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Identifying Critical Corridors During an Area-Wide Disruption by Evaluating Network Bottleneck Capacity

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Abstract

This paper applies the min-cut max-flow theorem combined with a grid cell disruption method over a large transportation network, to identify the importance of network locations in providing travel capacity when a community is evacuating (say, from wildfire). We develop metrices that look at the importance and contribution of individual links to network bottleneck capacity in traveling from the evacuating community to the shelter community. The purpose of this is to determine the network location that is the most restrictive of all, and more importantly, where it is in reference to the evacuating community location. We apply this method to the highway network of Alberta, Canada, with evacuating communities identified as those that have been under wildfire threat historically and/or are expected to in the future. We find that in all cases, network locations that contribute the greatest share of bottleneck capacity, are located adjacent to these evacuating communities. Next, we look at combining the measure for multiple fire-prone communities, finding that the highways in remote northern Alberta are important despite some of them having lower capacity than the multi-lane highways in the south. Application of this simple method can support provincial and local municipal governments in deciding which communities require more detailed emergency evacuation studies to better identify and communicate transportation network deficiencies to provincial and federal bodies that would be making infrastructure investments towards community health and resilience.

Keywords: Min-cut Max-flow, Wildfire evacuation, Bottleneck capacity, Grid cell disruption

1. Introduction

This paper broadly identifies facilities on a provincial highway system that are critical (or important) to a community's evacuation capability – facilities that, if found inaccessible or non-operational, could hinder evacuation efficiency. We identify the maximum flow or bottleneck capacity between an origin (evacuating community) and destination (host community) using the min-cut max-flow (MCMF) theorem (Ford and Fulkerson, 1956) and a grid-based scanning system. The purpose of our work is to provide a relatively quick and simple network scanning process for understanding the importance of network facilities, in terms of their contribution to egress movement capacity for a community under potential danger. The grid-based approach – grouping link segments within a grid cell to quantify their characteristics – allows us to capture the area-wide impact of a wildfire, while balancing the need for road network details against computational efficiency. Using this approach, we identify where the most capacity-critical roadway elements are located on a network for the origin evacuating community, by developing and applying metrics that reflect these roadway elements' contributions to OD bottleneck capacity. Our work can be used to support provincial agencies (or any other overseeing a large number of communities across a large area) in gaining some basic quantitative understanding of risk and infrastructure needs throughout their large jurisdictions within their long-term strategic planning activities, to determine which individual communities and locations on the transportation network warrant further study. Such studies may include, but are not limited to, community-specific transportation infrastructure investment needs, development of fire mitigation strategies around communities and along the transportation network, and community evacuation plans.

Whether for long-notice (e.g., hurricane, flood) or short notice (e.g., wildfire) evacuations, long-term strategic planning is important for agencies that must allocate limited emergency planning resources across several communities and provide effective evacuation plans (Kalafatas and Peeta, 2006). Wildfires typically lead to short- or no-notice evacuations (i.e., evacuations that must occur within minutes to hours of notice) as the occurrence, intensity, progression, and propagation rates of wildfires vary depending on a range of factors like fuel accumulation, wind speed, wind direction, and humidity (Demange et al., 2020). Due to this immediacy, past wildfire evacuation studies have focused on simulating movement out of individual communities and/or small geographic regions (Cova and Johnson, 2002; Yerushalmi et al., 2021). However, for agencies covering large regions with many different (large and small) urbanized areas potentially under wildfire threat (combined with limited transportation networks), it is difficult, if not infeasible, to conduct these detailed studies for each individual community. Thus, simple tools to measure and compare risk levels are necessary for allocating more resources towards detailed assessments of communities at higher risk versus those at lower (to no) risk. Our method is one such tool to quickly identify capacity-critical roadway elements for communities potentially under evacuation threat.

We demonstrate our method by applying it to five fire-prone communities within the province of Alberta, Canada. Northern Alberta, sparsely populated with many small communities and covered by boreal forest, has been experiencing an overall increasing trend in wildfire activity. Many communities have been under wildfire threat historically and/or are expected to in the future. These communities often have limited ground transportation systems and access to the rest of the province as well as the provincial highway network.

The rest of the paper is organized as following: first, we briefly discuss wildfire evacuation and network vulnerability analysis and highlight our contribution to the existing literature. Next, we lay out our proposed measures in the Method section. In the subsequent sections, we discuss our case study followed by the results and discussions. Finally, we draw the conclusion while proposing potential future studies.

2. Literature Review

A disaster may result in community evacuations to remove people from danger (Arşık and Sibel Salman, 2013; Cova et al., 2009; Dombroski et al., 2006; Helderop and Grubesic, 2019a, 2019b; Li et al., 2019; McGee, 2019; Toledo et al., 2018). Because most evacuations occur mainly via the ground transportation network, most studies have focused on ground transportation network vulnerability and identification of critical network element(s) (Mahajan and Kim, 2020; Miller-Hooks et al., 2012; Oliveira et al., 2014; Wang et al., 2015). There is extensive literature on measuring and understanding transportation network characteristics, including their performance and ability to support movement in emergencies and network disruptions (Jenelius et al., 2006; Machado-León and Goodchild, 2017; Sullivan et al., 2009). However, there has been less work towards understanding wildfire-specific road network vulnerability, which is, in turn, required to plan community evacuation support strategies and infrastructures.

Strategic wildfire evacuation planning across a large jurisdiction with multiple communities is a difficult task, as it may be unknown where wildfires may originate, and how they will move and grow (and often very quickly). Thus, there are few wildfire evacuation planning studies whose geographic scopes encompass multiple regions and communities. Most existing evacuation studies are scenario-based, focusing on smaller regions or single communities (Henry et al., 2017; Li et al., 2015; Shahparvari et al., 2016a; Toledo et al., 2018). Unlike long-notice evacuations with more than 24 hours of advanced warning (i.e., hurricanes and some floods), wildfire evacuations usually require that an entire population leave within minutes to hours with little to no time to prepare (Noh et al., 2009). As a result of this, roadway capacity around the evacuating community is often of concern. Most literature focuses on evaluating and planning exit movement at the Wildland Urban Interface (WUI) around communities using simulation (Beloglazov et al., 2016; Li et al., 2019; Wolshon and Marchive, 2007), travel demand modelling methods (Intini et al., 2019), and optimization (Church and Cova, 2000; Cova et al., 2011; Lim et al., 2012, Shahparvari et al., 2016b, 2015). Studies have also been conducted to understand behavior and decision factors during evacuation (Cova et al., 2009; Cova and Johnson, 2002; Dombroski et al., 2006; Toledo et al., 2018), and challenges during the evacuation process (Beverly and Bothwell, 2011; McGee et al., 2015; McGee, 2019). A few studies investigate large-scale wildfire evacuation planning. Shahparvari et al. (2016b, 2016a) looked into multi-region evacuation planning, while Taylor and Freeman (2010) evaluate the large-scale evacuation of Australian bushfires. However, these studies are similar to the community-level studies in that they assume the entire region evacuates due to a major wildfire – they are not concerned with strategic planning for potential wildfires that can occur anywhere across a large region.

While most studies observe network topology and measure network performance by travel time using the shortest path (Jenelius and Mattsson, 2015; Mahajan and Kim, 2020; Sullivan et al., 2010), other factors such as community exit capacity, bottleneck locations, and the impacts of road disruption on evacuating capacity are also important (Zhang and Alipour, 2020). Staes et al. (2021) used data collected from radar detectors to identify bottleneck locations and the time to reach capacity. The min-cut max-flow (MCMF) theorem can be used to find the bottleneck capacity (or maximum allowable flow) and location over all possible routes within a network, for an origin-destination (OD) pair (Ford and Fulkerson, 1956). This theorem has been used to determine the capacity (and routes contributing to this limiting capacity) of en-route air sectors in aviation (Krozel et al., 2007; Namuduri and Soomro, 2017). This theorem has been applied on ground transportation networks to identify the bottleneck capacities/maximum flow between OD pairs across a network (Dong and Zhang, 2011; Kim et al., 2008; Moore et al., 2013; Qu et al., 2019; Yang et al., 2008) reduce congestion (Abdullah and Kien Hua, 2017; Hua and Abdullah, 2017), and to estimate the earliest clearance times of, and arrival to, communities (Baumann and Skutella, 2009; Church and Cova, 2000; Zheng and Chiu, 2011). Only a handful of literature applies this theorem for evacuation planning: Yang et al. (2008) did a theoretical study of the application of the min-cut max-flow (MCMF) theorem to assign evacuation flow by identifying bottleneck locations and their capacities on a network relative to an evacuating community. Kim et al. (2008) applied this theorem in their study of evacuation due to power plan failure, proposing contraflow at the bottleneck section to increase the egress capacity. These studies found that bottlenecks appeared at egress points but, depending on network topology, bottlenecks may occur farther downstream, particularly for remote communities.

Thus, this paper aims to provide a method to illuminate where and to what degree of importance network facilities have in providing transportation capacity between evacuating communities and their host communities, across a large region, using the MCMF theorem with the grid disruption approach and two performance measures (escape capacity criticality and max-flow impact index, introduced in Section 3.3). The method provides a common platform to quickly and easily evaluate many communities across a large region, to support strategic efforts in allocating resources towards communities that may be at greatest risk in a wildfire evacuation event. These resources would be used to further study each community in greater detail and develop detailed evacuation plans and identify necessary infrastructure investments. Our contributions are in the development of a simple, fast, and easy-to-apply network capacity scanning method for a real-life, large-scale network (as opposed to the test networks common in the literature), using the grid-based approach, that provides a first step in identifying potentially problematic network locations towards facilitating a more targeted and detailed community analysis in strategic planning stages. We see this method as a first step towards the development of detailed community wildfire evacuation plans, and infrastructure investment and maintenance plans.

3. Method

We assess the importance of the contributions of network links to the bottleneck capacities between evacuating communities and their destinations (host communities) using the MCMF theorem combined with grid cell disruption. The MCMF theorem can be applied to find the maximum flow per unit time using all available routes in a network without exceeding capacity. Observing how the removal of a set of links within a grid affects the maximum flow between an origin and destination can help identify the importance of these links in a community evacuation. We use grid cell disruption, as opposed to doing so link by link, to reduce computation time. These methods are discussed here.

3.1 Min-Cut Max-Flow Theorem

Let us define a cut to be a set of links that, when removed, separate a network into two sub-networks. A min-cut occurs at the minimum capacity location on the network between an origin-destination (OD) pair – this is the network bottleneck for the OD pair. The min-cut is not always unique, and there may be multiple min-cuts in a network. Max-flow is the maximum flow allowed through the network for an OD pair and is equivalent to the min-cut capacity (i.e. the bottleneck capacity for a transportation network (Kim et al., 2008)).

To illustrate with an example, say $G(N, L)$ is a network with nodes and links shown in Figure 1~~Figure 1~~. The values in parentheses are link capacities, in flow units per unit time. Nodes O and D are origin and destination with a population of 30 and 50, respectively. Removing links b and c divides the network between O and D in two, with cut capacity of 20 (=10+10). Similarly, $\{a\}$, $\{c, d, e, f\}$, and $\{e, f, g\}$ are other sets of links that, if cut, isolate O and D. Each cut set has a capacity and the lowest cut capacity, among all possible cuts, is 15 at $\{e, f, g\}$ (Figure 1~~Figure 1~~b). Thus, link set $\{e, f, g\}$ is the min-cut (i.e., bottleneck) for this network with a maximum allowable flow (or bottleneck capacity) of 15 flow units per unit time (Figure 1~~Figure 1~~c).

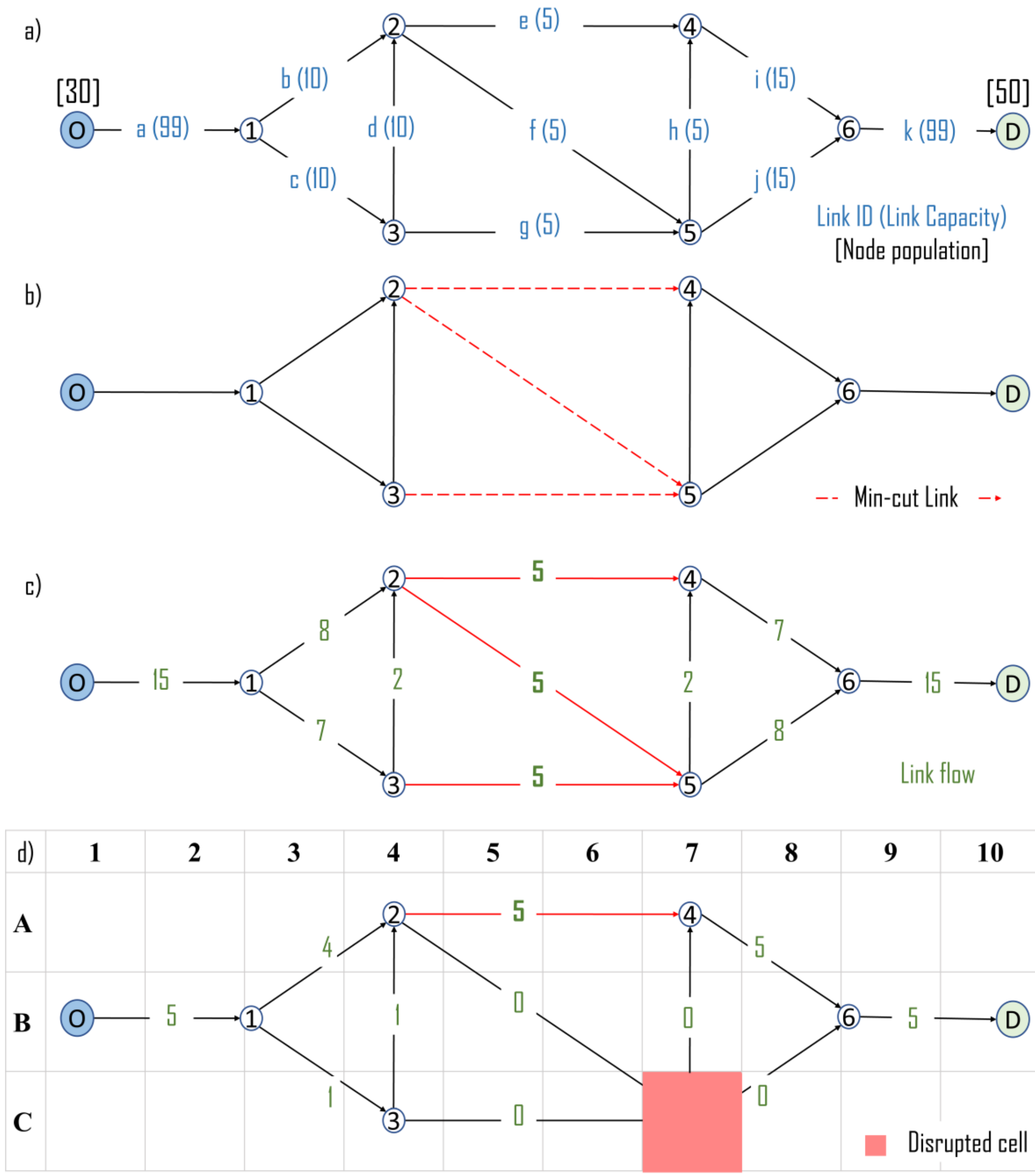

Figure 1: Min-cut Max-flow example: a) Network, b) Min-cut between O and D, c) Max-flow between O and D, and d) Residual network with disrupted cell C7

We can determine the importance of a link (or group of links) in contributing to an OD pair's network bottleneck capacity by applying this theorem before and after removing the link.

3.2 Grid Disruption

Natural disasters like wildfires and earthquakes are likely to disrupt multiple links at close proximity (Günneç and Salman, 2011). A grid-based approach, grouping link segments within a grid together, can mirror the area-wide disruption following such disasters (Jenelius and Mattsson, 2012). Also, modelling the disruption of individual links one-by-one on a large network can be computationally expensive with a scanning method – computation times will be multiplied by the average number of links contained within cells. We follow previous researchers (Günneç and Salman, 2011; Helderop and Grubesic, 2019a, 2019b; Jenelius and Mattsson, 2015, 2012) and overlay a grid with cells of equal shape and size over our study network, introduced in Section 4.1 and Figure 2~~Figure 2~~, in order to investigate area-wide network failure. The cell size of a grid is chosen based on study scope, network scale, and computational capabilities. It is finer for studies over smaller geographic scales, with denser transportation network (e.g., 20x20 m^2 for a small urban community (Helderop and Grubesic, 2019b, 2019a)) or coarser for larger regions (e.g., 25x25 km^2 for the Swedish road network (Jenelius and Mattsson, 2012)). A smaller cell size will emphasize road network characteristics and yield similar results to a single link failure analysis, while a larger cell size will shift focus to disruption characteristics (Jenelius and Mattsson, 2015, 2012). Moreover, another wildfire evacuation study focuses on the area within a 10 km radius of a target location (Beverly and Bothwell, 2011). Therefore, considering the size of our study area (1.5 times that of Sweden) and network density, we choose a 20x20 km^2 square cell grid consisting of 70 rows and 44 columns to cover our study area. The Alberta highway network appears in 920 of the 3,080 resulting cells. We believe this grid balances road network detail needs against computational efficiency. Note that in a community-focused analysis of local roads, a smaller cell size like that of Helderop and Grubesic (2019b, 2019a) should be adopted.

We disrupt grid cells containing network elements one at a time. When we disrupt a grid cell, we assume that all network elements contained within the cell are effectively disabled or removed, leaving a residual network. For the example network in Figure 1, a grid of 10 columns and 3 rows is overlayed on the network, and cell C7 is disrupted to obtain the residual network (Figure 1d). The performances of the base and residual networks are compared using the metrics introduced in Section 3.3 to determine whether, and to what degree, links in a disrupted grid cell contribute to OD's bottleneck capacity. A reduction in a residual network's bottleneck capacity indicates that the network elements of the disrupted cell contributed to its bottleneck capacity.

3.3 Escape Capacity Criticality and Max-flow Impact Index

We present metrics measuring the contribution of network links to the bottleneck capacity between an evacuating community and the destination host community. The purpose is to identify where the facilities contributing significantly to the bottleneck capacity are with respect to the evacuating community.

Escape capacity criticality measures the contribution of network elements within a grid cell to the bottleneck capacity between an evacuating community and a destination. We first determine the bottleneck capacity between ODs (i, j) on an existing network, F_{ij}. Disrupting grid cell c, i.e., removing all links within the cell, leaves a residual network. We recalculate the bottleneck capacity between i and j for this residual network with disrupted cell c, F_{ij}^c. We compare F_{ij} and F_{ij}^c to calculate escape capacity criticality.

$$Cr_c = \begin{cases} \frac{\sum_i \sum_{j \neq i} \frac{F_{ij} - F_{ij}^c}{F_{ij}}}{\sum_i \sum_{j \neq i} \delta_{ij}^c}, if \ \sum_i \sum_{j \neq i} \delta_{ij}^c > 0 \\ 0 \qquad , if \ \sum_i \sum_{j \neq i} \delta_{ij}^c = 0 \end{cases}, Cr_c \in [0,1] \qquad \text{(Eq. 1)}$$

Where:

Cr_c = Escape capacity criticality of network facilities of grid cell c

F_{ij} = Bottleneck capacity from origin i to destination j on the existing network (before disruption)

F_{ij}^c = Bottleneck capacity from i to j on the residual network (after disrupting cell c)

$\delta_{ij}^c = \begin{cases} 1 \ , if \ F_{ij} \neq F_{ij}^c \\ 0 \ , otherwise \end{cases}$

Higher Cr_c values indicate that the network facilities in c make a greater contribution to the network bottleneck capacity of an OD pair. A Cr_c of 1 means the disruption of links within disrupted cell c will completely disconnect all OD pairs. A Cr_c of 0 means that no OD pairs are affected by c's disruption, i.e., $F_{ij} = F_{ij}^c$ for all i and j.

Escape capacity criticality considers all OD pairs to be of equal importance. However, because communities differ in population, wildfire occurrence likelihood, and economic and administrative roles, the ability to consider these in a metric of general network impact may be useful. Thus, we assign a weight ω_{ij} on the bottleneck capacity reduction between each OD pair. One could use community population size, natural disaster, and evacuation likelihood, or other considerations to determine weights. When a cell disruption degrades bottleneck capacity, the impact is calculated by taking the average of the weighted change of the bottleneck capacity reciprocal across all OD pairs:

$$MI_c = \frac{\sum_i \sum_j \Delta M_{ij}^c}{N} \qquad \text{(Eq. 2)}$$

Where:

MI_c = Max-flow impact index of cell c

$$\Delta M_{ij}^{c} = \begin{cases} \omega_{ij}\left(\frac{1}{F_{ij}^{c}} - \frac{1}{F_{ij}}\right), & if F_{ij}^{c} > 0 \\ \omega_{ij} & , Otherwise \end{cases}$$

ω_{ij} = Weight for i, j

N = Total OD pairs = $\begin{cases} I * (I-1), & if\ I = J \\ I * J & , if\ J \notin I \end{cases}$

Here, we use the demand between i and j as the weight ω_{ij} (Eq. 2), obtained using a production-constrained gravity model $\left(\omega_{ij} = D_{ij} = \frac{P_i P_j d_{ij}^{-2}}{\sum_j P_j d_{ij}^{-2}}\right)$. P_i and P_j are the populations of the origin and destination communities, respectively, and d_{ij} is the shortest distance between these communities according to Dijkstra's algorithm. When only one OD pair is considered, we use the origin population for the weight, i.e., $\omega_{ij} = P_i$.

Recall the example network (Figure 1a), where the min-cut capacity between an origin (*O*) and destination (*D*), F_{OD}, was 15 units and the population of node *O*, P_O, was 30. Now, disrupting cell C7 (Figure 1d) will generate a residual network in which links *f*, *g*, *h*, and *j* are disconnected. Applying the MCMF theorem on this residual network, the maximum allowable flow (or bottleneck capacity), F_{OD}^{C7}, is determined to be 5 flow units per unit time while $\{e\}$ being the min-cut (i.e., bottleneck) for this network. Using Eqs 1 and 2, the *Cr* and *MI* for cell C7 are 0.67 and 4.0, respectively. The *Cr* value suggests that road segments within this cell contribute to 67% of the bottleneck capacity between OD.

3.4 Method Implementation

We used the Boykov-Kolmogorov algorithm (Boykov and Kolmogorov, 2004) in MATLAB for calculating bottleneck capacity, F_{ij} for the existing (undisrupted) network from each origin i to predetermined destinations j. We then remove all links within cell c to obtain the residual network and, using the same algorithm, recalculated bottleneck capacity after disruption, F_{ij}^{c}. We repeated this for all OD pairs, using Eqs 1 and 2 to calculate Cr_c and MI_c for cell c. We then restore the links in c and move on to the next cell, repeating this process until all cells are analyzed.

4. Case Study

4.1 Study Area

The province of Alberta, Canada covers 660,000 km^2, with about 75% of its population of over four million concentrated in the economic regions of Edmonton (the provincial capital) and Calgary (Statistics

Canada, 2019) (Figure 2~~Figure 2~~). The northern part of the province is sparsely populated and thus served by a sparse transportation network. The largest urbanized areas in northern Alberta are Fort McMurray in the east and Grand Prairie in the west, with permanent populations of about 60-70,000 as of 2016. Boreal forest covers 57% of the province, covering nearly the entire northern half (Alberta Wilderness Association, 2019). Unlike the forests of the Pacific Northwest, boreal forests are more susceptible to wildfires (Natural Resources Canada, 2020a). With increasing extreme fire-weather days and decreasing soil moisture, the boreal forest is becoming more flammable (Stralberg, et al., 2018), and an increasing trend in both frequency and intensity of wildfires is expected in Alberta (Bush and Lemmen, 2019).

Among all Canadian provinces and territories, between 1980 and 2018 Alberta had the second-highest 10-year average of wildfire occurrences (Natural Resources Canada, 2020b) as well as total wildfire evacuations (Natural Resources Canada, 2020c). Some of the largest wildfires, in total hectares, are the 1982 Keane, 2002 House River, 2011 Richardson, 2016 Horse River, 2019 McMillan, and 2019 Chuckegg Creek Fires (Alberta Wildfire, 2020a). The Horse River Fire, also known as the Fort McMurray wildfire, led to the costliest evacuation in Canadian history (Insurance Bureau of Canada, 2016). Approximately 90,000 people were evacuated over five days from Fort McMurray, the central urban area of the Alberta oilsands industry. The Chuckegg Creek Fire resulted in the evacuation of several communities including High Level and Slave Lake. Surrounded by boreal forest, High Level is the northernmost town in Alberta, experiencing multiple wildfires each year and holding the record for most class E[1] wildfires in the province since 2006 (Alberta Wildfire, 2020b). The town of Slave Lake is also frequently threatened by wildfire, and evacuated with the surrounding municipal district in the 2011 Richardson Fire. The towns of Edson, Whitecourt, as well as Yellowhead and Mackenzie Counties, are other potentially fire-prone communities in Alberta, and also have limited access to the transportation network given their remote locations. Therefore, we aim to determine the locations and capacities of bottlenecks on the Alberta Highway network with respect to these communities. Alberta's evacuation guidelines state that a host community can accommodate evacuees that number up to 10% of the community's population (Government of Alberta, 2018). Therefore, the nearest major economic centers, with the necessary capacity to provide evacuees with shelter, other services, and supplies, were selected as host communities and we assume that all evacuees will travel to their nearest economic centers.

[1] Wildfire classification defined for a final burnt area exceeding 200 ha.

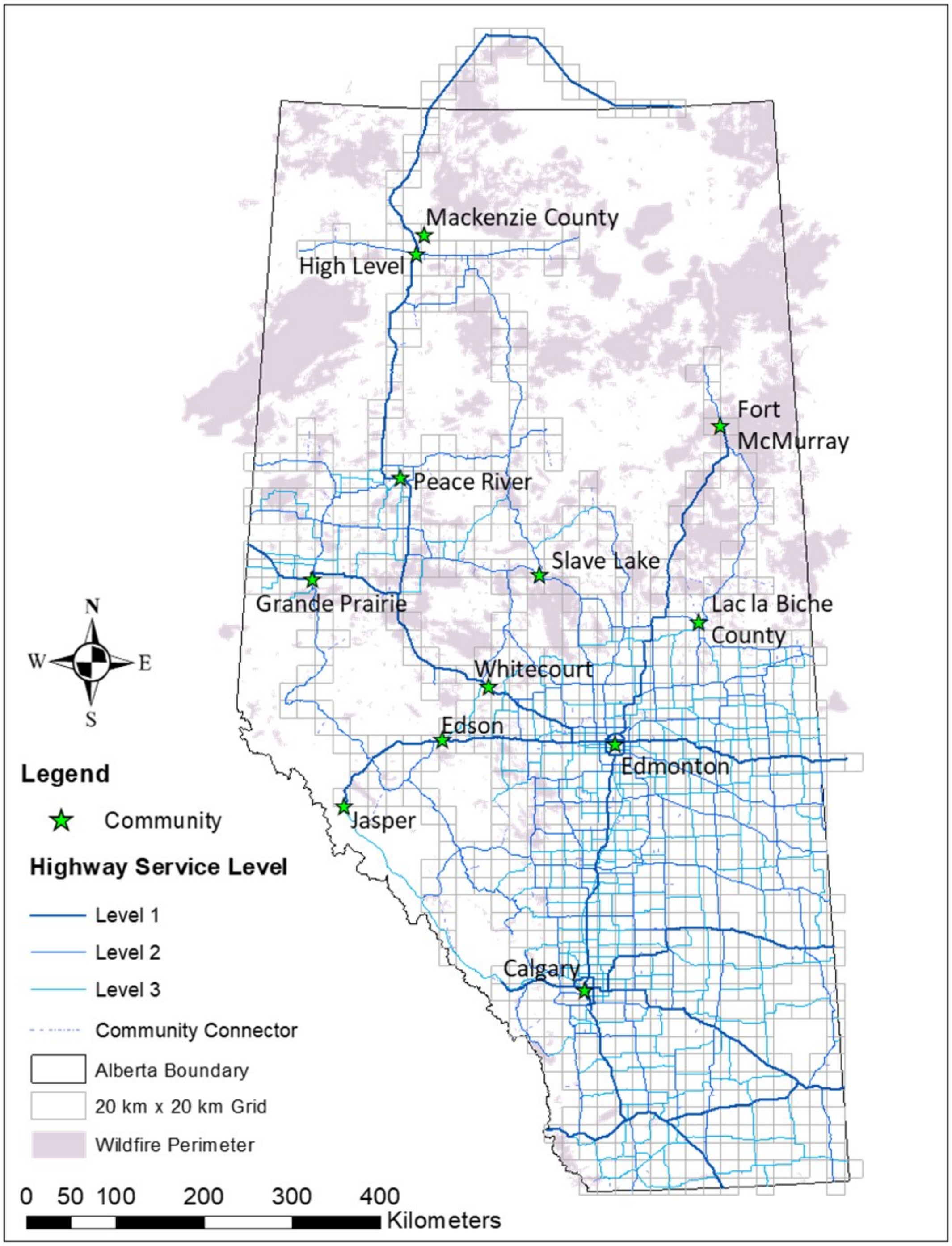

Figure 2: Map of Alberta

4.2 Provincial Highway Network

Alberta's provincial highways are divided into four service classes (Levels 1 through 4) based on Annual Average Daily Traffic (AADT) estimates, vehicle composition, etc. (Stantec Consulting Limited, 2007).

Level 1 highways are the core routes of the National Highway System serving inter-provincial and international trips. Level 2 arterial highways accommodate intra-provincial long-distance travel and feed into Level 1 highways. Level 3 collector highways primarily facilitate inter-county trips and can be accessed by Level 2 or 4 facilities. Level 4 local highways accommodate local movement. In this study, we consider Levels 1-3 facilities, aggregating Level 4 facilities to represent them with virtual connectors that feed evacuating demand to higher-level facilities.

4.3 Data Collection

We obtained the highway network shapefiles from Alberta Transportation, which contained the attributes of each highway segment (e.g., route number, lane number, posted speed limit, presence of median, capacity, etc.). In the absence of detailed information regarding lane widths, shoulder widths, etc., we used the number of lanes, presence of median, and highway level to calculate base capacities using the Highway Capacity Manual (Transportation Research Board, 2016). We also accessed community boundary shapefiles from Statistics Canada, and population center locations and census data through 2016 *GeoSuite* (Statistics Canada, 2017a, 2017b), a Statistics Canada tool. The data contains community name, type, code, Statistical Area Classification (SAC) type, the population counts for 2016 and 2011, total dwelling count, area, and representative point (i.e., community centroid) coordinates for communities.

5. Results

We assessed five relatively remote and potentially fire-prone communities, assuming evacuation to the nearest major economic center(s). The communities studied in this paper have a remoteness index (RI) between 0.4-0.7 (Alasia et al., 2017). The remoteness index for a community i is calculated as the log of the sum of the ratio of population of each population center k (Pop_k) and the travel time between community i and population centers k $\left(C_{i,k}\right)$: $RI_i = ln \sum_k \left(\frac{Pop_k}{C_{i,k}}\right)$. These communities differ with respect to their access to the provincial highway network. As expected, the facilities contributing most to OD bottleneck capacity are adjacent to evacuating communities[2]. In addition, we find that, depending on network topology and connectivity, a highway with low capacity may contribute a higher share to the

[2] This was found to be true in all cases whether or not Level 4 facilities were included.

bottleneck capacity around a community than a similar low-capacity highway in a denser part of the province.

5.1 Edson to Edmonton and Grande Prairie

The Town of Edson had a population of 8,414 as of 2016 and has four egress alternatives. The multilane Hwy 16 runs east-west through the town, Hwy 748 serves as a collector highway at Edson's northern periphery, and Hwy 47 runs south just west of the town boundary. When moving from Edson to Edmonton and Grande Prairie, the importance of facilities is illustrated in Figure 3a.

Cells east of Edson have high Cr values, indicating that the multilane Hwy 16-eastbound is important to facilitating short-notice evacuation out of Edson. Disruption of these cells will divert evacuees to the two-lane highways, Hwys 748 and 47, at a reduced total bottleneck capacity. The cell immediately west of Edson has a Cr value of 0.25. Disrupting this cell will only allow an eastbound evacuation on Hwy 16-eastbound and collector Hwy 748, at a 25% decrease in bottleneck capacity. If we look at cells further west on Hwy 16, their escape capacity criticality is 0.02. Links within these cells contribute very little to the bottleneck capacity and disruption of these cells will result in only a 2% decrease in bottleneck capacity as evacuees have alternative routes (Hwys 47 and 748) to escape.

Hwy 40-north is one of two Level 1 highways connecting Edson and Grand Prairie, with a Cr value of 0.27. Theoretically, Hwy 40 can also be used to reach Edmonton, but it is a much longer route. Although it has been shown that people are more likely to use familiar routes in an evacuation (Sadri et al., 2014), Hwy 40 provides an alternative egress for emergency managers to direct evacuees as needed. The low Cr value for cells along Hwy 40 suggest that it has a very low contribution to the bottleneck capacity and other highways (primarily Hwy 16) are more important in this regard. Although Hwy 40-north and Hwy 40-south have equal contributions to bottleneck capacity between Edson and Edmonton, Hwy 40-north contributes more to the bottleneck capacity between Edson and Grande Prairie than that of Hwy 40-south. As a result, the combined effect shows a higher Cr value for Hwy 40-north. Furthermore, Edmonton, being a closer and larger service center than Grande Prairie, will attract more evacuees. Therefore, routes to Edmonton (i.e., Hwys 16 and 40-south) have higher MI values.

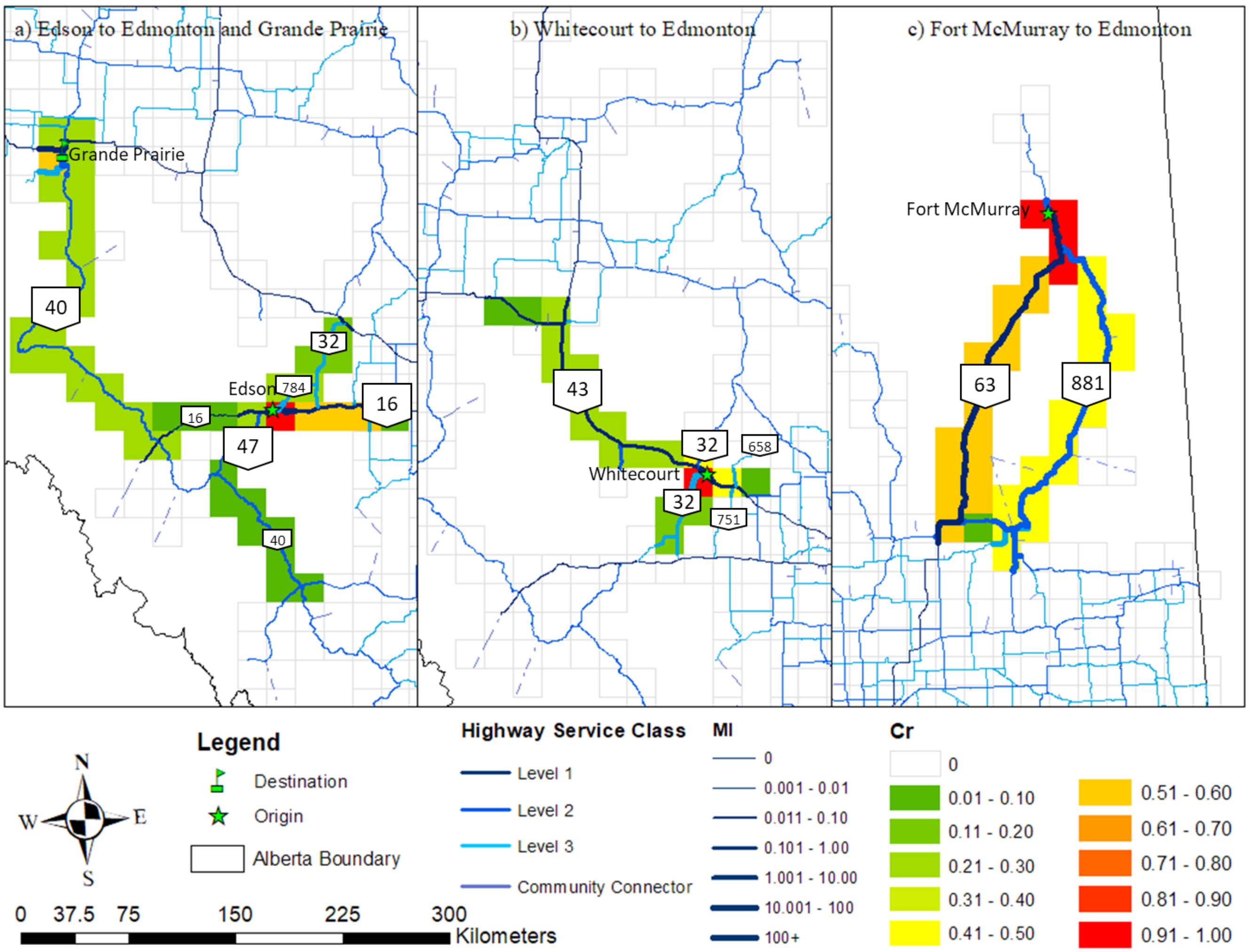

Figure 3: *Cr* and *MI* for a) Edson to Edmonton and Grande Prairie, b) Whitecourt to Edmonton, and c) Fort McMurray to Edmonton

5.2 Whitecourt to Edmonton

Whitecourt is a town of approximately 10,000 located 180 km northwest of Edmonton, at the juncture of Hwy 43 (running roughly east-west) and Hwy 32 (north-south) (Figure 3b). To leave Whitecourt using provincial highway facilities, evacuees must take Hwy 43 (both eastbound and westbound) or Hwy 32 (southbound). Hwy 43 is a multilane highway and thus has a higher capacity than that of the two-lane Hwy 32. Evacuees can either travel northbound on Hwy 32 after traveling west for 7 km on Hwy 43, or continue on Hwy 43. Figure 3b shows the results of applying the two metrics. A Cr value of 0.42 indicates that Hwy 43 (eastbound) in the immediate vicinity provides 42% of the bottleneck capacity. The same highway facility in the adjacent cell directly east has a lower Cr (= 0.11), because when this segment of

Hwy 43 is not operational, 89% of the bottleneck capacity can be provided when evacuees use Hwy 658 and Hwy 751. We observe the high Cr value of the cell immediately north of Whitecourt and low Cr values for the westbound segments of Hwy 43 in a similar fashion. If the wildfire grows north of Whitecourt, egress routes using Hwy 32 (northbound) and Hwy 43 (westbound) may be inaccessible. For cells containing Hwy 32 (southbound from Whitecourt), $Cr = 0.2$ – lower than that of the westbound segment of Hwy 43. Emergency managers may want to consider prioritizing fire suppression and encroachment away from facilities with the highest Cr values, and consider investments to maintain facility infrastructures, in order to preserve higher community evacuation capacities (and thus, potential community evacuation speed).

5.3 Fort McMurray to Edmonton

Fort McMurray is a city in the heart of Alberta's oilsands industry. It is connected to the rest of the province via a single multilane, divided provincial highway facility, Hwy 63 (Figure 3c). Further south, it splits into Hwy 63-south and Hwy 881 (the latter a two-lane undivided facility). Therefore, Hwy 63 north of this intersection is critical with $Cr = 1.0$. South of the intersection, Hwy 63 has a higher Cr value than that of Hwy 881, due to differing directional capacities and thus, contributions to the bottleneck capacity from Fort McMurray to Edmonton. Disrupting either Hwy 63-south or Hwy 881 (over the "loop") reduces bottleneck capacities by 58% and 41%, respectively. Although Hwy 881 is not typically used for regular travel between the two cities (it is not as direct or fast as Hwy 63), it provides an important contribution to the overall travel capacity necessary during an evacuation scenario. During the 2016 Horse River Fire, due to traffic management (or lack thereof), Hwy 63 experienced significant congestion while Hwy 881 was largely underutilized (Woo et al., 2017). Overall, given the lack of facilities directly southbound out of Fort McMurray, contraflow operations at least to the intersection of 62/881 should be considered as part of the emergency management plan, if only to facilitate more capacity and easy left-turn access onto Hwy 881. The provincial government has considered an additional roadway southbound from Fort McMurray, given its concentrated population within the boreal forest (Global News, 2016).

5.4 High Level to Peace River

Hwy 58 runs east-west and Hwy 35 runs north-south through High Level, the northernmost town in Alberta. There are only two direct access highways – Hwys 35 and 58 – to evacuate south towards Peace River, the nearest economic center (Figure 4a). With approximately the same capacity, Hwys 35, 58, and 88 contribute to the bottleneck capacity equally, and disruption of any of these highways will obviously reduce the bottleneck capacity to half due to lack of alternatives. Therefore, we observe Cr values of 0.5

for these highways. However, $Cr = 0$ for Hwy 986 because in the event of it not being accessible, evacuees can travel further south on Hwy 88 and take a detour to Peace River (or another host community).

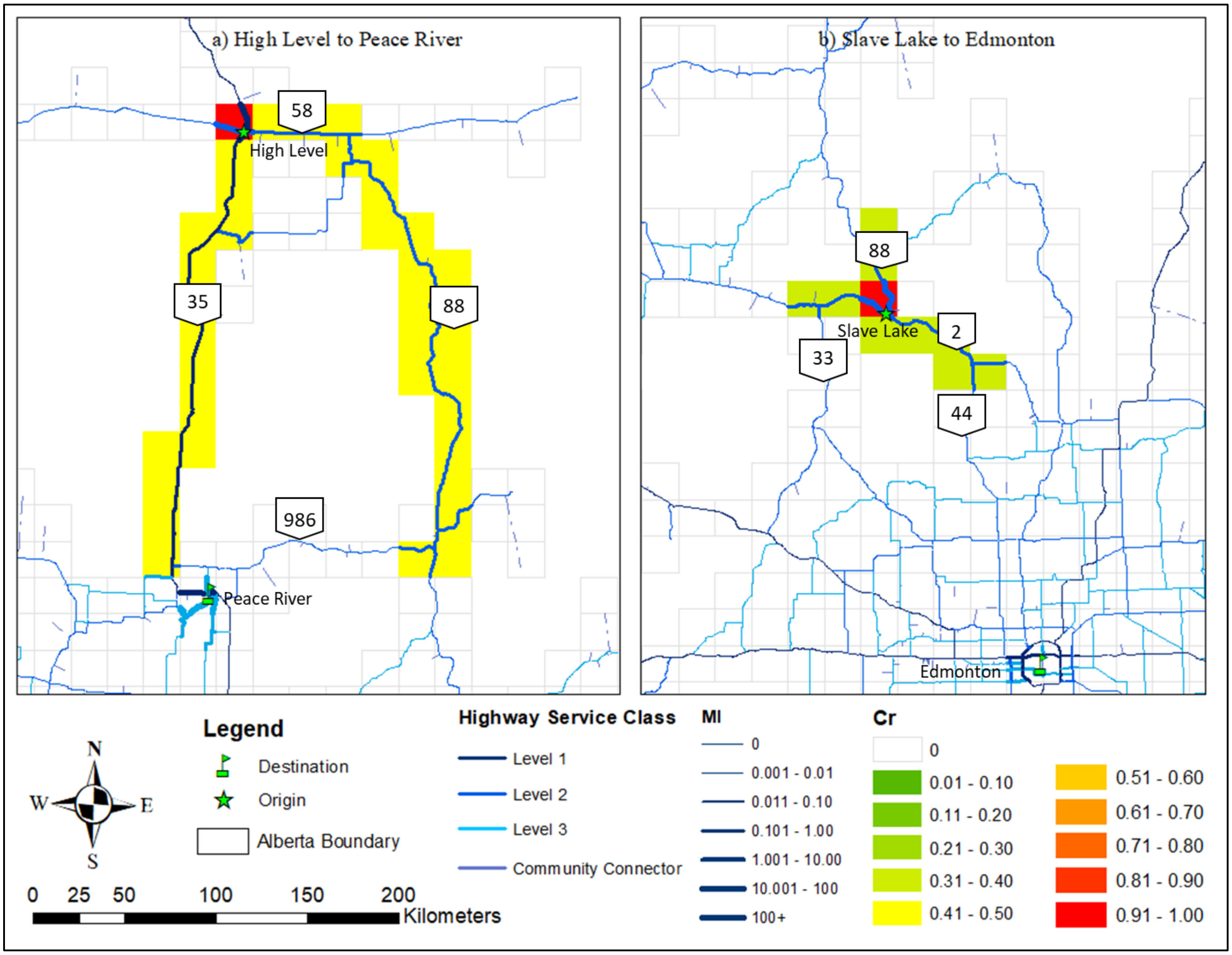

Figure 4: *Cr* and *MI* for a) High Level to Peace River, and b) Slave Lake to Edmonton

5.5 Slave Lake to Edmonton

Slave Lake, a town of 6,651 residents as of the 2016 census, is located west of the intersection of Hwys 2 and 88, two-lane Level 2 highways with directional capacities of 2000 vph. Unlike Edson or Whitecourt, there are three main travel routes of equal capacity, out of Slave Lake: northbound on Hwy 88, eastbound on Hwy 2, and westbound on Hwy 2. As per Figure 4b, all three routes contribute equally to the bottleneck capacity between Slave Lake and Edmonton. Once westbound travelers are past the intersection of Hwy 2 and Hwy 33, or eastbound travelers past Hwy 2 and Hwy 44, they have more alternatives to reach Edmonton and thus Cr values beyond these points are zero.

5.6 Multiple Communities to Edmonton

Figure 5 illustrates the average escape capacity criticality and max-flow impact index for ten wildfire-prone communities evacuating to Edmonton. We are not assuming communities are evacuating all at once. Rather, we aim to identify the segments that, on average, contribute more to community bottleneck capacities, and have higher community evacuation demands.

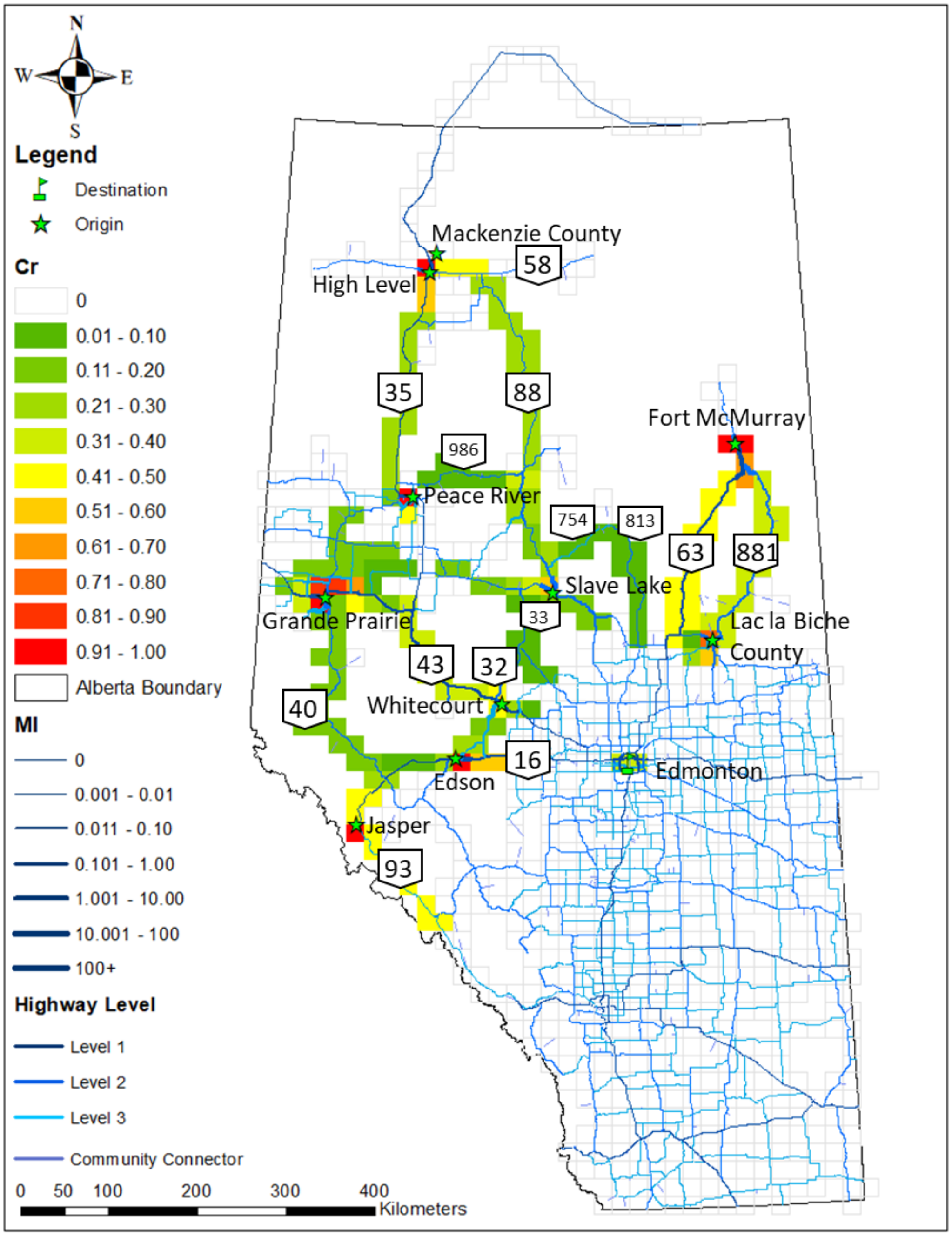

Figure 5: ***Cr*** **and** ***MI*** **for evacuating from 10 communities to Edmonton**

As shown earlier, cells immediately adjacent to origin communities are most critical, reinforcing the importance of community-level evacuation studies and municipal evacuation plans (Cova et al., 2013). As expected, cells covering denser parts of the network (and thus, with more routing alternatives) are of lower criticality compared with those covering sparser parts. Hwy 63 directly south of Fort McMurray, Hwy 35 directly south of High Level, Hwy 16 directly east of Edson, and Hwys 16 and 93 adjacent to Jasper are among the most critical. Disrupting these facilities will reduce bottleneck capacity by 50% or more. Despite that Hwys 43 and 16 have a higher capacity than that of Hwy 881, cells along Hwy 881 have Cr values higher than Hwy 16 (westbound of Edson) and the same as Hwy 43 due to lack of alternative routes. This suggests that solely referencing capacity for prioritizing highway investments in light of emergency evacuation needs can be misleading, because depending on network topology and connectivity, a highway with low capacity may contribute a higher share to the bottleneck capacity around a community. Cells on Hwys 986, 754, 813, and 33 add very little to bottleneck capacity as several alternative routes are available and hence can be assigned a lower priority.

Hwys 63-south (on the "loop" with 881), 93, and 58 have similar Cr values, but the MI value for Hwy 63 is higher than those of Hwys 93 and 58. These facilities serve communities where the transportation network is sparse. However, Fort McMurray has a larger population, and thus, disrupting Hwy 63 will have a much greater impact than disruptions on facilities serving the much smaller communities of High Level or Jasper.

6. Conclusions

We assess the bottleneck capacity of a road network for evacuating communities throughout Alberta. During a wildfire, major roadways important to a community's egress may become inaccessible, reducing the capacity available for community members to quickly evacuate towards their destination. Therefore, we investigate the importance of roadway facilities by applying two new measures, Cr and MI, that determine the contribution of these facilities to network bottleneck capacity between an evacuating community and its host community.

Our result confirms that, based on long-distance roadway network topologies, all critical links are located in the vicinity of communities, affirming wildfire evacuation studies that focus on the immediate area around an evacuating community. Higher roadway link Cr values are observed where the network is sparse, and communities have few alternatives. In such cases, roads with low capacity and/or less-travelled roads may be critical to accommodating evacuating traffic, yielding higher Cr values than roads with the same capacity in a denser part of the network. If a community has multiple alternatives with the same Cr

values (e.g., Slave Lake, High Level, Jasper), agencies can look at other characteristics of the infrastructure, traffic operations, and demand to prioritize and develop evacuation routes. We also considered evacuation demand alongside bottleneck capacity to determine the weighted importance for road segments. Roadways serving multiple and/or large communities will have higher MI values, despite offering the same contribution to bottleneck capacity (Cr).

This simple method can become a tool in an agency's strategic wildfire evacuation planning activities, particularly to guide the allocation of limited emergency planning resources to communities across its jurisdiction – resources that can go towards communities found to be at higher risk for evacuation problems. These resources can be used to support geographically specific, operational studies that model the dynamic and stochastic nature of evacuation movement, resulting in detailed community evacuation and emergency operations plans, and identification and prioritization of infrastructure needs. Our results may also be used to inform fire management strategies, such as decisions at trigger point locations.

There are many directions for further research. This method can be adjusted with finer cell size and local road and congestion effect to study egress opportunities within a community. An important next step is to calculate other measures through the grid disruption method by mapping out fire pathways, and how fire pathways interact with the roadway network (including the density of interactions within grid cells). Also, there is an abundance of literature on accessibility measures, which may be adapted and applied through this grid disruption method to support short-notice wildfire evacuation from a strategic planning perspective.

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