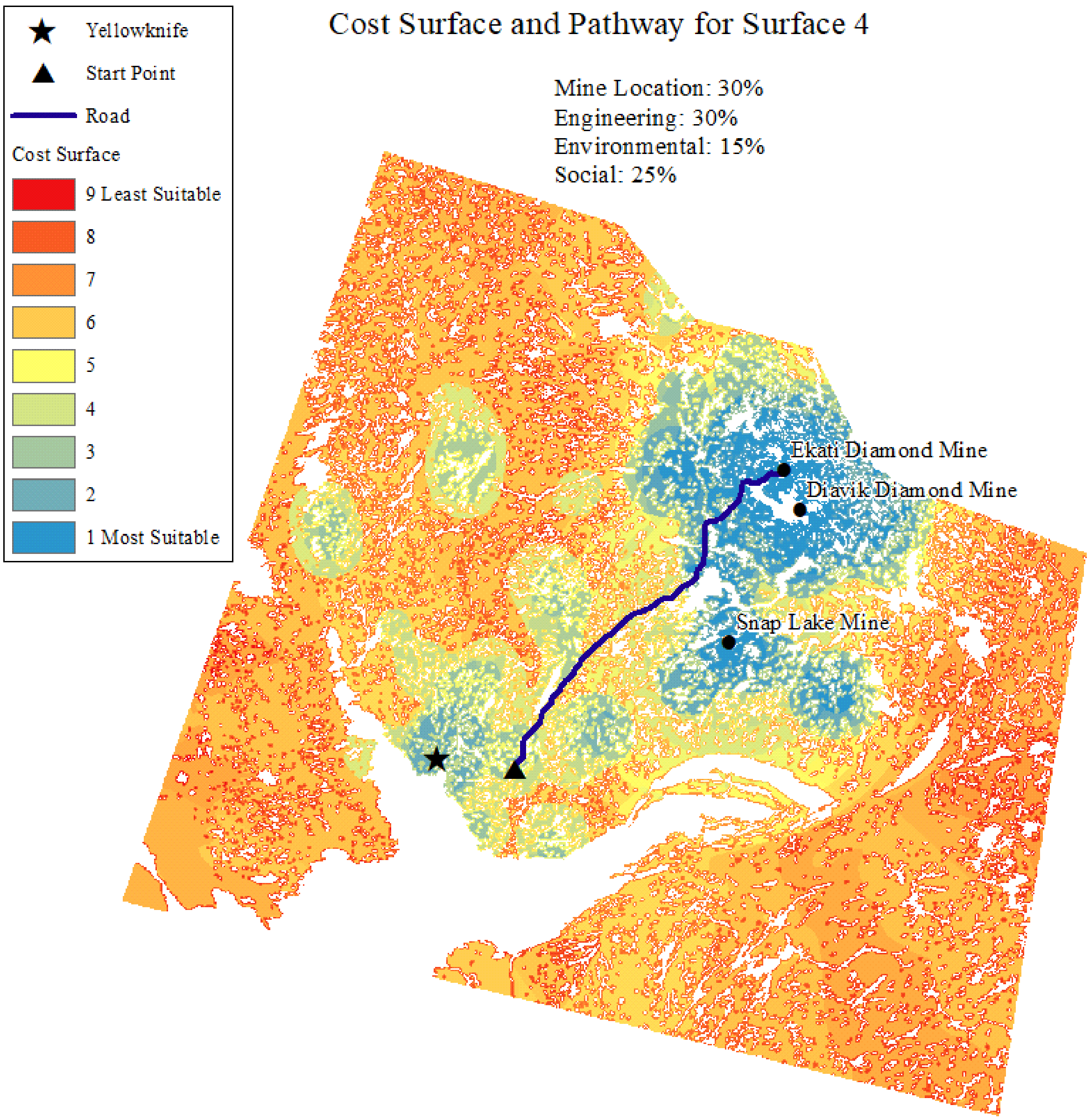
Cost surface and pathway for surface 2



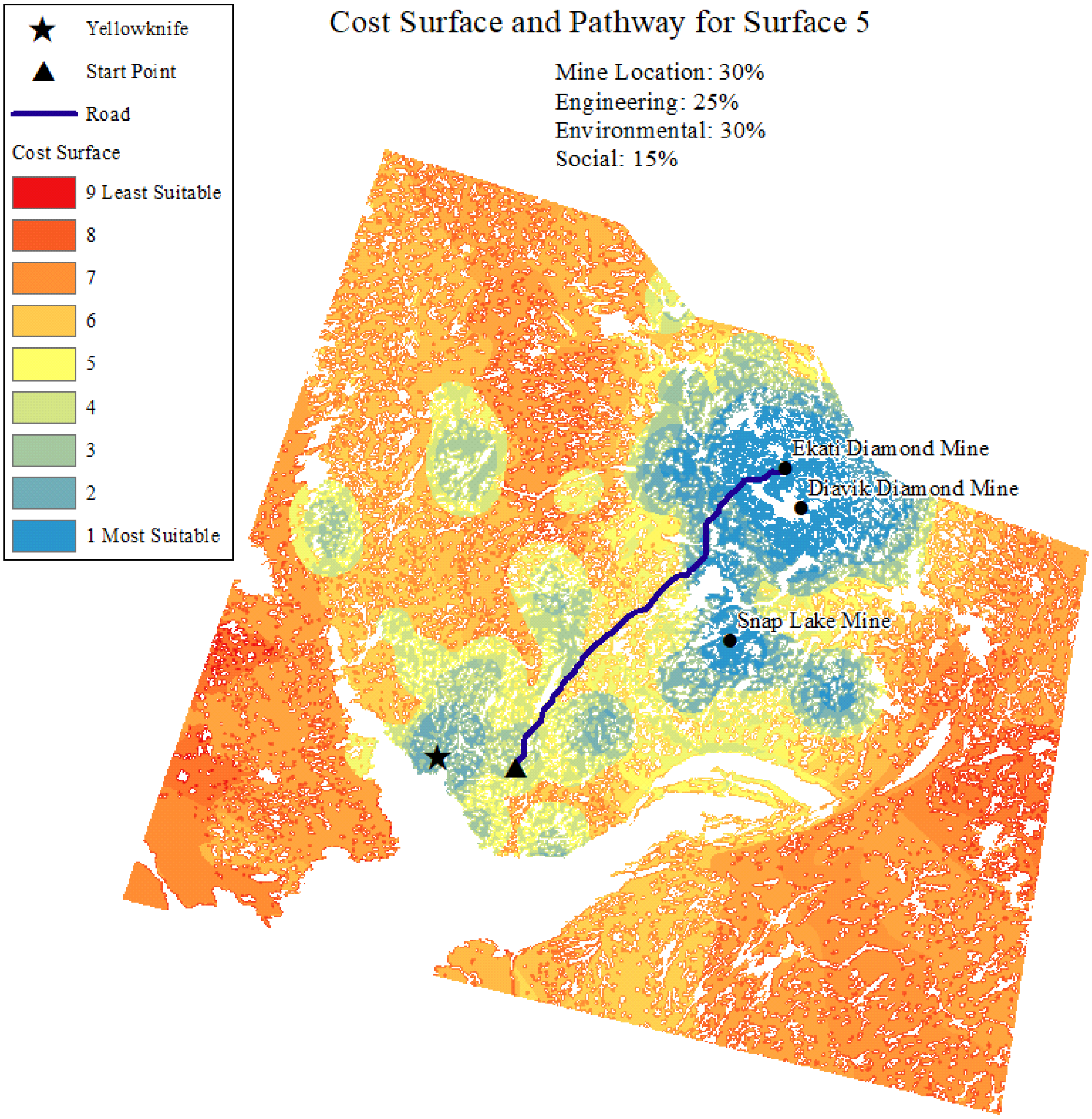
Cost surface and pathway for surface 3



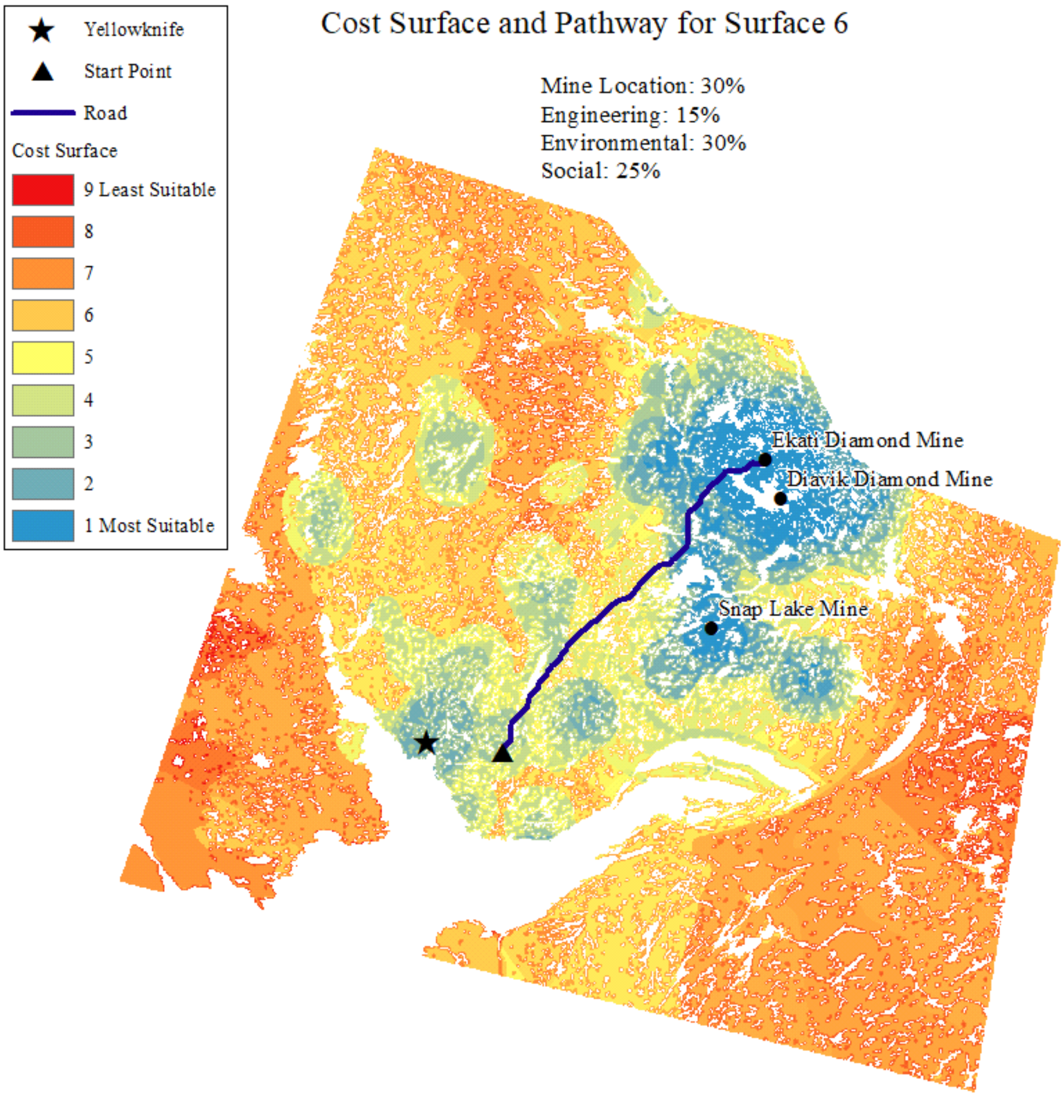
Cost surface and pathway for surface 4



Cost surface and pathway for surface 5



Cost surface and pathway for surface 6



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