Vulnerability Assessment and Capacity Scan of Alberta's Provincial Highway Network

by

Kasturi Mahajan

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Department of Civil and Environmental Engineering
University of Alberta

Abstract

Extreme events can have serious consequences, ranging from economic losses to loss of life. Past natural disaster events have shown that highway networks are critical to transporting people from danger, but are also not immune to direct disruption and damage by these events. This is certainly true for the highway system in the province of Alberta, Canada, which is sparsely serviced and prone to wildfires and floods. It is critical for transportation authorities to understand which communities are likely to be susceptible during emergency events, as well as where transportation facility disruptions will have a greater impact on the overall network performance.

In this thesis, I have developed and/or calculated several topological and network scanning measures to assess the performance of provincial highway system in northeastern Alberta under emergencies. The measures provide insights about the transportation network topology and locations of communities (within the network) with respect to their vulnerability to extreme events, as well as the network's capabilities to respond (i.e. transport people to safety) during these events. The measures are based on vulnerability and robustness, well-accepted definitions in the literature for network performance assessment. In the context of this work, vulnerability is defined as inability of the transportation network to perform its intended function during emergencies. The function of transportation network during emergencies is transporting individuals to a safe location where basic and emergency services may be available. The measures based on vulnerability identify susceptible communities based on their location in the network (connectivity) such that they may be distant from all services in the province. Robustness is defined as defined as the ability of the transportation system to maintain capacity and connectivity in face of threats. The measures based on robustness determine system's connectivity and reduction in capacity for multiple link removal.

I constructed a representation of the network and communities, as well as a grid-based network scanning method to implement the proposed measures. The results of the vulnerability measures indicate that communities in the Regional Municipality of Wood Buffalo are highly susceptible to network disruptions and natural disasters, given that relatively significant populations are located quite far from designated emergency service centers, and served by a very limited transportation network. The measures also suggest that some communities may have difficulty evacuating during an emergency because of a high ratio of population versus immediate exits. The results can provide guidance on where (along the network) placement of interim emergency supplies may be beneficial, as well as identify key aerodromes/airstrips that are well-located to provide alternate transport means during network disruptions.

The results of robustness measures identify sections of provincial highways that, if disrupted, will result in significant capacity reductions for larger population evacuating to Edmonton (the key service center when evacuating from northeastern Alberta). The capacity scanning measure also identifies isolating links in the study area – network facilities that, if disrupted, isolate entire communities.

The findings of this work can be useful to provincial emergency planners in strategically placing emergency services and alternate transport modes for multi-modal evacuations. The proposed measures assess the performance of the transportation network under emergencies i.e. identify communities and highways susceptible to emergency events and disruptions, and hence may be useful in considering locations for future infrastructure investments.

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Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

1.1 Background

Both natural and human-caused extreme emergency events such as earthquakes, hurricanes, floods, wildfires, and acts of terror can result in a significant economic loss, environmental damage, injuries, and in extreme cases, loss of life. The province of Alberta has not been spared from such events. The 2011 Slave Lake Wildfire, 2013 Southern Alberta floods, 2016 Fort McMurray Wildfire, and 2017 Kenow Wildfire caused significant damage to property, infrastructure, and the environment, and also prompting evacuations. The 2016 Fort McMurray wildfire resulted in the largest evacuation in Alberta history with 88,000 people evacuated. It was also the costliest disaster in Canadian history to date, at an estimated insured cost of 8.86 billion dollars (Snowdon 2016). Furthermore, large-scale evacuations place enormous demands onto the long-distance transportation network over a very short time period.

1.2 Motivation and Research Question

Understanding characteristics of the transportation network – particularly, quantifying features that pertain to how the network may perform under evacuation demands – is important for transportation engineers, planners, and emergency management specialists. With increasing frequencies of extreme natural events throughout the world, the literature on this subject has grown rapidly over the past decade. Alberta, although relatively sparsely populated, has isolated pockets of large populations in boreal forest due to its natural resource based economy. Due to the heightened risk of wildfires, emergency preparedness in Alberta is critical. The existing emergency management plans in Alberta only outlines roles and responsibilities for response and considerations for planning during emergencies and disasters. However, they do not consider (describe) tools or measures to assess the emergency and evacuation-related characteristics of Alberta transportation network. Considering these issues, this research work investigates which communities may face challenges evacuating and accessing services and disruption of which highways will result in operational degradation for the transportation network, in Alberta, during emergencies and disruptive events.

1.3 Objectives and Tasks

The specific objectives of this work are:

i. Vulnerability assessment of communities: To develop quantitative measures that identify vulnerable communities in northeastern Alberta during emergencies. Vulnerability of communities is measured based on how easily they can access emergency services based on their locations and how easily a population is able to evacuate from their community when it is under threat.
ii. Highway capacity and routing scan: To develop a network scanning framework that determines network degradations, i.e. reduction in highway network connectivity and capacity in event of disruptions. These measures identify highway links that result in high capacity reductions if compromised.

To attain the first objective, six measures based on the definition of vulnerability that primarily focus on network topology and community population, to identify critical communities are proposed. Vulnerability is defined as inability of the transportation network to perform its intended function during emergencies. The function of transportation network during emergencies is transporting individuals to a safe location where basic and emergency services may be available. For the second objective, a measure that focuses on highway capacity scans to identify critical transportation network facilities, founded on the definition of robustness, is proposed. Robustness is defined as the ability of the transportation system to remain connected and maintain capacity in face of threats.

I constructed a network model of the provincial highways (represented as links) and communities (represented as centroids) to implement the measures. Figure 1-1 shows the northeastern quadrant of Alberta and the Regional Municipality of Wood Buffalo that served as the two geographical test areas (each for a particular set of measures) for this research. The northeastern quadrant of Alberta is unique in that the transportation network (including the provincial highway network) is extremely sparse, yet also contains a very large urban center (with population of 66,573). A sparse network combined with a highly concentrated population like Fort McMurray, particularly in an area covered largely by boreal forest, is cause for concern in terms of emergency management.

This issue became evident during the 2016 Fort McMurray Wildfire (Woo et al. 2017). Hence, I have focused on Alberta's northeast quadrant and the RMWB for this study.

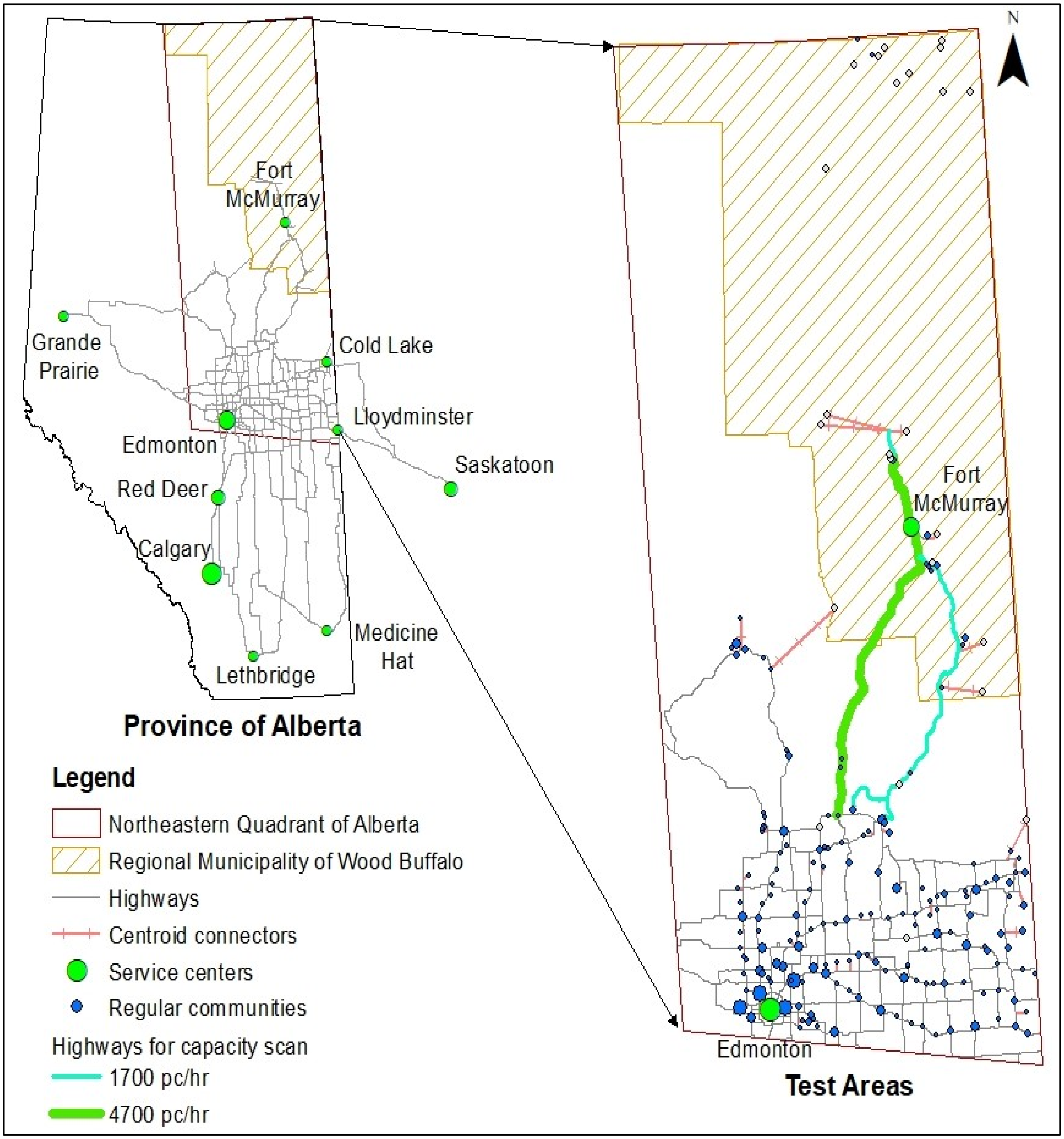

Figure 1-1 Northeastern section of Alberta (study area)

This work contributes to the existing literature on vulnerability assessment of transportation networks under emergencies and in development of evacuations plans and policies by proposing measures to assess emergency characteristics of the highway network and applying them to the provincial network of Alberta. This work may provide guidance on where placement of interim emergency supplies may be beneficial, and identify aerodromes/airstrips that may acts as alternate transport modes during network disruptions and emergencies.

1.4 Thesis Outline

Chapter 2 of this thesis provides background information on emergency management planning in Alberta and a review of the literature on network performance assessment under emergencies and disruptions. Chapter 3 introduces the sources of data and discusses the composition of the network model of northeastern Alberta, including the types of nodes and links used to construct the model. Chapter 4 introduces the performance measures and discusses their results. Finally, Chapter 5 presents the conclusions of this study and a discussion of future work.

Chapter 2
Background and Literature Review

This chapter covers transportation planning for emergencies in Alberta, as well as the literature on transportation network performance assessment for emergencies and evacuations. I first introduce background on disaster and emergency management planning in Alberta, next, provide definitions of key terms in the literature and then introduce network performance measures under three categories (topological, operational, and accessibility-based).

2.1 Emergency and Disaster Management Guidelines in Alberta

The Government of Alberta has prepared emergency plans that are regulated by subject matter expert departments (ministries) that are responsible for prevention, preparedness and recovery from disasters and emergencies, within the government. The Alberta Emergency Management Agency (AEMA), a separate department within the Government of Alberta, is responsible for coordination between these subject matter expert departments for emergency planning and management. The Community and Evacuation Guideline and Planning Considerations (May 2018), by the Government of Alberta, is the only document that outlines some emergency planning considerations with respect to transportation planning in Alberta (Alberta Government 2018). This document outlines points that must be considered by the local municipalities when developing their evacuation plans. According to this document, the local evacuation plans must:

- Determine areas/facilities that could be at risk from specific hazard, the probability of occurrence and the consequences of the hazard.
- Identify evacuation destination and resources required to reach the destinations, from the areas/facilities that are at risk, during emergencies.
- Identify travel routes and traffic control equipment in coordination with Alberta Transportation (Ministry of Transportation in Alberta), that will be used during evacuations.

This document also mentions consideration of alternative modes for evacuation especially for localities with single or limited routes, however, in terms of guidelines only covers evacuations by road.

In addition, Alberta Transportation (the ministry of transportation in Alberta) prepared the Emergency Operations and Disaster Plan (May 2017) that outlines the roles and responsibilities within the emergency management system and the ministry of transportation (Alberta Transportation 2017). This document only defines framework for decision making during disasters and coordination with departments within the government to mitigate these disasters. It is more about response to emergencies than strategic emergency planning.

These documents only highlight the considerations for emergency planning, however, do not provide any measures or tools to implement these considerations.

2.2 Definitions

In the context of emergency preparedness, transportation systems are assessed with respect to their vulnerability and robustness to disruptive events, and flexibility and resilience in response to these events (Faturechi and Miller-Hooks 2014b). There are many definitions of these terms within the literature; I will cover those most prevalently used.

Vulnerability can be defined as a system's susceptibility to disruptive events, measured by its ability (or inability) to perform intended functions with satisfactory performance when impacted by such events (Berdica 2002). However, it does not consider the probability of disaster (risk) (Jenelius, Petersen, and Mattsson 2006). Measures of vulnerability estimate the severity of consequences of a disruption irrespective of its probability of occurrence (Mattsson and Jenelius 2015). Owing to its importance, various theories are developed for the quantification of network vulnerability and are applied to the large-scale transportation network (Taylor and Susilawati 2012).

Flexibility can be defined as the ability of a system to recover from, or absorb, the effects of a disruptive event, regardless of how much its performance during the event degrades (Faturechi and Miller-Hooks 2014b, 2014a). On the other hand, robustness measures how well (at some predetermined level of functionality considered acceptable) a system continues to operate during a disruption (Faturechi and Miller-Hooks 2014b). Robustness focuses on system strength with respect to remaining functionality during disruption, rather than the loss due to, or recovery from (Jenelius et al. 2006). Researchers have often used robustness, instead of flexibility, to measure transportation network performance under disruption (Sullivan, Aultman-Hall, and Novak 2009).

Resilience definitions overlap with those of flexibility and robustness. Resilience is defined as a system's ability to resist and absorb the impact of disruptions (Bruneau et al. 2003). Resilience measures cover a system's operational performance during disruption, as well as the system's ability to restore itself back to normal (or close to normal) operations. A robustness assessment focuses only on the network's performance in the event of highway disruptions without considering the recovery aspect. Unlike robustness, the network resilience accounts for the performance during the disruption and recovery after the disruption (Zhang et al. 2018). The network performance can be assessed using any one or combinations of the above assessment methods.

2.3 Performance Measures

2.3.1 Topological Measures

Network topology is an abstract representation of transportation system as a network of nodes and links (Zhang, Miller-Hooks, and Denny 2015). Topological measures have roots in graph theory and are used to describe networks based on the relative locations of nodes and links, and their interconnections. These measures do not consider how the network is used (i.e. its operations) (Faturechi and Miller-Hooks 2014b), and are therefore basic network descriptors. Measures such as degree, betweenness, and closeness are some typical measures that fall under this category and are also used in this research. Degree is defined as number of links attached to a node (Sun et al. 2018). Betweenness measures the extent to which a node lies on paths between other nodes. Closeness measures proximity a node is to all other nodes (Yin et al. 2018).

Sun et al. (2018) studied the impact of an intentional attack on nodes with high degree (highest number of links attached) and betweenness (frequently traversed nodes) in an urban rail network. The authors demonstrated that targeted removal of high degree or betweenness nodes is more impactful than random node removal. Recently, topological measures have also been applied to assess the vulnerability of public transit networks (Cats and Jenelius 2018; Gai, Du, and Deng 2018; Zhang et al. 2018). Yin et al. (2018) studied the relationship between road centrality (measure of how pivotal a road is) and land use patterns using topological measures (Yin et al. 2018). In another study, Sun et al. (2014) conducted a topological analysis of the air transportation system of Germany and employed betweenness to measure the performance of the network and identify nodes with maximum number of shortest paths passing through them. According to the study results, nodes with high betweenness are used by more flights and are operating at or near the capacity and disruption of these will result in susceptibility of entire transportation network.

2.3.2 Operational Measures

Operational (or system-based) measures focus on the performance of a transportation system with respect to travel time, travel distance, flow, and/or capacity, allowing for more complete operational assessment of the consequences of disruption, as the impact on network users is considered. Some of the operational measures are based on the results of demand-supply interactions (output from travel demand models). Zhang et al. (2015) utilized measures based on flow and network connectivity to quantify transportation network's ability to resist and absorb the impact of disruptions (resilience of the networks). Jenelius et al. (2006) define link importance and regional vulnerability to network failures based on the increase in travel time after a link disruption. The increase in travel time describes the inability of transportation system to perform intended function with satisfactory performance. Scott et al. (2006) identify and rank critical network links based on user equilibrium travel time increases caused by link closures.

In the work by Adams, Bekkem, and Toledo-Durán (2012), resilience of the interstate corridor from Hudson to Beloit, Wisconsin, US is measured by plotting sampled truck speeds and counts against duration of the event. They measure resilience of the network based on its degradation and recovery time. Cox, Prager, and Rose (2011) compared passenger kilometre travelled by the attacked mode and the substitute mode to measure resilience of the overall transportation system. An increase passenger kilometre travelled by the substitute mode after disruption implies network operation restored back to normal and thus resiliency of the overall system. El-Rashidy and Grant-Muller (2014) applied linear regression to establish a relation between the increase in total travel time after a link closure and attributes such as flow, link length, free-flow speed and congestion density for the road network of Delft, Netherlands. They developed a single vulnerability index that takes into account all the attributes together to study their effect on network performance (i.e. increase in travel time). They achieved a high correlation between the vulnerability index and the total travel time with a R^2 of 0.91.

Researchers have also developed reliability measures that describe probability of the network performing its function under given operating conditions. Connectivity reliability is the probability that a connection between node pairs exists even when one or more links are removed. The connectivity reliability can be seen as a binary problem (either the network is connected or it is not) and hence has limited application to test the connectivity of network in everyday situations but may be applicable for abnormal situations such as earthquakes (Al-Deek and Emam 2006). Travel time reliability is the probability of a trip completion within specific period of time (Clark and Watling 2005). The travel time reliability is the function of fluctuating link flows and driver's route choice (Lam and Xu 2000). Measures of travel time reliability can be helpful in determining quality of service provided to network users (Yang, H. K., and Tang 2000). Capacity reliability is the probability that a network can accommodate specific levels of demand (Chen et al. 2002). Researches indicate that capacity reliability together with travel time reliability can be useful in planning traffic management schemes for urban area (Taylor 2000; Yang et al. 2000).

Some studies employ mathematical modeling and optimization to assess network vulnerability (system's susceptibility to disruptive events). He and Liu (2012) modeled the day-to-day traffic evolution for a disrupted network based on the empirically observed data (actual traffic flows) obtained for the 2007 collapse of I-35W Mississippi River Bridge in Minneapolis, Minnesota. They found that existing traffic assignment models may not be suitable for modeling traffic evolution under network disruption as they are based on drivers past perception of travel cost. A disruptive event could change the network operation significantly and hence driver's perception of travel cost based on past experience may not be as useful. To solve this problem, they developed a model that predicts flow patterns and corrects the perception of travel cost based on actual traffic volumes.

Chen and Miller-Hooks (2012) used a stochastic mixed-integer program to measure network resilience and identify post-disaster actions for inter-modal freight networks. Their mathematical formulation determined the optimal recovery activities (cost, time and efforts) such that the network resilience is maximised subject to budget constraints. Zhang et al. (2015) present measuring network resilience as an optimization problem. They measure resilience of the network with respect to flow that can be accommodated, connectivity between origin-destination pairs and average reciprocal distance between all origin-destination pairs, pre and post-disaster. They formulated each of these resilience measures as a two-stage stochastic program with first stage as the disaster preparedness and second stage as disaster recovery.

2.3.3 Accessibility Based Measures

The ease of community population to reach services during emergency defines its accessibility. Taylor et al. (2006) assess vulnerability in road networks by considering the impacts of accessibility reduction on communities to reach various service centers due to network degradations (they measured road network vulnerability in terms of accessibility reduction due to its degradations). In their work, service centers are categorised based on population, which represents the availability of public and private sector facilities in each service center. Sohn (2006) applied the accessibility measures to identify critical links based on reductions in accessibility for flood damages in Maryland, US. Taylor and Susilawati (2012) developed a remoteness index for rural areas, quantifying the extent of community isolation and the transportation network's contribution to this isolation. Lu and Peng (2011) developed accessibility based measures to identify vulnerable regions in South Miami, Florida under scenarios of sea level rise. Balijepalli and Oppong (2014) developed an index to measure serviceability of critical roads (based on accessibility) for the dense urban road network of York, England. Based on its results, they also developed a traffic diversion plan for flooding in York. Alasia et al. (2017), at Statistics Canada, developed a remoteness index for Canadian communities based on how many cities and towns with selected services are located within a given radius of a community, the sizes of these proximate service centers and the travel cost to these service centers. They classified the service centers based on health, legal, financial and retail services.

2.4 Simulating and Measuring Network Disruptions

Various network modeling techniques are used by researchers to study the impacts of network degradations (Jenelius and Mattsson 2012; Jenelius et al. 2006; Erath et al. 2009). The studies based on these modeling techniques are differentiated based on the number of highway links disrupted. Most studies for performance assessment of transportation network under disruption are based on single link failure or scenario specific number of links removal (Erath et al. 2009; Sohn 2006). Alternately, Jenelius et al. modeled random area disruptions that cause failures on links within the area disrupted (rather than pre-specified scenarios involving certain link groups) (Jenelius and Mattsson 2012; Jenelius et al. 2006). The authors proposed an approach where disrupted areas are identified by grid cells. All roadway links located within a disrupted grid are assumed to be closed for some (pre-specified) period. Grid cells are determined to be most critical when their closures result in a significant increase in total travel time through the network (Jenelius and Mattsson 2012). The grid-based approach allows for a complete, uniform assessment of disruptions over an entire network.

An important consideration in studies of performance of network under disruptions, specifically when considering re-routing and alternate routes, is isolating links. An isolating link is defined as the sole connection between one subset of a network to the rest, where its disruption leads to isolation of the subset (Erath et al. 2009; Jenelius et al. 2006; Sullivan et al. 2010, 2009). It can be challenging to measure the impacts of an isolating link failure on network performance, because this failure leads to two independently functioning sub-networks.

Jenelius et al. (2006) reported that the calculation of the increase in travel cost (travel time) is not applicable when isolated sub-networks due to a link disruption are formed. In their case, travel cost between two nodes in different sub-networks became infinite. To obtain the finite and reasonable value of travel cost, they introduced the concept of 'unsatisfied demand,' which identifies the trip that cannot be completed by reaching the destination as a result of isolation. They used two separate measures, one measured increase in travel cost for non-isolating links and second measured the unsatisfied demand for the isolating links. Erath et al. (2009) developed a measure based on the economic evaluation of increase in travel time and distance as a result of traffic re-routing. However, they did not consider the isolating links while calculating the measure and only checked the presence of bypasses around the isolating links. Researchers have yet to quantify the effects of isolation on trips that originate or are destined for locations within an isolated sub-network. In actual cases of such events, other transportation modes such as air or marine have been used (Boone 2018; Woo et al. 2017); these are overlapping/parallel transportation networks not considered as part of the original network.

2.5 Summary

The existing emergency plans for Alberta Transportation network only outline considerations for emergency planning and management. Measures and tools to assess the performance of transportation network under emergencies and disruptions have not been applied in Alberta.

Different categories for the performance assessment measures for networks under emergencies and disruptions exist in the literature. In this review, I focused on performance measures under three categories: topological, operational and accessibility-based, because of their relevance to the research work in this thesis. The topological performance measures are based on the relative locations of nodes and links in the network, while the operational measures focus on network performance with respect to travel time, distance, flow, and capacity. The accessibility-based measures describe the ease with which communities can reach services during emergencies. The topological and accessibility measures proposed in this thesis, identify communities susceptible to disruptive events based on their location within the network. Some of the proposed accessibility measures, are based on node-link interconnections but additionally consider the community population. The proposed network scanning measure identifies highway facilities whose disruption affects network connectivity and reduces overall capacity for communities in the study area and thus describe qualities of the highway links (similar to operational measures described in Section 2.3.3).

The performance measures proposed in this thesis address the definitions of vulnerability and robustness given in Section 2.2. Vulnerability is defined as a system's ability (or inability) to perform intended functions with satisfactory performance during disruptive event. In the context of this research, we define vulnerability as inability of the transportation network to perform its intended function of transporting individuals to a safe location where basic and emergency services may be available. Also, robustness is generally defined as the ability of the transportation system to continue operation and maintain some functionality in face of threats. However, in this thesis, I define robustness as the ability of the transportation system to maintain connectivity and capacity under disruptions, meaning if disruption of certain highways results in a significant capacity reduction or isolation of communities then the network is deemed to be less robust to such disruptions.

Most studies in the literature assess the performance of the transportation network under single link disruption or scenario specific link disruption. In this work, a grid-based approach similar to that proposed by Jenelius and Mattsson (2012) is applied in which multiple links covering areas an area are disrupted and scans for the network for total capacity reduction are performed. The scans of the network identify critical links that, if disrupted, lead to a significant or total highway capacity reduction for certain communities. It also addresses the problem of identifying isolating links and measuring the impacts due to their disruption. Isolation links are network facilities that, if disrupted, isolate entire communities.

This research adds to the existing literature on performance assessment of transportation networks under degradations and disruptions by proposing measures to ascertain the characteristics of transportation network under emergencies. Based on application to Alberta Transportation network, outcomes of this study act as an evidence-based support for planning the usage of highway network under emergencies and disasters. The outcomes of the proposed measures can be useful for emergency management specialists and agencies to strategically allocate resources to prepare and plan for emergency and disaster events.

Chapter 3
Network Model Building

This chapter describes the construction of the highway network model of northeastern Alberta using data collected from various sources, to which measures of performance assessment are applied.

3.1 Data Collection

The transportation network model of northeastern Alberta was represented using set of nodes and links. The network model consists of communities, provincial highways and highway intersections. Community data consists of community location (coordinates), extent (boundaries), name, type (city, town, etc.) and population. The highway data includes length, location (coordinates), coordinates of junctions along the highway, highway speeds and capacities. I gathered this data from various sources and used it to build the network model of northeastern Alberta.

3.1.1 Communities

Alberta Municipal Affairs has categorized communities in Alberta as hamlets, summer villages, villages, towns, cities and Indian Reserves (Alberta Municipal Affairs 2017). The hamlets, summer villages, villages, towns, and cities are distinguished based on population and total area coverage of a community, while Indian Reserves (as they are officially referred to by Statistics Canada) are distinguished based on the total area coverage. Detailed definitions for each these community types are as follows:

- Hamlet: An unincorporated community within the boundaries of a municipal district or specialized municipality. A community can be a hamlet if it consists of five or more dwellings and has a generally accepted boundary and name (Alberta Municipal Affairs 2017).
- Summer village: An incorporated community that generally has a permanent population less than 300 inhabitants and has seasonal (non-permanent) inhabitants (Alberta Municipal Affairs 2017).
- Village: A community of at least 300 inhabitants (Alberta Municipal Affairs 2017).

- Town: It has a minimum population of 1,000 and may exceed 10,000 unless it requests a change to city status (Alberta Municipal Affairs 2017).
- City: A highest form of incorporated urban municipality with a minimum population of 10,000 (Alberta Municipal Affairs 2017).
- Indian Reserve: A reserve is not governed by a municipality but is federally regulated (i.e. the federal government has exclusive legislative authority for reserves). It may vary in size from 441 ha to 143,532 ha (Alberta Municipal Affairs 2017).

I obtained the geographic locations of communities and their boundaries from AltaLIS, a private source for base mapping data for Alberta (AltaLIS 2017). Though this data is provided by a private company, it is publically available online. In this dataset, municipal boundaries for all communities (except hamlets) are represented as polygons; hamlets are represented as nodes. I converted the communities that are represented as polygons into nodes using ArcMap. The final network representation consisted of all communities represented as nodes.

3.1.2 Population Data

I obtained population data for each community from Geosuite, a Statistics Canada tool (Statistics Canada 2016). Geosuite contains populations from the 2016 census for all standard units of geography. I obtained the data for census dissemination areas, the lowest level of disaggregation in the hierarchy of standard geographic units used by Statistics Canada (Statistics Canada 2015). I calculated a community's population by summing the populations of all census dissemination areas within the community municipal boundary.

3.1.3 Provincial Highway System

I limited the transportation network model representation to provincial highway facilities only, and did not consider local and winter roads. For interregional (i.e. long distance) travel during emergencies, travel is overwhelmingly provided via the provincial highway system (Scott et al. 2006). The data on the provincial highway system was obtained from Alberta Transportation's GIS section. In this dataset, a single highway is represented as several small segments; I then merged these segments to create a single highway link between two intersections. The length of each highway link between two intersections was calculated using ArcMap. Because I only considered provincial highways, northern communities connected by only winter roads were designated as disconnected (i.e. isolated from the network).

3.2 Transportation Network Representation

I constructed a network representation of northeastern Alberta using the data described in Section 3.1. Communities are represented using centroids. The nodes in the network represent intersections while the links represent the provincial highways.

3.2.1 Nodes

I classified nodes into three types, which are described in further detail below. Because community population generators technically are not considered nodes, they are included in this list (for organization purposes) but labeled distinctly as community centroids. An example of node types in the Regional Municipality of Wood Buffalo (RMWB) is shown in Figure 3-1. This figure only shows RMWB to present a clear example of the network representation. However, node types in the entire network model for northeastern Alberta are shown in Appendix A.

3.2.1.1 Type 1 Community Centroids

For the purpose of network representation, a community population is aggregated and represented as a centroid. Community centroids located at an offset from the highway network, are connected to the highway network using centroid connector links (dummy links). For example, community centroid of Fort McMurray is located at an offset from Highway 63 link and is connected to Highway 63 using a centroid connector link (Figure 3-1).

3.2.1.2 Type 2 Centroid Connecting Node

This node type facilitates connection of community centroids to the provincial highway network. Therefore, one end of the centroid connector link is the community centroid and the other end is the centroid connecting node.

3.2.1.3 Type 3 Highway Node

Locations in the network where the highways intersect or branch are represented as highway nodes.

3.2.2 Links

I have classified links in the network as one of two types, which are introduced below. Link types in the RMWB are shown in Figure 3-1, while those for the entire northeastern Alberta network are contained in Appendix A.

3.2.2.1 Type 1 Centroid Connector

The link connecting a community centroid to the highway network is a centroid connector link. Since these do not represent true highway facilities, they are excluded when calculating the total distance (of the path) between an origin-destination pair. All centroid connector links are assigned a uniform length of 2,000 metres, so that it is easy to deduct this distance from the total path distance between all origin-destination pairs. I adopted this approach to maintain consistency with Alberta Transportation's provincial network model. As mentioned earlier, one end of the centroid connector link is a community centroid and other is a centroid connecting node.

3.2.2.2 Type 2 Highway Link

All other links (besides centroid connector links) represent the provincial highway system, and have lengths equal to the corresponding highway distance.

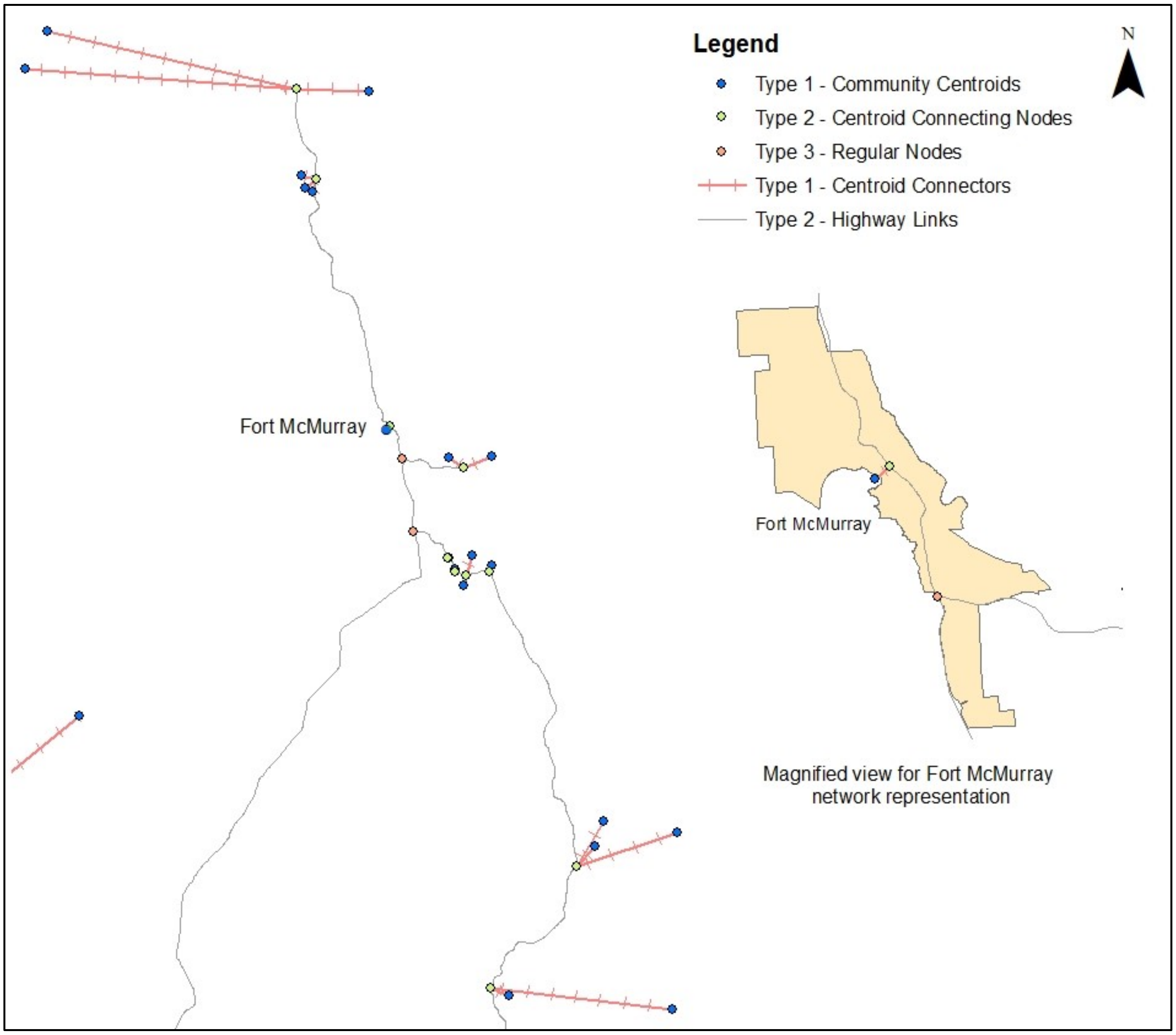

Figure 3-1 Network representation of northeastern Alberta

3.2.3 Network Graph

I prepared the 'EdgeTable' (ET) and 'NodeTable' (NT) in MATLAB (Figure 3-2). The EdgeTable contains information about the links such as link end nodes, weights (link lengths), types and unique IDs assigned to each link. The NodeTable contains node X co-ordinates (longitudes), Y co-ordinates (latitudes), types and again unique IDs assigned to each node. A graph G of the network was then made using the EdgeTable and the NodeTable. G is the undirected graph with direction-less links connecting nodes in the network. In an undirected graph, link directions are not specified such that an edge can be traversed in both directions.

EdgeTable

733x4 table

	1 EndNodes		2 Weight	3 Type	4 ID
1	28	31	1.4099e+04	0	1
2	31	35	1.3736e+05	0	2
3	52	54	3.6147e+05	0	3
4	50	52	4.0570e+04	0	4
5	40	50	6.6178e+04	0	5
6	28	17	1.5412e+05	0	6
7	35	40	8.4037e+03	0	7
8	35	37	1.2040e+04	0	8
9	40	37	1.9584e+04	0	9
10	35	30	7.9012e+04	0	10
11	31	30	1.8951e+05	0	11
12	17	19	2.7338e+05	0	12
13	17	11	1.8747e+05	0	13
14	37	36	1.6745e+05	0	14
15	9	11	1.3514e+05	0	15

(a) EdgeTable (ET)

NodeTable

600x4 table

	1 X	2 Y	3 Type	4 ID
1	2.5680e+05	6.1180e+06	1	1
2	3.0746e+05	6.1203e+06	0	2
3	4.8405e+05	5.9818e+06	0	3
4	5.0504e+05	5.9697e+06	0	4
5	5.1500e+05	6.1220e+06	0	5
6	5.4951e+05	5.9498e+06	0	6
7	5.5440e+05	5.9498e+06	0	7
8	5.5542e+05	6.0000e+06	0	8
9	5.6816e+05	5.6555e+06	1	9
10	5.7471e+05	6.0197e+06	0	10
11	5.8038e+05	5.7853e+06	1	11
12	5.8435e+05	5.9082e+06	0	12
13	5.9062e+05	5.8213e+06	0	13
14	5.9233e+05	6.0758e+06	1	14
15	5.9576e+05	5.9003e+06	0	15

(b) NodeTable (NT)

Figure 3-2 (a) EdgeTable (ET) and (b) NodeTable (NT) for MATLAB Graph

3.2.4 Gridding

I overlaid the study network (in RMWB) with a grid of 12 km × 12 km in ArcMap to model disruptions as per Section 4.2. The minimum distance from a community (in our case, Saprae Creek) to the highway network (Highway 63) in the study area is 12 km; hence, I chose a 12 km × 12 km gridding to represent a worst-case scenario. Another reason I selected a 12 km × 12 km grid was because of the size and extent of the 2016 Fort McMurray Wildfire. The wildfire spread approximately 12-15 km on the first day, resulting in a mandatory evacuation for the community of Fort McMurray (largest community in this area). A "disrupted" grid represents the location of the disrupting event, and highway links located within a grid are associated to that grid. Each grid was "disrupted" individually– meaning, network links within a disrupted grid are assumed to be unusable.

3.3 Summary

A network model of northeastern Alberta was built using data gathered from sources listed above. I obtained the community data from AltaLIS and represented them as centroids (type 1). The link connecting a community centroid to the highway network is a centroid connector link (link type

1). The other end of the centroid connector link is a centroid connecting node (node type 2). Intersections in the network were represented type 3 nodes. The provincial highway data was obtained from Alberta Transportation's GIS section and the highways were represented as type 2 links. The scope of work in this thesis was limited to provincial highways, as long-distance travel during emergencies significantly depends on the provincial highways. A graph of the network was made in MATLAB using 'EdgeTable' and 'NodeTable' which contain information about links and nodes respectively. The measures described in Chapter 4 are applied to the graph of the network to evaluate the performance of the network during emergencies.

Chapter 4
Network Performance Measures

I developed a set of performance measures of vulnerability and robustness to apply to the study network. In some cases, I modified existing performance measures introduced and/or applied in other studies (Alasia et al. 2017; López et al. 2017; Taylor and Susilawati 2012). I will note three major points here. Firstly, I do not focus on assessing the performance of the network over time, meaning measures proposed in this thesis are static in nature. Secondly, the performance assessment framework is deterministic. Finally, the proposed performance assessment measures do not consider traffic dynamics but, rather, are meant to address considerations for strategic planning.

I proposed seven measures of network performance and categorized each measure as one of two types as shown in Figure 4-1: *i*) those characterizing/quantifying network vulnerability, defined as susceptibility or inability of the transportation network to perform its intended function (transporting individuals to safety and provision of access to services) and *ii*) those quantifying network robustness, defined as the ability of the transportation system to maintain connectivity and capacity in face of threats. In this thesis, the six network vulnerability measures identify vulnerable communities by location and population and also, describe basic network topological characteristics as related to vulnerability. The network robustness measure is populated using network scans for highway capacities; they identify capacity reductions that degrade the network's robustness. The measures are identified in Figure 4-1.

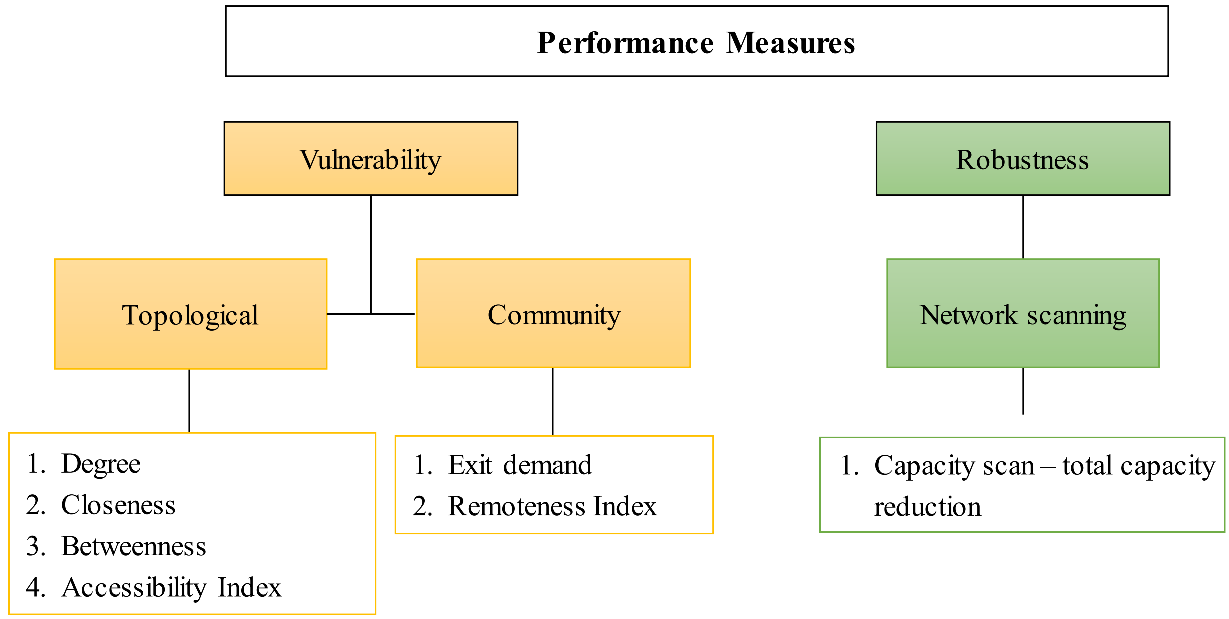

Figure 4-1 Classification of performance measures

4.1 Measures of Network Vulnerability

Vulnerability in this thesis is defined as the inability of the transportation network to perform its intended function during emergencies. The main function of the transportation network during emergencies is to transport individuals to a safe location where basic and emergency services are available. Using these measures, I measure how easily communities can access emergency services based on their locations, and how easily a population is able to evacuate from their community when it is under threat. The vulnerability measures are further categorized as topological and community measures as shown in Figure 4-1. Recently, topological measures have been used to assess the vulnerability of public transport networks, because these measures are relatively easy to understand and implement (Cats and Jenelius 2018; Gai et al. 2018; Zhang et al. 2018) The community measures consider populations in addition to the network topology serving communities, thus allowing for assessment of the consequences of disruption for these populations.

I used the following four measures, which are based only on basic topology, to assess network performance: 1. degree, 2. closeness, 3. betweenness, and 4. Accessibility Index. Next, I implemented the following two measures that consider basic topology as well as community populations: 1. exit demand, and 2. Remoteness Index. The value of a measure for each community was calculated and compared with those of other communities in the study area to identify relatively vulnerable communities.

4.1.1 Study Area

I implemented the topological measures for the entire northeastern quadrant of Alberta (north and east of Edmonton) (Figure 4-2). All communities represented in the network are considered as travel origins (i). Vulnerability of these communities to extreme events was assessed in terms of access to service centers, treated as destinations (j). Service centers are major cities within Alberta with population greater than 20,000. All major cities that could be service providers in the province during an emergency have a population greater than 20,000; hence this was set to be a threshold for the definition of a major service center. Services centers in the study area are: Edmonton, Calgary, Grande Prairie, Red Deer, Lethbridge, Medicine Hat, Cold Lake, Lloydminster, Fort McMurray (actually officially considered an urban service area), and Saskatoon. Saskatoon was included as a service center because it is the closest major city and well-connected using major highways to some communities on the Alberta-Saskatchewan border. In an emergency, it would be logical for some to actually travel to Saskatoon instead of a city within Alberta, because of its proximity and connectivity via major highways.

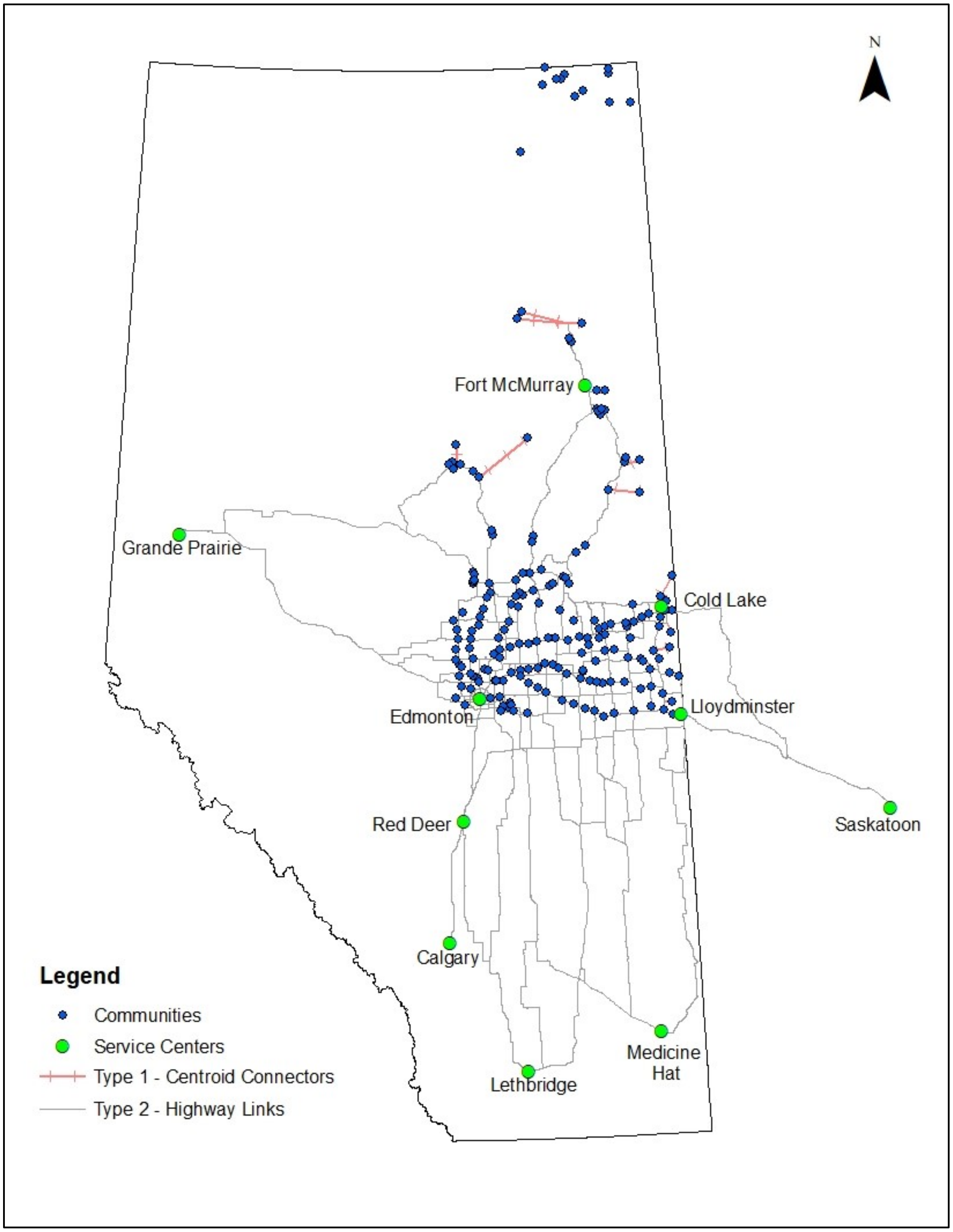

Figure 4-2 Study area for network vulnerability measures

4.1.2 Shortest Path Analysis

I assume that in an emergency, residents of a community i would travel to the service centers j using the shortest path (minimum distance path), represented as d_{ij} in the graph of the network G.

This assumption is reasonable given that the model only represents provincial highway facilities and thus, facilities with speed limits of 80 km/hr and higher (i.e. we are not considering, for instance, gravel roads with speed limits of 40 km/hr). If a community centroid does not have any path to a destination then d_{ij} takes a value of infinity (disconnected community centroid) (Mattsson and Jenelius 2015). I used Dijkstra's shortest path algorithm to perform the shortest path analysis for all communities in G. Dijkstra's shortest path algorithm finds the minimum cost path, among all paths, between an origin and destination by searching from the starting node and creating a shortest path tree to the destination node (Noto and Sato 2000). Of all nodes connected to a starting node, a minimum distance node is registered as part of the shortest path tree. This node is in turn set as the next starting node. This process continues until the destination node is reached and a shortest path tree is built.

4.1.3 Notations

I will use the following variables to define the topological measures introduced in Section 4.1.4 and community measures introduced in Section 4.1.5:

i	Origin community
k	Communities other than i
j	Service center
P	Set of communities in the network; $i, k \in P$
M	Total number of service centers j in network; $M = 10$.
L	Set of nodes in the network; $P, M \in L$
l	Any node other than i; $k, j \in l$; $l \in L$
n_{ij}^{k}	1 if shortest path between i and j passes through k; otherwise zero
n_{ij}	1 if community i and service center j are connected
a_{il}	1 if community node i and l are directly connected; otherwise zero
d_{ij}	Length of shortest path between community i and service center j
$\overline{d_{j\forall i}}$	Average of shortest path lengths to j from all i
p_i	Population of community i
p_j	Population of service center j

4.1.4 Topological Measures

I introduce each topological measure, and show the results after their application to the study network.

4.1.4.1 Degree

Degree (D_i) refers to the number of links directly connected to the node i (Sun et al. 2018). For the study network, I used the measure of degree to count the number of immediate exits (highways) out of a community.

$$D_i = \sum_{l=1}^{L} a_{il} \tag{1}$$

Figure 4-3 shows the results of the degree for all communities in the study area. A community with a higher degree indicates it is well-connected and can evacuate easily as compared to other communities in the study area. Several communities have a $D_i = 1$, which include Namur Lake Indian Reserves #174A, #174B, Fort Mackay Indian Reserve #174C, Saprae Creek, and Clearwater Indian Reserve. Nodes with degree two or more indicate that at least two directions of travel are available.

With $D_{FMM} = 2$, Fort McMurray residents can leave via Highway 63 southbound and northbound. However, Highway 63 northbound does not connect further into the highway network, to a service center destination. Highway 63 southbound is the only route to reach a service center (any city). Therefore, in this case, degree is not a true indication of evacuation routes available. To address this, the measure can be modified to consider the number of exits leading to service centers within a certain radius. Another limit to this measure is that population is not considered. With only one true exit (although $D_{FMM} = 2$,) efficient evacuation of Fort McMurray (66,573 in the 2016 census) proved problematic in May 2016. Fort McKay also has degree 2 but population of only 742; hence, evacuations of both Fort McMurray and Fort McKay would prove to be quite different from one another. Therefore, this measure is one that would need to be checked against other data (especially population) and measures to gain any valuable insights about potential evacuation scenarios. Considering population with degree, Fort McMurray is the only community that should be marked as critical within the study area.

It is also important to check degree at the other end of the only link connected to a node with degree 1 (degree 1 indicates the node has only one link attached to it). If the degree at the other end of the link is 2 or greater, as in case of Saprae Creek, then residents will have more routes available to them as they move away; if not, then we know that route choices remain limited (this is often the case in sparse networks).

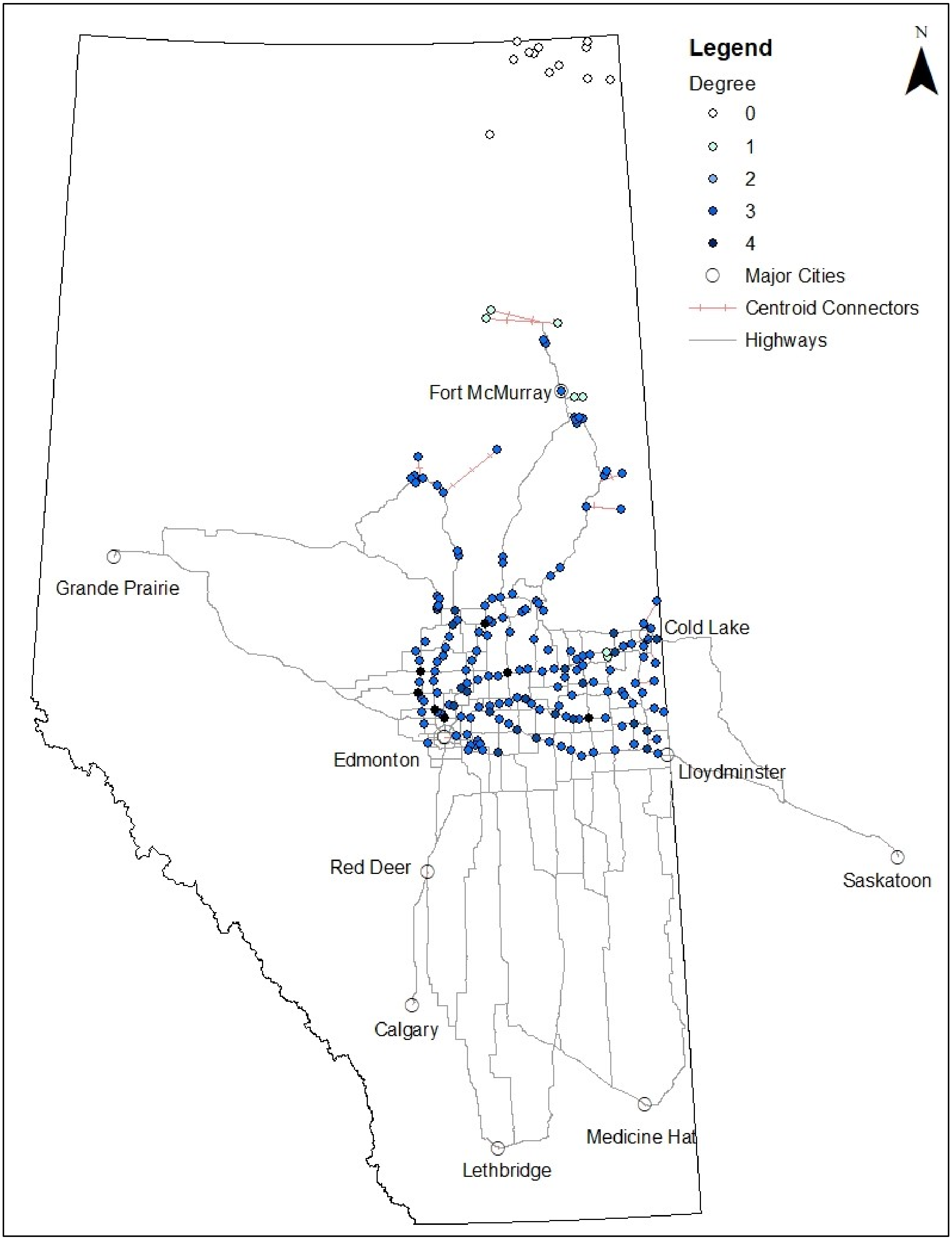

Figure 4-3 Degree results

4.1.4.2 Closeness

Closeness (C_i) is a measure of community's accessibility (community's ease of reaching) to services in the network. More specifically, it measures how close a node is to the service centers along the shortest path. The closeness of community i can be defined as follows (López et al. 2017):

$$C_i = 1 \Big/ \sum_{j=1}^{M} d_{ij} \tag{2}$$

Equation 2 implies that a community i will have a lower closeness value (C_i) if the sum of the distance to every service center is high. Communities with low closeness may be remote in terms of reasonable access to services during an emergency. The closeness result for each community are shown in Figure 4-4. The lowest (non-zero) closeness value is 1.11 (closeness values range from 1.11-2.81 for the study network) for the communities of Fort Mackay Indian Reserve #174C, Namur Lake Indian Reserve #174B and #174A due to their relatively remote locations to all the service centers (located in the center of the province in the Highway 2). Closeness values increase towards the center of the province with highest closeness value at 2.81 for Ardrossan.

Closeness is only based on the shortest path to the service centers, however, it does not consider connectivity and/or population (strength indicators) of the service centers. In order to account for true evacuation movements towards a service center based on its population and connectivity, I have proposed Accessibility Index in Section 4.1.4.4 and Remoteness Index in Section 4.1.5.2.

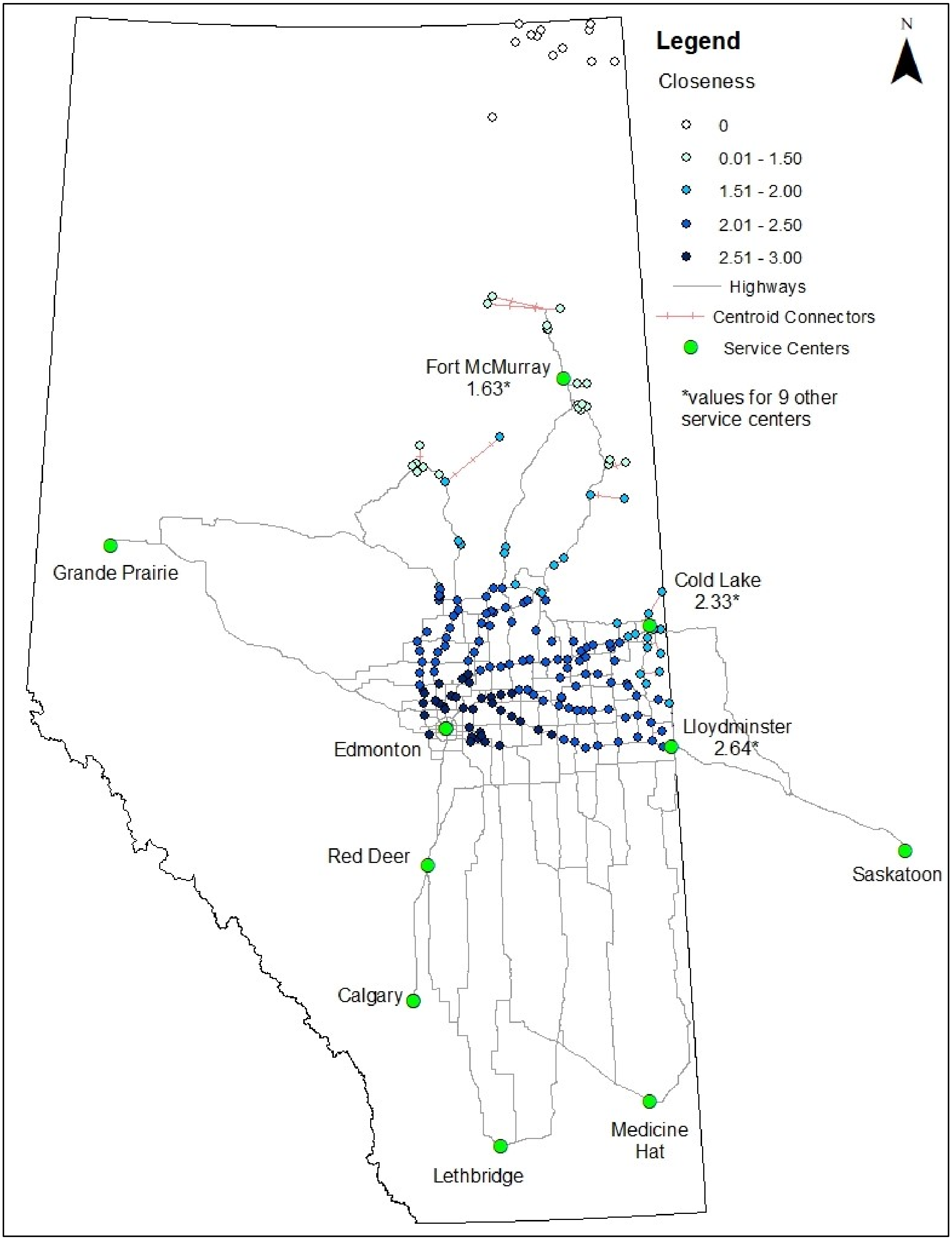

Figure 4-4 Closeness results

4.1.4.3 Betweenness

Betweenness (B_k) provides a count of how often a given community node (k) serves as an intermediate community between other communities (i) and service centers (j) (Li et al. 2017; Sun and Guan 2016). Betweenness is a commonly used measure in graph theory, typically used to identify critical nodes that, if removed, would significantly degrade the network. In this work, I adapt the concept of betweenness by "flipping" this perspective – using it to identify communities that are critically located, and are thus key locations for emergency services. Betweenness of community k is defines as:

$$B_k = \sum_{i}^{P} \sum_{j}^{M} n_{ij}^{k} \Big/ \sum_{i}^{P} \sum_{j}^{M} n_{ij}, \qquad k \neq i;\ i, k\ \in P \tag{3}$$

A community with a relatively high betweenness score is one that is located on routes between communities and service centers at a greater frequency, and therefore more likely to be traversed. In this study area (Figure 4-5), 23 (of 188) communities have a betweenness score of zero, indicating they are not located between any communities and service centers and therefore comprise the boundaries of the studied network. Communities with betweenness values from 0.06-0.10 are in the intermediate group (these comprise 23% of all communities). Communities with the highest betweenness scores (0.16-0.20) are mainly located along Highways 63, 28 and 16. Shortest paths from communities in the study area to service centers often fall on one of these three highways. The Town of Redwater and Hamlet of Opal each have the highest betweenness score of 0.20 among all communities in the study area, indicating they have the maximum number of shortest paths passing through them.

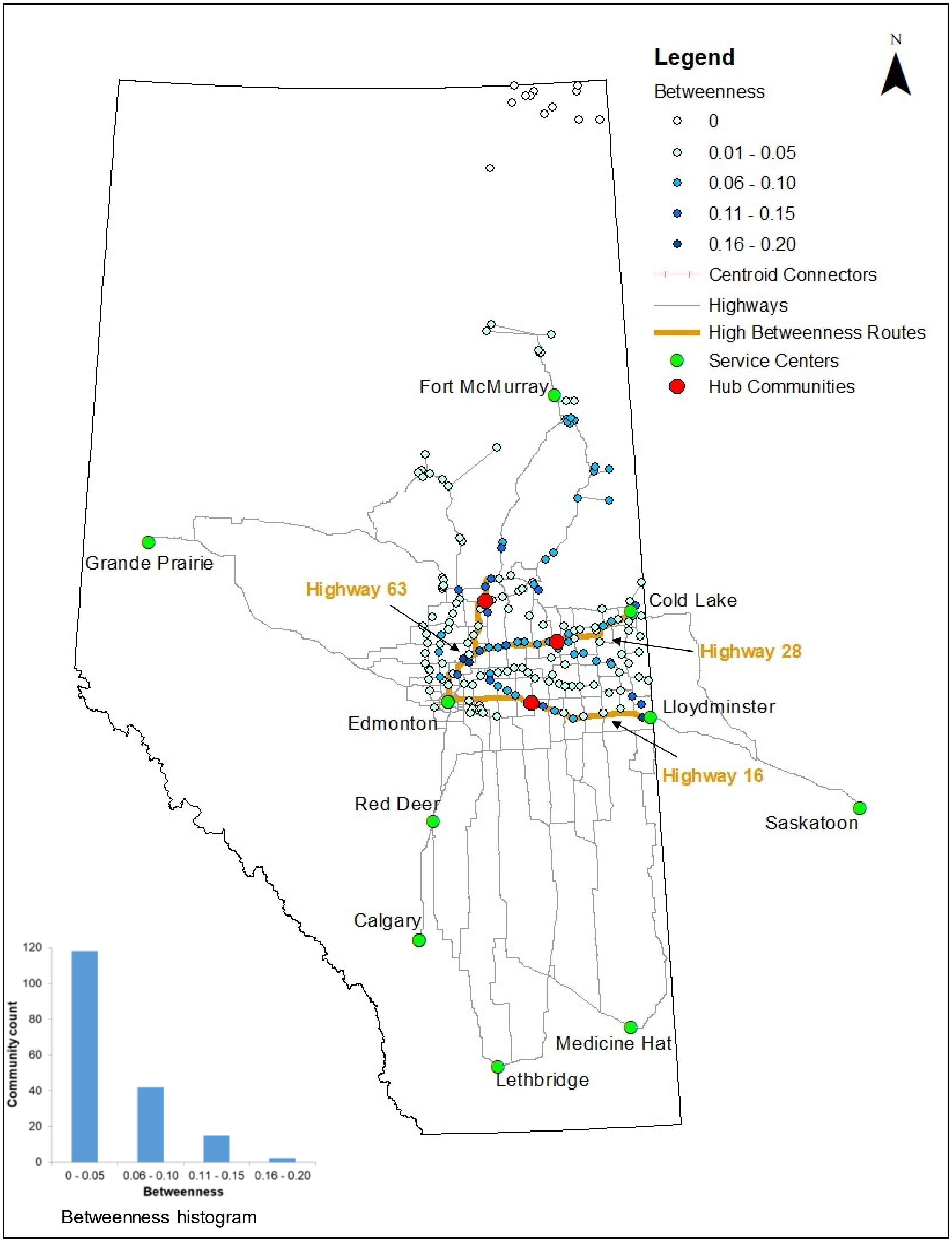

Figure 4-5 Betweenness results

Disruption of highway links to communities with high betweenness scores would have a disproportionate impact on the network, as this would interrupt a larger number of shortest paths between communities and service centers. Communities on Highway 28 between Radway and Edmonton have relatively high betweenness scores, as all shortest paths from communities in northeastern Alberta are along Highway 28 (Figure 4-5). Therefore, disruption of Highway 28 can significantly degrade network efficiency.

A map of betweenness scores such as that of Figure 4-5 can be mapped against those of natural disaster risk (i.e. wildfire and flood maps), such that emergency management planners can understand where disruptions would result in greater risks to populations, and the highways they would utilize.

Most significantly, betweenness results can offer important and concrete guidance to emergency management planners regarding where services and supplies ought to be placed, and where multimodal transfers may be developed and/or existing ones utilized. Communities with high betweenness may be good locations to store supplies (fuel, water, first aid, firefighting equipment, etc.); evacuees may access supplies on their way out, and emergency crews can access on their way towards the event. Use of these key locations can help to ease both evacuation stress and event impact. For the three highways identified above, candidate communities for emergency service/supplies location (due to high betweenness scores) are the Village of Boyle on Highway 63, Ashmont on Highway 28, and the Town of Vegreville on Highway 16. In addition, some types of emergencies may require airlift for some evacuees (or even provide additional transport capacity); therefore, existing aviation infrastructure near these communities can also be identified to further accommodate emergency air services.

4.1.4.4 Accessibility Index

The Accessibility Index (AI) is a modification of the Accessibility and Remoteness Index of Australia ($ARIA$) adopted by the Australian government (Taylor and Susilawati 2012). They developed $ARIA$ by first categorizing service centers by population and then calculating the network distance from a community to the service center in each category. For the AI measure, I consider the shortest path distance from a community i to all service centers j in the province, rather than just the nearest. The rationale for this change is that during a major emergency such as the 2016 Fort McMurray wildfire, evacuees travelled to, and accessed services in, cities throughout the province, although they did concentrate in Edmonton and Calgary. Accessibility Index for community i (AI_i) is defined as the ratio of the shortest path distance between community i and service center j to the average distance of all communities to that service center, summed for all service centers:

$$AI_i = \sum_j d_{ij} \Big/ \overline{d_{j\forall i}} \tag{4}$$

When calculating the average distance of all communities to the service centers, isolated communities not connected to the provincial highway system are excluded. For all isolated communities, $d_{ij} = \infty$; therefore, if they were included in the calculation of the average distance of all communities to the service center, AI could not be calculated. A higher AI value for a community i implies that it is more distant from all service centers, compared to the average distance of all communities to service centers.

AI can be seen as a modification of the closeness measure introduced in Section 4.1.4.2. Both measures calculate the shortest path distance from a community to each service center. However, AI is governed by the distance of the shortest path to the most central service center, while closeness calculates shortest path to all service centers irrespective of the service center strength (population or connectivity). Therefore, if a central service center (for which the average distance to all communities is relatively low as compared to the other service centers) is very distant from the target community, AI for the target community will take a high value.

Figure 4-6 shows AI values for communities in the study area. If a community has a lower AI, it is relatively close in distance to central (well-connected) service centers. The Hamlet of Ardrossan has the lowest AI at 8.02. AI values are lower for communities closest to Edmonton and gradually increase as we move away from the center of the province (where the network is densest and most service centers are located). Communities in the Regional Municipality of Wood Buffalo (RMWB) have comparatively high AI values, because the only service center located in the RMWB is Fort McMurray (while all other service centers are quite distant). If RMWB had other service center(s) besides Fort McMurray alone, AIs in this region may decrease. Fort Mackay Indian Reserve

#174C, and Namur Lake Indian Reserves #174B and #174A have the largest AIs at 18 as they are quite remote from the well-connected service centers in the center of the province.

AI values are largely determined by how well the service centers are connected to communities throughout a network. A well-connected service center represents hub strength and hence better service provision. If a community is located farther from a well-connected service center, it will have a higher AI value. In the current network, the service centers of Edmonton, Calgary, Cold Lake, Lloydminster, and Fort McMurray are best connected to communities in the study area. However, if we consider all communities in the province (southern and eastern communities in addition to the currently considered northeastern communities) for the calculation of AI, other service centers such as Lethbridge, Medicine Hat, and Grande Prairie would be equally well-connected. This would increase the community AI values. Hence, to measure the true hub strength of service centers, its distance from all communities in the province and not just communities in the sub-set of the province (northeastern Alberta) should be considered in the future. I note here that considering a smaller number of service centers for the analysis will not change the outcome of the measure, as results are relative for communities in the study area.

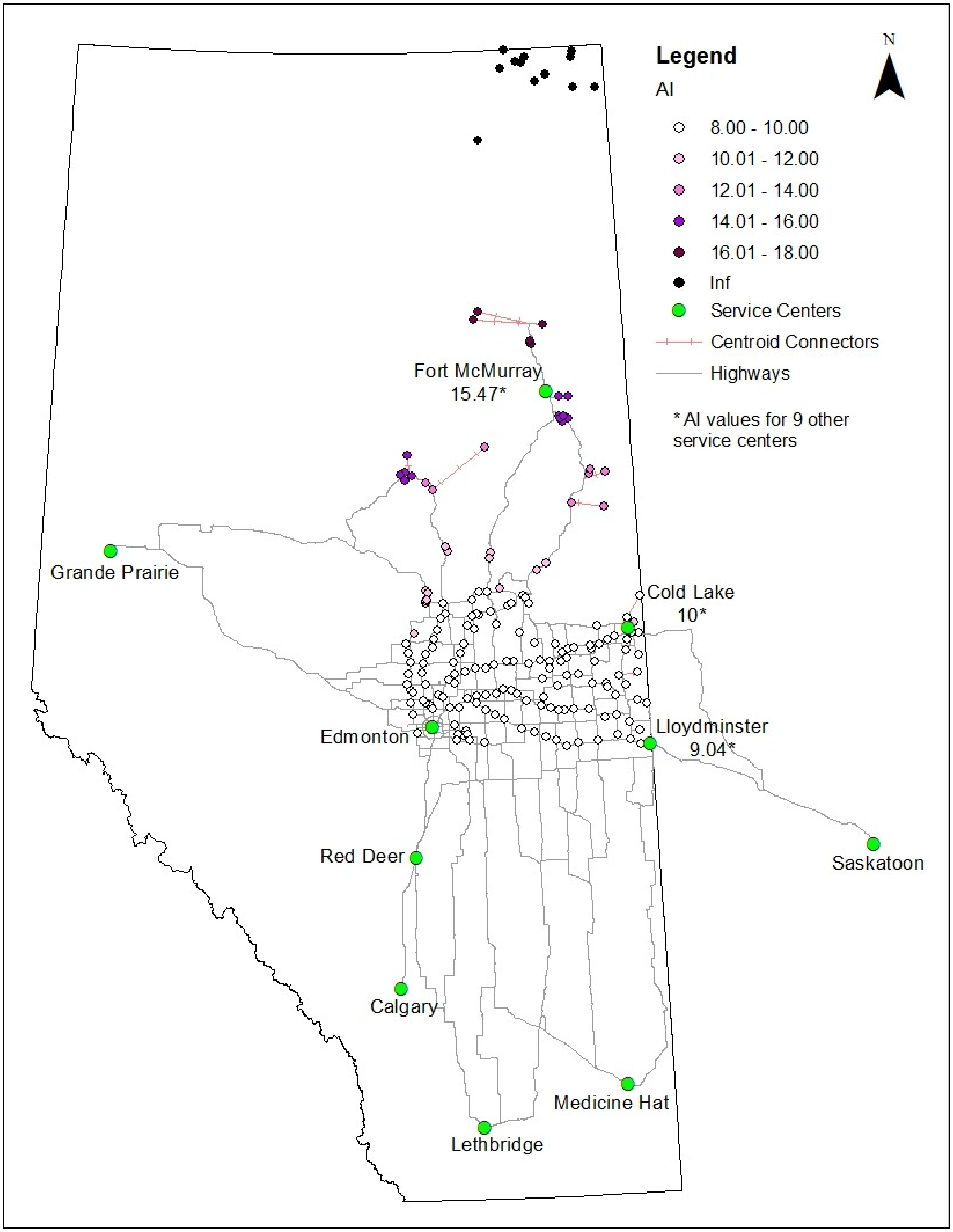

Figure 4-6 Accessibility Index (*AI*) results

I calculated the AI values of the service centers within the study area (Fort McMurray, Cold Lake and Lloydminster – marked by asterisk in Figure 4-6) to the remaining service centers as well. Fort McMurray has the highest AI value of the three service centers, given its location in the remote RMWB. Note that AI values calculated for the three service centers are not comparable to the values calculated for the other communities, because their set of service centers is the complete 10 assumed for all communities, minus itself. However, we can normalize AI values by the number of service centers considered, for comparison purposes.

Table 4-1 shows normalized AI for communities in the RMWB, including Fort McMurray. We can observe that Fort McMurray's AI is comparable but somewhat higher than those of surrounding communities. If Fort McMurray residents had to evacuate, they would have to travel much farther to reach a designated service center, while if surrounding communities' residents needed to evacuate, they would simply travel to Fort McMurray.

Table 4-1 Normalized *AI* Values for RMWB Communities

Community	**Normalized *AI***
Anzac	1.51
Clearwater Indian Reserve #175	1.57
Conklin	1.30
Cowper Lake Indian Reserve #194A	1.38
Fort Mackay	1.73
Fort MacKay Indian Reserve #174	1.73
Fort MacKay Indian Reserve #174C	1.79
Fort MacKay Indian Reserve #174D	1.73
Gregoire Lake Estates	1.51
Gregoire Lake Indian Reserve #176	1.51
Gregoire Lake Indian Reserve #176A	1.51
Gregoire Lake Indian Reserve #176B	1.51
Janvier Indian Reserve #194	1.38
Janvier South	1.38
Namur Lake Indian Reserve #174B	1.79
Namur River Indian Reserve #174A	1.79
Saprae Creek	1.57
Winefred Lake Indian Reserve #194B	1.30
Fort McMurray (service center)	***1.72***

4.1.5 Community Measures

Topological measures alone are not sufficient in characterizing a transportation network with respect to disruption and emergency evacuation scenarios. In this section, I propose performance measures that incorporate network topology as well as populations to characterize community vulnerability in emergencies.

4.1.5.1 Exit Demand

Exit demand (ED_i) for a community i is an estimate of evacuation demand (population) per exit. This measure is a simplified version of Clearing Time Estimate as proposed by Church and Cova, which estimates the time required to clear a neighbourhood of its inhabitants (Church and Cova 2000). ED for a community i is defined as the ratio of the population of that community to the number of immediate exits:

$$ED_i = \frac{p_i}{D_i} \tag{5}$$

I directly compared the population with number exits. However, in future work, evacuation demand should be calculated by number of vehicles leaving a neighbourhood, requiring estimation of data on vehicle occupancy rates. A high population community with fewer exits will require more time (and difficulty) to evacuate, and hence will score a higher ED value.

ED scores for the study area range from 5 to 33,287. The ED results are shown in Figure 4-7. ED values, population and exits for communities are shown in Figure 4-8 for comparison.

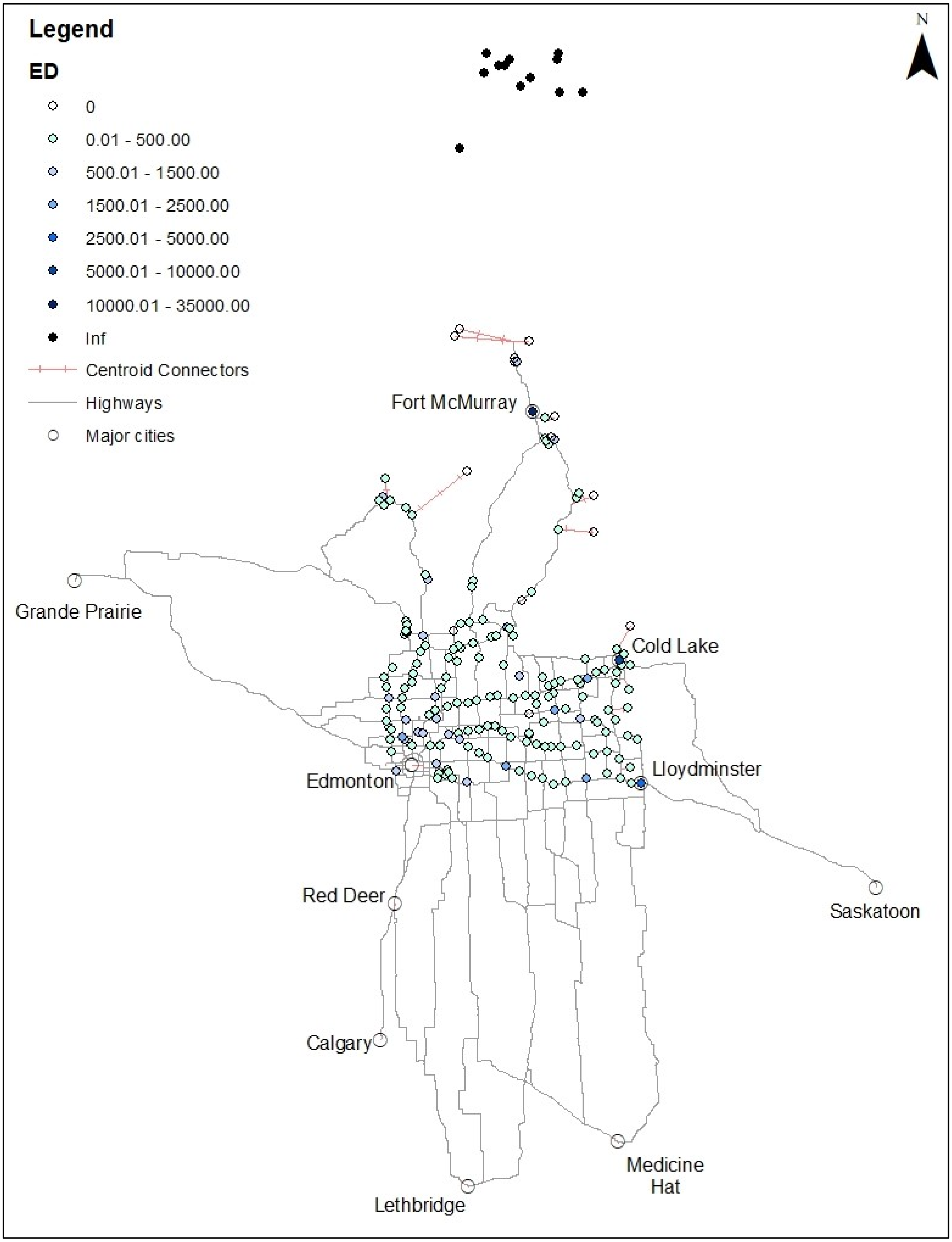

Figure 4-7 Exit demand (ED) results

According to Figure 4-8, ED values increase relatively uniformly from 5 to 2,462 (ED value 2,462 is for Town of Morinville). After 2,462, the next score is 4,911 for Lloydminster (roughly twice of 2,462 as for Morinville). The next value, 7,481 for Cold Lake, is 1.5 times that of ED for Lloydminster. ED of 33,287 for Fort McMurray is roughly 9 times that of Cold Lake and 13 times that of the Lloydminster. Given, how number of exits of community varies only between 2-4, communities that have a significantly higher ED scores than others represent a large size community with only few exits. For instance, Fort McMurray has the highest ED score (ED_{FMM} = 33,287), as it has a population of 66,573 and only two exits (although it should also be stated that northbound Highway 63 may not serve as a "true" exit).

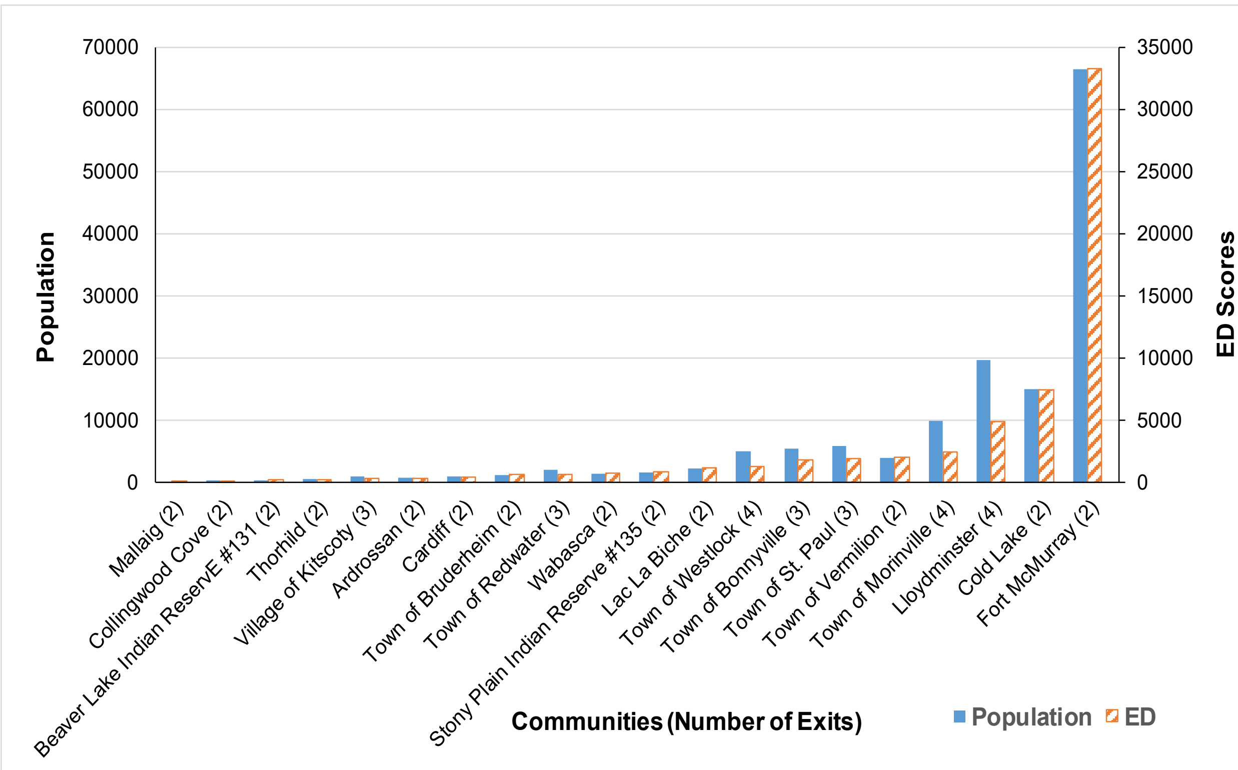

Figure 4-8 Community exit demand (ED), population and number of exits comparison

4.1.5.2 Remoteness Index

The Remoteness Index (RI) considers basic topology as well as community populations. I developed RI by modifying the index proposed by Alasia et al. 2017; because the latter was developed for a national-level model, and travel cost from the at-risk community to service centers only within a predefined radius is considered. In a sparsely populated and serviced area like northeastern Alberta, relatively large cities are likely to be located much farther away than in other studied networks. In addition, as mentioned in Section 4.1.4.4, people are likely to drive quite far to major cities like Calgary and Edmonton. Therefore, I considered the travel cost to all service centers in the province. A community's RI is defined as the ratio of a service center's population to the shortest distance from the community to that service center, summed for all the service centers in the study area.

$$RI_i = \ln\left(\sum_{j=1}^{M} \frac{p_j}{d_{ij}}\right) \tag{6}$$

A community located farther from larger service centers will have a lower value of RI. Figure 4-9 displays the Remoteness Index (RI) results. A community located at a greater distance from large (population) service centers will have a lower RI value. Therefore, RI values are highest for communities closest to Edmonton, and decrease sharply for communities farther north.

For northernmost communities not connected to the provincial highway network, $RI = 0$. Fort Mackay Indian Reserve #174C and Namur Lake Indian Reserves #174B and #174A have RI values between 1.51 and 2, lower than those of other communities in the study area. These communities are quite distant from the service centers, with the closest (Fort McMurray) being significantly smaller than the others. Ardrossan has the highest RI of 4.02, indicating that it is overall closest to the largest service centers.

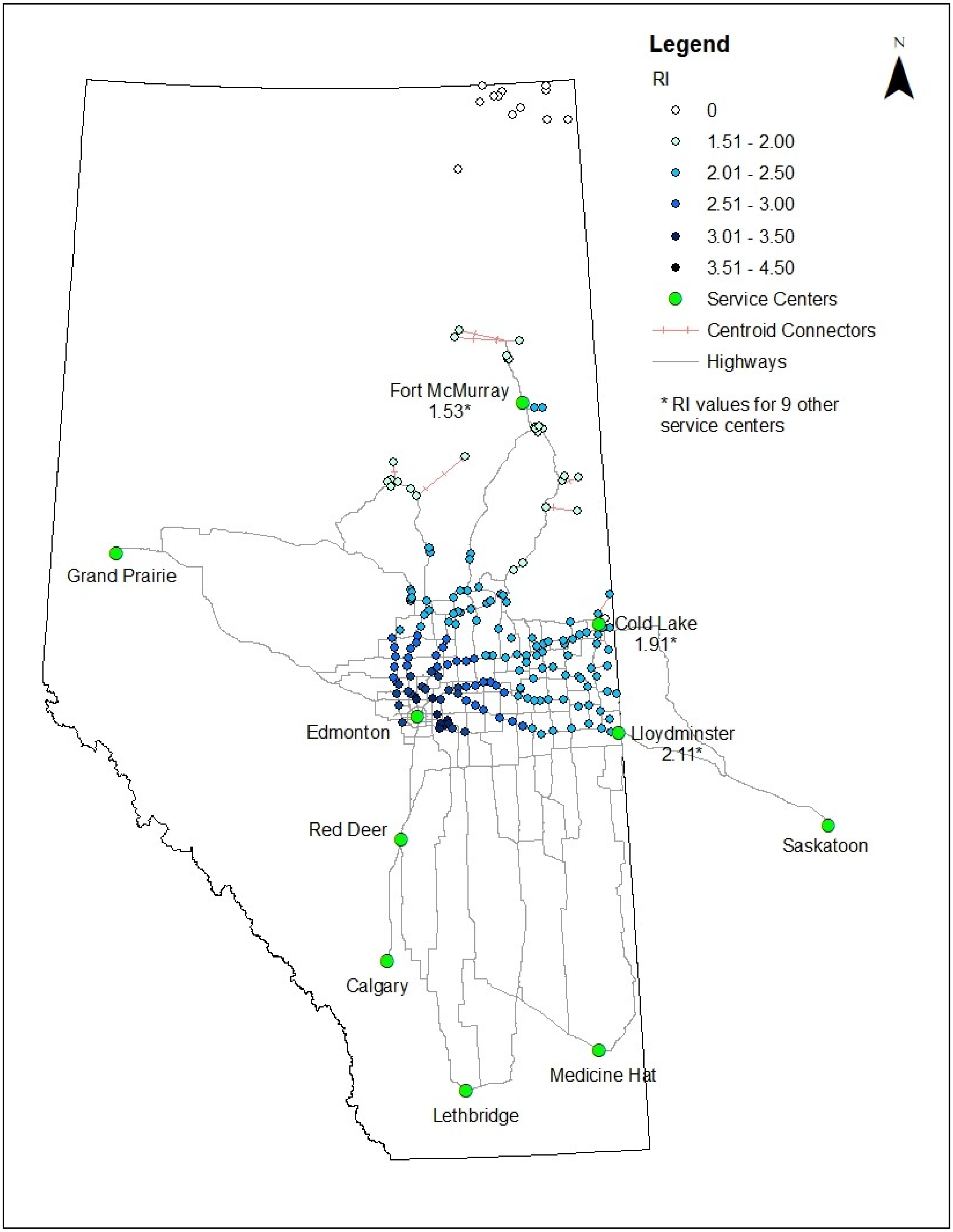

Figure 4-9 Remoteness Index (*RI*) results

Like AI, the RI values of communities also designated service centers (Fort McMurray, Cold Lake, Lloydminster) were also calculated to all remaining service centers (i.e. all but itself; values are again marked with asterisks in Figure 4-9 and presented in Table 4-2. Similar to AI, Fort McMurray's RI is most critical among the three service centers. Table 4-2 indicates that Fort McMurray's normalized RI is comparable to other communities within RMWB.

Table 4-2 Normalized RI values for RMWB Communities

Community	**Normalized *RI***
Anzac	0.18
Clearwater Indian Reserve #175	0.20
Conklin	0.18
Cowper Lake Indian Reserve #194A	0.17
Fort Mackay	0.17
Fort MacKay Indian Reserve #174	0.17
Fort MacKay Indian Reserve #174C	0.16
Fort MacKay Indian Reserve #174D	0.17
Gregoire Lake Estates	0.19
Gregoire Lake Indian Reserve #176	0.19
Gregoire Lake Indian Reserve #176A	0.19
Gregoire Lake Indian Reserve #176B	0.19
Janvier Indian Reserve #194	0.17
Janvier South	0.17
Fort McMurray (service center)	***0.17***

4.1.6 Discussion and Comparison of Measures

Measures based on network topology and community population were applied to the network of northeastern Alberta to identify vulnerable communities. Vulnerable communities were identified based on i) difficulty to evacuate: measured by degree and exit demand (ED) ii) accessibility (ease of reaching) to province's major service centers using the shortest distance path: measured by closeness, Accessibility Index (AI) and Remoteness Index (RI). In addition, betweenness identifies locations that may be good candidate locations to store supplies (fuel, water, first aid, firefighting equipment, etc.).

ED determines the difficulty to vacate a neighbourhood more precisely than degree, as it considers population in addition to number of exits. A high population community with a low number of exits is more critical than low population community with low exit. ED identifies Fort McMurray, Cold Lake and Lloydminster as the most vulnerable communities in northeastern Alberta.

Closeness, AI and RI measure the accessibility of the communities to the service centers during emergencies. Closeness identifies vulnerable communities just based on the shortest path distance to service center, AI employs shortest path distance to most central (well-connected) service center and RI is based on shortest path distance to highly populated service center. AI and RI are more appropriate measures as they place an importance to the type and proximity of service. RI differs from AI in that AI assumes that location centrality is the most important characteristic of a service center while RI places value on the service center's population. Given that RI is based on service center population, it is a reflection of the "draw" of more extensive services in the larger cities.

Communities in the Regional Municipality of Wood Buffalo (RMWB) are identified as the most vulnerable based on AI and RI, as they are comparatively distant from all service centers in the province. These communities (population >100) include: Fort McMurray, Fort MacKay Indian Reserve #174, Anzac, Saprae Creek , Janvier Indian Reserve #194, Greogoire Lake Indian Reserve #176A, Conklin, Greogoire Lake, Greogoire Lake Indian Reserve #176A and Janvier South. The closest service center to these communities is Fort McMurray, which is a poorly connected (as per AI described in Section 4.1.4.4) and a mid-sized service center (as per RI described in Section 4.1.5.2).

4.2 Network Scan

Although we are able to identify how difficult it is for communities to evacuate and access emergency services using topological measures, these measures are quite simplistic and do not determine where degradations in the network may occur. While topological measures consider only the arrangement in a graph, researchers have also incorporated passenger flow, travel cost and capacity to develop other, more rich measures to assess transportation network performance under disruptions (Sun and Guan 2016). The vulnerability of the network depends not only on the topological arrangement of communities and their population but also on qualitative properties of highway links such as capacity to handle the surge of demand during evacuation. The system-based network measures proposed in this section overcome some limitations of the topological measures, by considering capacities of the network links.

I present a method to assess the reductions in capacity for facility disruptions. If removal of links (modeling facility disruption) results in significant capacity reductions or isolation of a community (complete capacity reduction), then the network is deemed susceptible (less robust) to such disruptions. Because many disruptive events (such as wildfires) affect more than one highway facility, and rather, affect areas (under which multiple facilities or links may be located), I simulate disruption using grids that are meant to represent areas of disruption. Simple measures of capacity and route changes before and after disruption are presented. Based on the capacity scan, I identify highway links that lead to maximum reduction in overall highway capacity when disrupted. Finally, outcomes of capacity scans after multiple link failure, simulated using grids, will be presented graphically.

4.2.1 Study Area

For the network scan to determine capacity reductions, I focused on the Regional Municipality of Wood Buffalo (RMWB), with its highly sparse provincial highway network. The map of the study area (Figure 4-10) identifies communities (blue circles) and provincial highway facilities (Highway 63, Highway 69, Highway 881 and Highway 858) considered for the network scanning. I assessed before and after disruption capacities for all routes from these communities to reach Edmonton, the major service center when evacuating from northeastern Alberta. Given the small populations of communities in the RMWB (Fort McMurray being the only city with a sizable population), the dense network near Edmonton can easily accommodate evacuation demand from these regions. For this reason, I focused on the highway network further to the north, where the network is sparse.

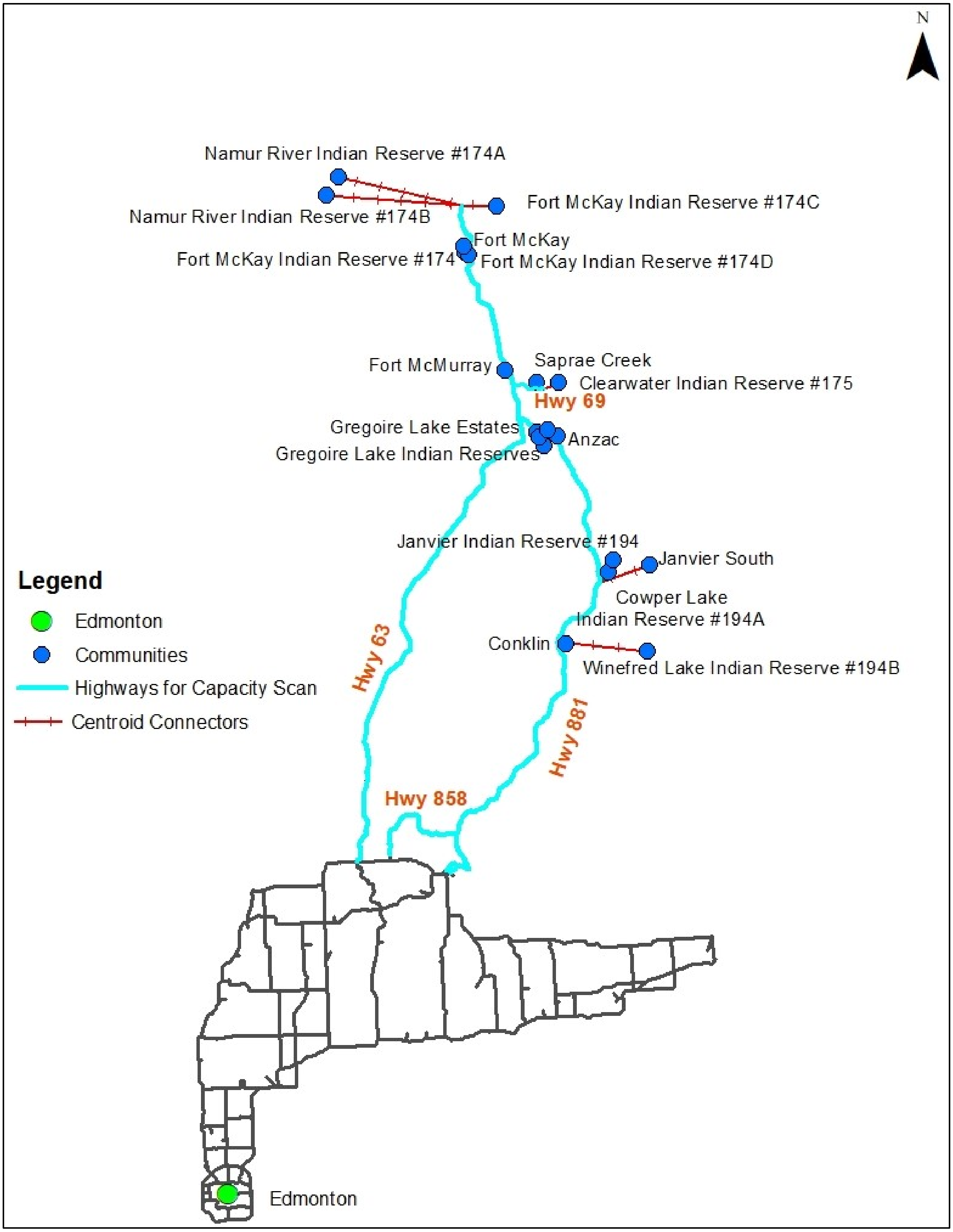

Figure 4-10 Study area for capacity scan

4.2.2 Modeling Disruption Scenario Using Grids

The grid-based disruption can be modeled in two ways: i) grids that are susceptible only to specific scenarios are disrupted, ii) all grids, one at a time or many at a time, are disrupted irrespective of the scenario type. In this thesis, I disrupted all grids, one at a time. The study area was overlaid with a grid of 12 km × 12 km as shown in Figure 4-11. A grid represents the location of the disrupting event, and highway links located within a grid were associated to that grid. Each grid was "disrupted" individually– meaning, I assumed that network links within a disrupted grid are unusable. I modeled this in MATLAB by assigning an enormous distance (=10000000 metres) to the links within the disrupted grid. This approach enables us to understand the impacts of network disruption based on where it occurs geographically. Using the grid-based approach, each location in the study area is subject to the same intensity of events and hence a uniform consideration of disruptive events over the study area is ensured (Jenelius and Mattsson 2012). The reasoning behind this approach is that without climate data (i.e. wildfire risk), we cannot say where in the study area problems will arise, and hence, a uniform coverage approach is as appropriate as any other.

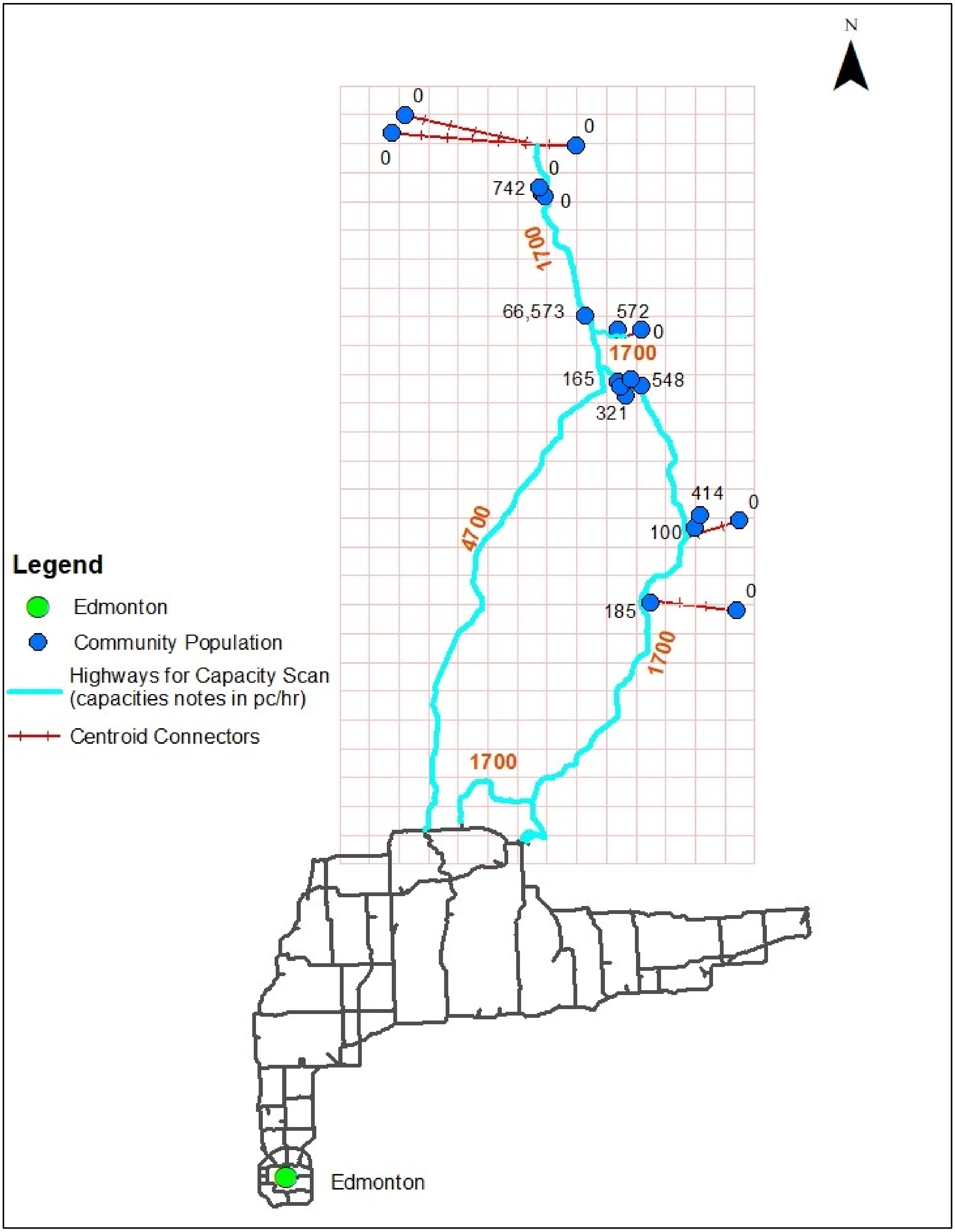

Figure 4-11 Grid (12x12 km) covering the study area

4.2.3 Highway Capacities

Capacities for the provincial highways in the study area were calculated based on uninterrupted flows analysis (Volume 2) from the 5th Edition of the Highway Capacity Manual 2010 (HCM2010) (Transporation Research Board 2010); link capacities were then added to the network model in MATLAB. According to HCM2010, capacity is the maximum hourly flow rate at which persons or vehicles can traverse a point or a uniform section of a lane or roadway during a given time under prevailing conditions (Transporation Research Board 2010). The analysis method for uninterrupted highways addresses three types of facilities:

- Freeways: highways with full access control and directions barrier-separated;
- Multilane highways: without full access control, with traffic signals or roundabouts spaced at least 2 miles apart on average, and
- Two-lane highways: with traffic signals, roundabouts, or stop-controlled intersections at least 2 miles apart on average.

Capacities are calculated based on free flow speed and number of lanes as per HCM2010 (Transporation Research Board 2010). In this thesis, I assumed free flow speed to be equal to the posted speed. The posted speed limits were estimated based on the design designation of each highway segment as per Table A.3.1 of Alberta Transportation's Highway Geometric Design Guide (Alberta Transportation 1999). The design designation depends on the number of lanes, highway surface (whether paved or gravel) and lane widths (determined from Google Maps). All highways except for the divided portion of Highway 63 (approximately Fort McMurray to Atmore) are two-lane highways; their capacities were calculated using Chapter 15 of HCM 2010. The divide portion of Highway 63 was considered a multilane highway with posted speed of 110 km/hr; it was analyzed as per Chapter 14 of HCM 2010. But because highways with a free flow speed greater than 96 km/hr cannot be analyzed using Chapter 14 of HCM 2010, this divided portion of Highway 63 was analyzed as a freeway as per Chapter 11 of HCM 2010.

4.2.3.1 Capacity Calculation for Two-Lane Highways

As per Chapter 15 of HCM 2010, the capacity of a two-lane highway under base conditions (i.e. "ideal" geometric, traffic, and environmental conditions) is 1700 passenger cars/hour/lane (pcu/hr/ln) in one direction, with a maximum of 3200 pcu/hr bi-directionally (Transporation

Research Board 2010). All calculated capacities for highways in the study area are listed in Table 4-3.

4.2.3.2 Capacity Calculation for Freeways

As per Chapter 11 of HCM 2010, the capacity for a freeway with free flow speed of 110 km/hr is 2350 pcu/hr/ln (Transporation Research Board 2010). The only highway analyzed as a freeway was the divided portion of Highway 63, with two lanes in each direction.

Table 4-3 and Figure 4-11 show capacities calculated for all provincial highways in the study area.

Table 4-3 Highway Capacities (as per HCM2010)

Highway	**Classification (HCM2010)**	**Roadway width (m)**	**Number of lanes per direction**	**Posted speed (km/hr)**	**Capacity (HCM2010) (pcu/hr/direction)**
63 (north of Fort McKay)	Two lane	9	1	100	1700
63 (divided)	Freeway	12.4	2	110	4700
881	Two lane	11.8	1	100	1700
858	Two lane	8	1	100	1700
69	Two lane	9	1	100	1700

4.2.4 Total Capacity Reduction

I implemented network scans that identify capacity deficiencies during facility disruptions, which I modeled by systematic grid disruption (which in turn indicates links disrupted). Recall that robustness is defined as the ability of the transportation system to maintain connectivity and capacity in face of threats. This measure determines the highway network's connectivity and capacity reductions from affected communities in the Regional Municipality of Wood Buffalo (RMWB) to Edmonton (the closest major service center) after multiple link disruption. If the multiple link disruption results in significant capacity reductions or isolation of a community, then the network is deemed susceptible (less robust) to such disruptions.

Note that for the network scans I do not include Fort McMurray as a service center even for points further north. This is due to the fact that if people are evacuating from the RMWB due to wildfire (the predominant concern in northern Alberta), it is unlikely they would evacuate to Fort McMurray over Edmonton or Calgary, given Fort McMurray's location within the boreal forest.

I first calculated the capacities of all paths from communities to Edmonton under the base case: normal (full capacity) highway operations. I calculated base case capacities by summing the capacities of all available paths (at their smallest capacity points) (Figure 4-11). Next, I overlaid the study area with a grid, and "disrupted" each grid individually. For each individual grid g disruption, I recalculated the capacities of all paths from all communities to Edmonton. I calculated the total capacity reduction (TC) from affected communities to Edmonton due to disruption of grid $\left(TC_g\right)$.

$$C_i^g = \frac{BC_i - DC_i^g}{BC_i} \tag{7}$$

$$TC_g = \begin{cases} \frac{\sum_{i=1}^{N}(C_i^g \times p_i)}{\sum_{i=1}^{N} p_i}, C_i^g \ \forall i < 1 \\ 1, otherwise \end{cases} \tag{8}$$

Where:

C_i^g Community i capacity reduction (to service center) due to grid g disruption

BC_i Total capacity of all paths from i to service center (Edmonton) in base case

DC_i^g Total capacity of all paths from i to service center (Edmonton) after disruption of g

p_i Population of community $i, i = 1 \dots N$

N Total number of communities in the study area, excluding communities in grid g

Greater total capacity reduction (TC) values indicate greater impact (to a larger population) after grid disruption. If the capacity reduction $C_i^g = 1$ for any community i, meaning that disruption of g leads to a total disconnection of i from Edmonton service center, then $TC_g = 1$. I adopted this approach such that the measure clearly indicates when a grid (containing isolating links) disruption leads to the complete inability for any community (irrespective of its population) to reach service center.

The results for network scanning for capacity reductions are presented in Figure 4-12. Communities that could be entirely isolated from service centers are those served by Highway 63 north of the 63/881 junction (Fort McMurray, Fort Mackay Indian Reserve #174A, Saprae Creek, Janvier Indian Reserve #194,) and Highway 881 (Conklin and Janvier South). These communities are located within boreal forest and therefore highly susceptible to wildfires. The rationale for assigning $TC = 1$, even for tiny communities, is that isolation of any population on the ground will require air evacuation. This situation occurred in the 2016 Fort McMurray wildfire; portions of Highway 63 south of Fort McMurray become unpassable, and individuals that had initially evacuated north were ultimately able to reach safety (in Edmonton or Calgary) by air.

The next highest TC values are 0.73 for grids containing the divided portion of Highway 63. Disruptions to this part of Highway 63 force all evacuating communities onto Highway 881, effectively reducing total highway capacity (southbound to Edmonton and possibly other points south) from 6400 pcu/hr to 1700 pcu/hr. Disruptions to Highway 881 result in $TC = 0.27$, less critical because Highway 63 capacity of 4700 pcu/hr southbound remains available to most communities to the north. Given the very simple configuration of this study network, Fort McMurray's population is almost always impacted by disruptions to highway links. Disruptions to Highway 63 north would result in lower TC values due to small impacted populations. However, because these communities are entirely isolated from the rest of the province without Highway 63, $TC = 1$.

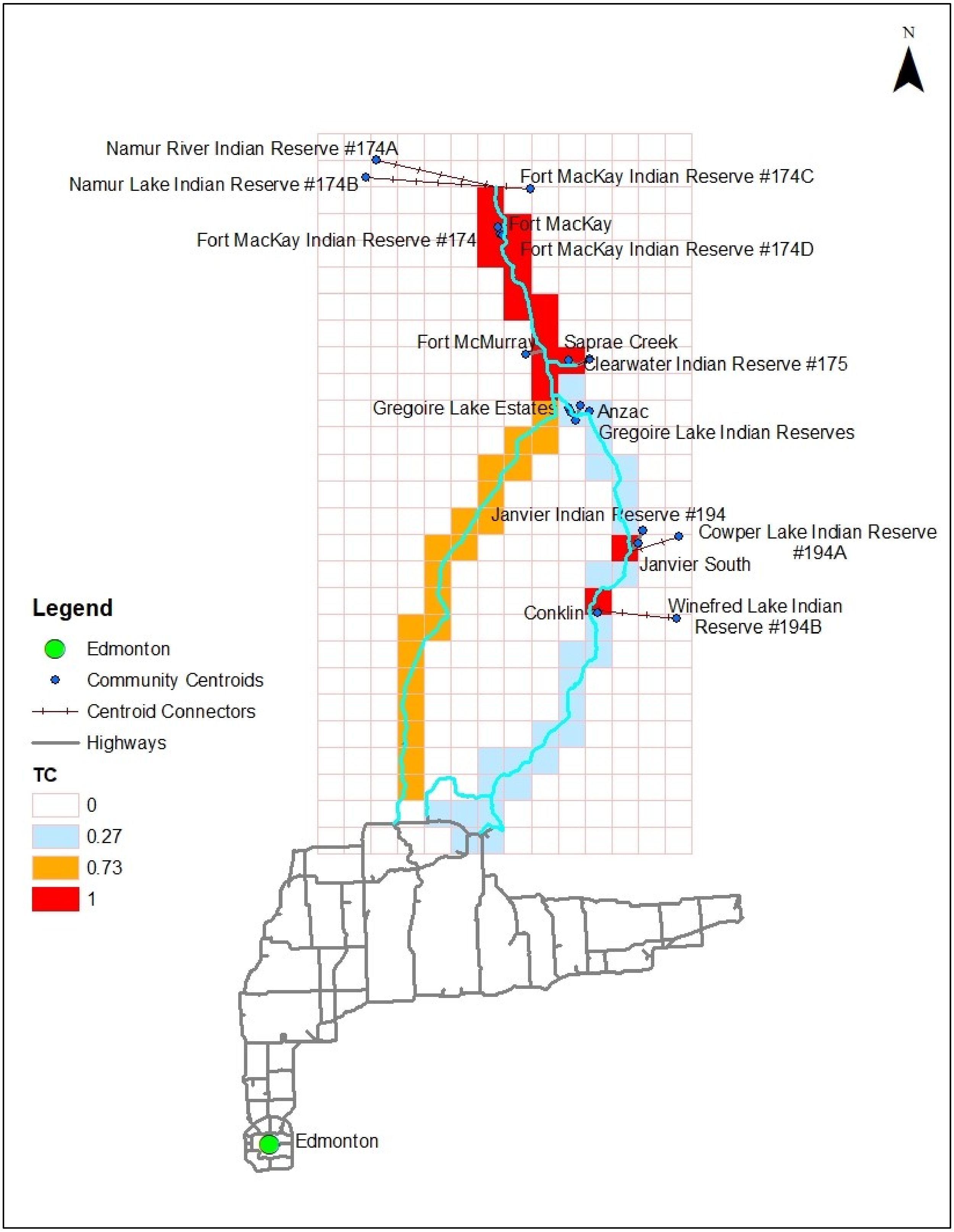

Figure 4-12 Total capacity reduction (TC) results

4.2.5 Discussion

Network scanning for total capacity reduction, described in Section 4.2.4, identifies: i) highways links that are sole connections (isolating links), whose disruption leads to isolation of some communities, and ii) highway disruptions that lead to significant capacity reductions for larger communities (Fort McMurray). Highway 63 north of the intersection of Highway 63 and 881, and Highway 881 at the intersections that connect to Janvier South and Conklin, are isolating links in the study area network. The communities (with population >100) that could be isolated due to disruption of these facilities are Fort McMurray, Fort Mackay Indian Reserve #174A, Saprae Creek, Janvier Indian Reserve #194, Conklin and Janvier South. It must be noted that these communities are located in boreal forest and hence are highly susceptible to wildfires. Alternate routes and transport modes for these communities to reach Edmonton or Calgary (major service centers) during emergencies must be considered. We performed a quick check of the alternate connections from these communities and the outcomes are described in Section 4.3. Disruption of Highway 63 starting from the intersection of Highway 63 and 881 to Atmore results in 73% reduction in total capacity for all communities in the study region. If this portion of the Highway is closed, communities are left to rely solely on Highway 881 (a much smaller capacity facility) during emergencies. Initiatives to build additional capacity out of Fort McMurray has been under consideration after the 2016 wildfire (Thurton 2017).

4.3 Summary and Discussion

Topological and network scanning measures were applied to the network model of northeastern Alberta to understand characteristics of the transportation network under evacuations and disruptions. Degree and Exit Demand (ED) identify communities that may face difficulty in evacuating the neighbourhood in efficient (timely) manner. Degree only counts the number of exits out of a community while ED also considers population in addition to number of exits. However, both these measures lack in identifying true evacuation exits (i.e. exits that traverse in direction of service centers). Betweeness is one of the important topological measure, as it identifies locations that may be strategic candidate locations to store supplies (fuel, water, first aid, firefighting equipment, etc.).

Closeness, AI and RI measure the accessibility of the communities to the service centers during emergencies. However, AI and RI are more appropriate measures to measure remoteness of communities as they place an importance to the type and proximity of service. Communities in the Regional Municipality of Wood Buffalo (RMWB) may be considered remote as their shortest path distances to designated service centers are high (high accessibility (AI) and low remoteness (RI) indices values).

The network scanning measure is useful in identifying provincial highways facilities that, if disrupted, will result in high capacity reductions for larger population evacuating to Edmonton. It also identifies isolating links in the study area – network facilities that, if disrupted, isolate entire communities. Disruption of Highway 63 in RMWB results in highest capacity reduction (73% - 100%) for all communities in the study area.

AI and RI only gives us information on a community's access to services. Neither measure tells us whether the shortest path is also the only path – i.e. on an isolating link. A map that combines AI and RI results with capacity scan results can identify communities that are most vulnerable by multiple measures. Figure 4-13 shows AI values overlaid on isolating links identified by capacity scanning. This map indicates that Namur Indian Reserves, Fort Mackay, Fort Mackay Indian Reserves, Saprae Creek, and Clearwater Indian Reserves have the highest AI values in the study area ($AI = 25 - 30$) and are also connected to the network via isolating links. These communities are not only the most vulnerable for service center access, but also the least robust in that they may be completely isolated in disasters. In fact, their closest service center of Fort McMurray is itself connected to service centers on an isolating link, which was closed during the second stage of the 2016 wildfire evacuation and over 20,000 people were flown out via oil sands camps airstrips (Boone 2018). If betweenness was calculated for Fort McMurray, it would be relatively high for that northern region. A service center with a relatively high betweenness, relatively low AI, and connected by an isolating link is problematic in emergencies, as demonstrated in 2016. Hence emergency management planners can identify such communities, and target transportation infrastructure improvements (whether on the highway network or other modes) to such critical locations on the network.

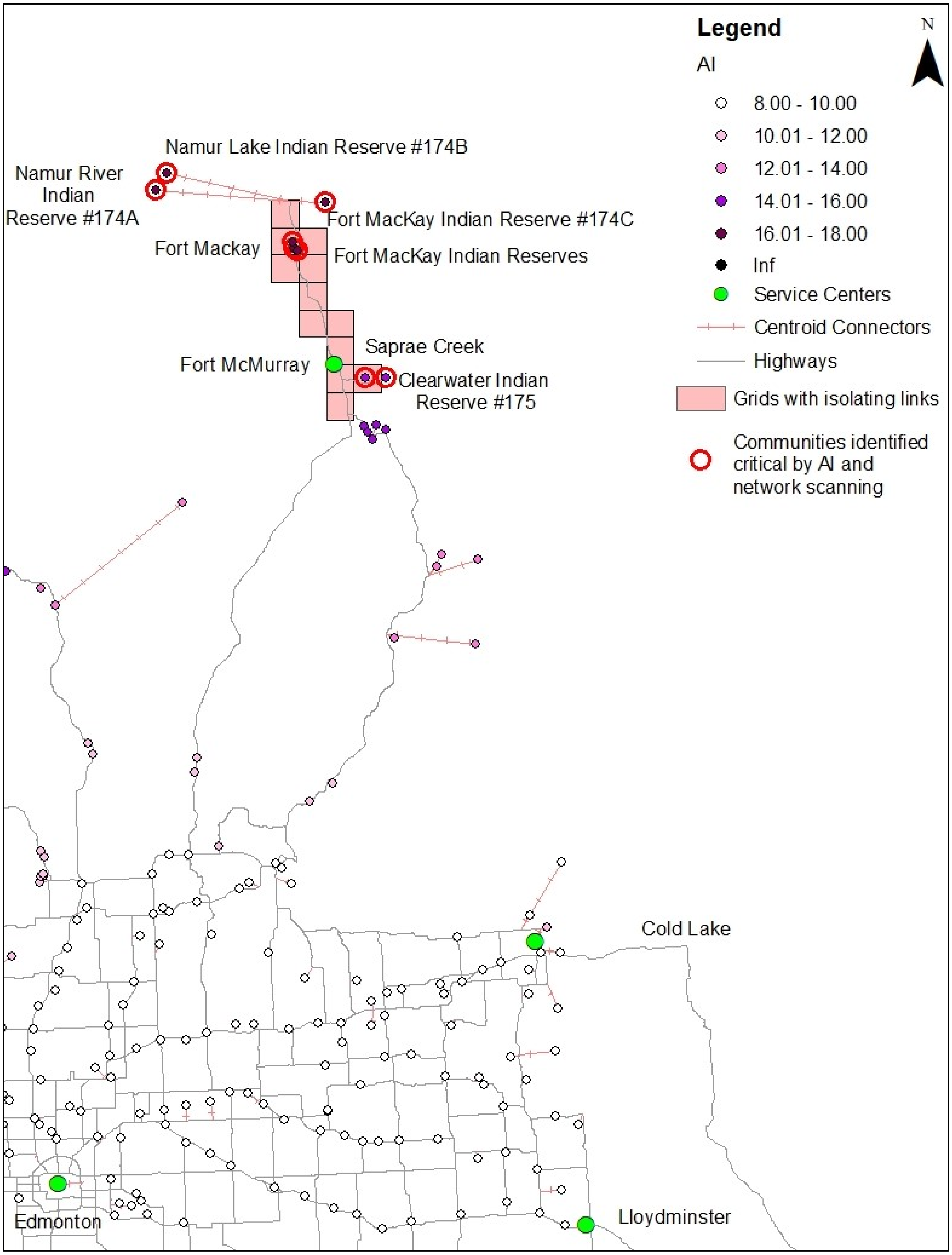

Figure 4-13 Accessibility Index *AI* results combined with network scan results

Using betweenness together with network scanning, one can identify communities to locate emergency supplies for citizens evacuating from an emergency and emergency personnel moving towards it. Additionally, aerodromes and airstrips near these communities can be used as multimodal hubs for air evacuation in cases of emergencies that cause both network disruption and community evacuation. Once these facilities are identified, emergency management planners can consider targeted improvements to ensure their readiness in emergency events. Improvements may be targeted to the facility itself or to roadway infrastructure connecting them to communities and the provincial highway system.

However, some sizable communities that may be completely isolated by facility disruption have aerodromes, such that evacuation can be coordinated by air (for smaller communities we expect that helicopters can be deployed much like in medical emergencies). In the study area, Fort McMurray, Fort Mackay Indian Reserve #174A, Saprae Creek, Janvier Indian Reserve #194, Conklin and Janvier South are identified as communities with population over 100, connected by isolating links (links whose disruption leads to isolation of some communities), and served by existing aerodromes (Figure 4-14). Local roadway connections from communities to these aerodromes may be incorporated into the network model, such that measures may be adjusted to account for multimodal evacuation should it be an option provided by emergency management plans. In future studies, the planning and logistical costs of coordinating multimodal emergency response versus highway infrastructure expansions may be evaluated.

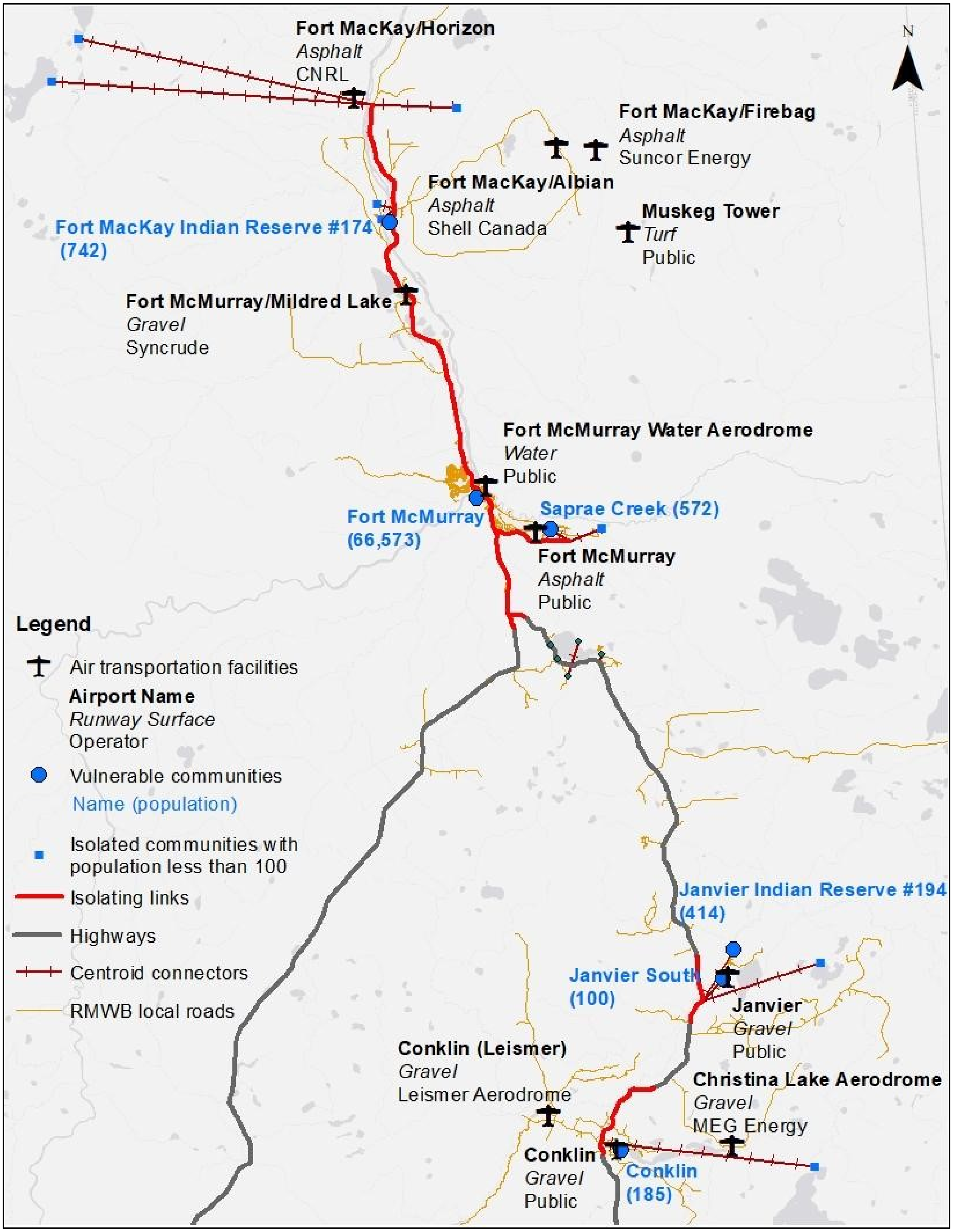

Figure 4-14 Vulnerable communities and proximate aviation facilities

Chapter 5
Conclusions

A summary of the work performed in this thesis and key findings are presented in this chapter. I also discuss the research contributions and provide recommendations for future work.

5.1 Overview

In this thesis, I identify communities, in northeastern Alberta, that may face challenges evacuating its neighbourhood, due to its size and fewer exits. I also identify communities in this region that are distant (along shortest path) from major cities in the province, and hence may not be able to easily access services during emergencies. Next, I identify highways in Regional Municipality of Wood Buffalo that if disrupted, will result in high capacity reduction for communities in this region to reach Edmonton.

A network model for northeastern Alberta with communities as centroids, intersections as nodes and highways as links was constructed in MATLAB and ArcMap. Measures are proposed and applied to the network model of northeastern Alberta to evaluate its performance during emergencies and disruptions.

Basic measures concerning network topology and community population (degree, closeness, betweenness, and exit demand), community accessibility to safety and emergency services (accessibility and remoteness indices), and transportation network performance (network scanning) founded on the concepts of vulnerability and robustness are proposed. Vulnerability is defined as defined as inability of the transportation network to perform its intended function (transporting individuals to safety and provision of access to services) during emergencies. Communities are identified vulnerable based on how easily communities can access emergency services based on their locations, and how easily a population is able to evacuate from their community when it is under threat. Robustness is defined as defined as the ability of the transportation system to maintain connectivity and capacity in face of threats. Highways whose disruptions result in significant capacity reductions and isolation of some communities are identified based on network scans.

5.2 Findings

Betweenness is one of the important topological measures, as it identifies strategic candidate locations for emergency resource allocation. Communities with the highest betweenness scores are also located along major highways in the study area, and may be good candidate locations to store supplies (fuel, water, first aid, firefighting equipment, etc.). Evacuees may access supplies on their way out, and emergency crews can access equipment on their way towards the event. Identification and use of these key locations, by emergency management planners, can help ease evacuation stress and event impact.

The accessibility (AI) and remoteness (RI) indices both measure a communities' access (by distance) to major cities in the province where evacuating residents can receive emergency services. But while AI measures service center quality/strength by its connectivity to all communities, RI uses service center population as the proxy. Given that RI is based on service center population, it is a reflection of the "draw" of more extensive services in the larger cities.

The network scan highlights the importance of Highway 63 in providing most of the ground transportation capacity and highway connectivity to RMWB communities, thereby contributing most towards robustness of the highway network in this area. Disruption of Highway 63 results in a 73% reduction in capacity for the communities in RMWB. The network scan also identifies isolating links – provincial highway facilities that, if disrupted, divide the network into two sub-networks and thus isolate communities from all service centers (thereby affecting network operation the most). Highway 63 north of the intersection of Highway 63 and 881, and Highway 881 at the intersections that connect to Janvier South and Conklin, are isolating links in the study area network.

When AI and RI results are combined with the network scanning results, communities in the Regional Municipality of Wood Buffalo (RMWB) are shown to be highly vulnerable to disruptive events, given their remoteness from major service centers in the province and connection to the provincial highway network by a single (isolating) link. Also, betweenness can be used with network scanning to identify interim strategic locations for emergency supplies and hubs for multimodal transfers during network disruptions.

Multimodal evacuation planning is critical in sparse networks such as northern Alberta. With limited to no redundancy in a sparse highway network, existing air facilities are often the only other means of evacuation. Therefore, I identified existing aviation facilities near communities that are connected not only by isolating links, but could also suffer from inadequate highway capacity. Emergency management planners should identify and consider these facilities into operational emergency plans.

5.3 Contributions

5.3.1 Practical Contributions

The existing emergency management plans in Alberta only outline roles and responsibilities in case of emergency response. They only state emergency planning and management considerations but do not provide tools or measures for transportation planning. By proposing measures for performance assessment of transportation networks under emergencies, I contribute to the planning for evacuation type use of transportation network in Alberta. I identify communities vulnerable to disruptive events, and highway links that would cause significant reduction in capacity, if disrupted. Alternate connectivity and additional capacity around these facilities must be planned in order to transport individuals from vulnerable communities to safe locations. Based on outcomes on this work, I also provide guidance on where placement of interim emergency supplies may be beneficial, as well as identify key aerodromes/airstrips that are well-located to provide alternate transport means during network disruptions.

5.3.2 Research Contributions

By proposing measures that assess emergency characteristics of the highway network and applying them to the highway network in northeastern Alberta, I add to the existing literature on vulnerability assessment of transportation networks under emergency and disruptive events. I also add to the literature on topological measures by flipping the concept of betweenness to identify communities that are critically located, and are thus key locations for emergency services.

I contribute to the existing literature on disruption of isolating links in transportation networks. Isolating links are network facilities that, if disrupted, isolate communities from the transportation network in question. The network scanning measure for capacity reductions identifies communities (even of smallest size) that can potentially be isolated and the facilities whose disruption lead to their isolation.

5.4 Limitations and Future Work

The measures of degree and exit demand, in some cases, may count exits that realistically do not lead to evacuation destinations. For Fort McMurray both these measures consider two exits (north and southbound Highway 63); as mentioned earlier the northbound Highway 63 leads to even sparser highway network where no services are located, and hence does not serve as an evacuation route. It is therefore critical to measure the number of exits out of a community that realistically lead to evacuation destination.

Since the capacity scanning algorithm considers capacities of all paths between an origin-destination pair, it may not perform as efficiently for a dense network where the calculation is to be performed for many paths existing between an origin-destination pair. The algorithm efficiency for application to a dense network can be improved by considering paths only within a certain radius that would suffice evacuation demand from a community.

I identify several key ways this work should be expanded and improved upon in the future. First, in continuing study of this sparse network, air transportation facilities (and their connecting roadways) should be incorporated into the network model. The measures presented in this thesis may be adjusted to account for multimodal evacuation should it be an option provided by emergency management plans. Second, the planning and logistical costs of coordinating multimodal emergency response versus highway infrastructure expansions may be evaluated. Third, local roadways should be incorporated into the model, to understand how local roadways contribute to providing community access and contributing to network robustness. Fourth, measure of exit demand may be modified to consider vehicle occupancy and capacity of exits paths, to understand the evacuation difficulty from supply and demand perspective. Finally, in a dense network (with several re-routing options available) evacuation flow may depend on selection of routes by the network users, hence network performance models that consider effects of disruption on travel behaviour may be considered. Future studies that focus on traffic assignment to assess performance of networks under disruption may be performed.

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Appendix A Network Representation for Northeastern Alberta