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Assessing the operational impact of infrastructure on Arctic operations

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Abstract

With the reduction of ice coverage in the Arctic, access to Canadian territorial waters such as the Northwest Passage is becoming feasible over a wider area and time span. As a result, maritime traffic through the area is expected to grow, increasing the likelihood of Canadian Armed Forces domestic operations in the region. We present analytical work on the effect of sparse logistical infrastructure on military operations in the Canadian Arctic region, whose purpose is to inform Department of National Defence and Canadian Armed Forces infrastructure investment decisions. We focus on a major maritime disaster scenario requiring the evacuation of a large cruise ship. We examine the transportation and logistics component of the problem using a mixed-integer programming capacitated vehicle routing model. Factors considered include the current Canadian Armed Forces force deployment and response posture, transit to forward operating locations, vehicle capacity, fuel requirements, the time-degradation of the medical state of the evacuees, and triage decisions at loading time. The model is applied over all feasible combinations of forward operating locations and a grid of accident locations to assess performance over the entire region and the impact of procedural and infrastructure changes.

Significance for defence and security

This scientific report lays out a means by which the Department of National Defence can assess the operational impact of changes to infrastructure on the Canadian Armed Forces' capability to operate within the Canadian Arctic.

Résumé

Avec la réduction de la couverture de glace dans l'Arctique, l'accès aux eaux territoriales canadiennes telles que le passage du Nord-Ouest devient possible sur une zone et une période de temps plus large. Par conséquent, le trafic maritime dans la région devrait augmenter, ce qui augmentera la probabilité d'opérations nationales des Forces armées canadiennes dans la région. Nous présentons un travail analytique sur l'effet d'une infrastructure logistique clairsemée sur les opérations militaires dans la région de l'Arctique canadien, dont le but est d'éclairer les décisions d'investissement dans l'infrastructure du ministère de la Défense nationale et des Forces armées canadiennes. Nous nous concentrons sur un scénario de catastrophe maritime majeure nécessitant l'évacuation d'un grand navire de croisière. Nous examinons la composante transport et logistique du problème à l'aide d'un modèle de routage de véhicule capacitif à programmation en nombres entiers mixtes. Les facteurs pris en compte comprennent la posture actuelle de déploiement et d'intervention des Forces armées canadiennes, le transit vers les lieux d'opérations avancés, la capacité des véhicules, les besoins en carburant, la dégradation dans le temps de l'état médical des évacués et les décisions de triage au moment du chargement. Le modèle est appliqué à toutes les combinaisons possibles d'emplacements d'exploitation avancés et d'une grille d'emplacements d'accidents pour évaluer les performances dans toute la région et l'impact des changements de procédure et d'infrastructure.

Importance pour la défense et la sécurité

Ce rapport scientifique présente un moyen par lequel le ministère de la Défense nationale peut évaluer l'impact opérationnel des changements apportés à l'infrastructure sur la capacité des Forces armées canadiennes à opérer dans l'Arctique canadien.

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1 Introduction

Canada's Arctic and North[1] is an important theme in the (Government of Canada 2017) defence policy *Strong, Secure, Engaged*. This importance is expected to grow over time, given that climate change,[2] advancements in technology, etc. will increase the region's accessibility, resulting in greater activity from a variety of sectors, including commercial ventures, research, and tourism (Government of Canada 2019b). In turn, the frequency and magnitude of incidents, such as search and rescue, natural and man-made disasters, etc., to which the Government of Canada must respond is expected to rise accordingly. In response, Government departments are undertaking activities to provide a safe, secure, and well-defended Canadian Arctic and North, including:

- the Canadian Coast Guard is extending the season for icebreakers to enhance, amongst other objectives, the Government's search and rescue response capability (Government of Canada 2018a);
- Transport Canada is strengthening its National Aerial Surveillance Program through building a hangar and accommodations unit in Iqaluit in order to improve its surveillance of ships within the region (Transport Canada 2017); and
- through Operation NANOOK, the Canadian Armed Forces (CAF) is improving how it operates in Arctic conditions, its coordination with Indigenous, federal and territorial governments and northern partners, and how it works with partners to best respond to safety and security issues in the Arctic (Government of Canada 2018b).

Even with such ongoing activities, the recent (Government of Canada 2019a) Arctic and Northern Policy Framework stated that "It is not difficult to imagine, for example, how a naturally-occurring or human-induced disaster in the Arctic Archipelago would place tremendous strain on the capacities of all levels of government, as well as on local communities, to support affected people and minimize the damage to affected wildlife, infrastructure, and ecosystems."

Anticipating an increase in activity and the potential for regional resources to be overwhelmed should an incident arise, in late 2016 Canadian Joint Operations Command (CJOC) staff identified that contingency planning for Arctic and northern operations is often hindered by a lack of an enterprise-wide view of North American Arctic infrastructure and an assessment of how it may be used to support such operations. In an effort to address this gap, in April 2017

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[1] We will follow (Government of Canada 2019a) for terminology: "The following approach to the use of "Arctic" and "northern" has been taken in this document: "Arctic" is used in the international context, when referring to the circumpolar Arctic (e.g. Arctic states), while "Arctic and North" is used in all domestic contexts." "Northern partners" refers specifically to domestic partners.

[2] The (Government of Canada 2019b) report on Canada's changing climate states that "loss of snow and sea ice is reducing the reflectivity [...] of the surface, which is increasing the absorption of solar radiation. This causes larger surface warming than in more southerly regions. Because of this and other mechanisms, Canada is warming faster than the world as a whole—at more than twice the global rate—and the Canadian Arctic is warming even faster—at about three times the global rate."

Deputy Commander CJOC endorsed that CJOC Operational Research & Analysis (OR&A) undertake a study whose objectives are reproduced verbatim as follows (Rempel 2017).

1. Investigate existing database(s) of Arctic infrastructure, including those within the Department of National Defence (DND)/CAF, Other Government Departments and Agencies (OGDAs), industry and Allied (Alaska and Greenland) Arctic infrastructure that may be used to support air, land and/or sea force projection and sustainment into the Northern Area of Responsibility (AoR).[3] Recommendations regarding the integration of these data sources should be provided;

2. Where there are discrepancies in the ways or none exist already, provide better context by defining and categorizing the infrastructure capabilities into logical groupings or codes;

3. Conduct an analysis whose objective is to assist with rationalizing current and future DND/CAF investment/divestment decisions regarding Arctic infrastructure;

4. Serve as a reference to support the review of Northern Plans and any future Northern operating and sustainment concepts (Chief of the Defence Staff 2018); and

5. Be accessible to and benefit the Whole of Government team's situational awareness of what infrastructure capabilities/resources are located within the Northern AoR.

In response to the first two objectives, (Chan and Rempel 2017) (i) identified seven heterogeneous data sources related to Northern infrastructure; (ii) extracted, transformed, and loaded these into a common data store; and (iii) designed and implemented software to explore and analyse the data. Within this context, *infrastructure* is defined as "permanent installations required for military purposes" and/or "resources (such as personnel, buildings, or equipment) required for an activity" (Merriam-Webster). The software, a Microsoft Excel based application, allows a user to explore the roughly 2600 identified infrastructures, their attributes, and group infrastructure into clusters based on their geographic proximity to each other. However, the authors concluded that many attributes relevant to conducting operations, such as available fuel at aerodromes, number of hospital beds, and other various capabilities within Indigenous and Northern communities, are not generally accessible through such data sources and thus direct contact with those responsible for each infrastructure may be required to perform detailed modelling.

Of the remaining objectives, numbers four and five focus solely on disseminating the study's results and thus do not require analytical support. However, the third objective does require analytical support, and is the focus of this Scientific Report. Regarding this objective, the study's proposal included the following statement (Rempel 2017).

> The analysis portion should leverage existing Contingency Plans (CONPLANs) (e.g. SOTERIA, LENTUS, LIMPID, etc.) to compare infrastructure data to

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[3] The term "Northern AoR" means Joint Task Force North (JTFN)'s AoR.

> operational intent in order to help identify gaps/seams with respect to the CAF's ability to conduct operations in the Arctic. The analysis could provide recommendations on mitigating strategies or options to address those gaps/seams.

As indicated in the above statement, the study's proposal requested that multiple CJOC CONPLANs be considered when identifying gaps/seams for the purposes of supporting infrastructure investment/divestment decisions. While regional CONPLANs exist, this request focuses on those plans that fall within the responsibility of CJOC J5 staff rather than the regional joint task force headquarters. Example analyses of the latter are found in (Eisler and Dobias 2015, 2017, Dobias and Eisler 2017).

Considering multiple CONPLANs is akin to considering multiple criteria/objectives, where each CONPLAN may have one or more associated criteria/objectives. For example, within CONPLAN SOTERIA, the major air disaster contingency plan, each infrastructure may be assessed as to how well it contributes to minimizing the number of deceased and minimizing the CAF's response time; within CONPLAN LIMPID, the maritime and coastal surveillance contingency plan, each infrastructure may be assessed as to the amount of traffic density that may be monitored from its location; etc. Thus, from an analytical perspective, multiple CONPLANs may be considered via multi-criteria decision analysis techniques, which are explicitly designed to handle multiple criteria, even conflicting ones. There are many examples of applying these types of techniques to support infrastructure investment/divestment decisions within a defence and security context, including:

- Ewing et al. (2006) who used multiple-objective decision analysis to determine the value of infrastructure to the Unites States Army and an installation portfolio model to develop the starting point to identify potential unit realignments and base closures;
- Mason and Kerzner (2010) who developed measures of effectiveness, covering operational impact, infrastructure condition and efficiency, and economic impact, to gauge the value of major infrastructure sites and employed a consensus ranking method to create a prioritized list of infrastructure sites to be considered for divestment;
- Caron et al. (2012) who used multi-criteria decision analysis to identify advantageous operational hub locations and combinations in the Arctic and North; and
- Lambert et al. (2012) who, within the context of the Afghanistan National Development Strategy, used a scenario-informed multi-criteria approach to prioritize major infrastructure investments in Afghanistan's Nangarhar province.

To apply a multi-criteria decision analysis approach within this study, first how well each infrastructure contributes to achieving the CAF's objectives within each CONPLAN must be evaluated (violet cells in Table 1). These values may then be combined (in some fashion) across the CONPLANs to estimate each infrastructure's overall value (orange cells in Table 1).[4] Subsequently, these values can be sorted to determine key infrastructure, be

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[4] It must be emphasised that value is not measured in monetary terms, but in change in operational outcomes.

Table 1: *Assessing infrastructure value within multiple CONPLANs. Violet cells represent the infrastructures' contributions to a specific CONPLAN. Orange cells represent the infrastructures' overall values. Green cells represent infrastructure portfolio values per CONPLAN.*

Infrastructure	CONPLAN				Overall infrastructure value
	SOTERIA	LENTUS	LIMPID	···	
Resolute Bay	🟪				🟧
Cambridge Bay					
Iqaluit					
Inuvik					
···					
Infrastructure portfolio value	🟩				

overlaid on a map to depict their geographic distribution and identify gaps/seams, etc. In addition, for each CONPLAN the infrastructures' values can be combined to create an infrastructure portfolio value (green cells in Table 1). In both cases, infrastructure changes can be proposed, their contributions assessed, and resulting changes in the infrastructures' values and portfolio value per CONPLAN computed and compared with baseline values in order to gauge the impact of such changes.

While considering multiple CONPLANs is preferred as it provides a more comprehensive view of each infrastructure's contribution and the impact of potential changes, doing so is a significant challenge. The combination of roughly 2600 infrastructures and the number of existing CONPLANs, between 10 and 20, translates into greater than $25,000$ contributions that must be assessed. In addition, using mathematical modelling to compute the infrastructures' contributions requires a significant amount, perhaps months, of computing time given the number of infrastructures and CONPLANs considered.

Thus, in consultation with CJOC J5 staff it was determined that this study focus on a single CONPLAN, specifically LENTUS, in which the CAF is presented with significant logistical demands.[5] Furthermore, CJOC J5 staff choose to focus on a single scenario—Major Maritime Disaster (MAJMAR) scenario occurring within the Northwest Passage (NWP)—for two reasons. First, from a logistical perspective it is a high demand scenario. Second, the CAF's response to a MAJMAR in Canada's Arctic has not been studied in detail, and thus such an analysis would be beneficial beyond this study's scope.[6]

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[5] CONPLAN LENTUS is concerned with aid to the civil power and is typically invoked to deal with emergencies and disasters. From a logistical perspective, the largest likely military response to a LENTUS event in Canada's Arctic involves an Immediate Reaction Unit (IRU) of approximately 500 persons, with associated equipment, plus an unspecified number of military aircraft.

[6] The CAF's response to a MAJMAR scenario in Canada's Arctic was discussed by Boileau et al. (2010), however their work focused on equipment and human physiology. Poitras (2017) also discussed the CAF's response to a maritime scenario in Canada's Arctic; however, the scenario involved two individuals in distress.

Because of the nature of the scenario the infrastructure considered is limited to airfields. This is based on the need for rapid deployment of assets and personnel to a random location, and the tenuous supply and facility situation at most communities compared with the needs of so many persons and vehicles. The physical infrastructure and limitations of the airfields themselves, other than types of aircraft that are able to operate from each runway, are not presently represented in detail. Thus, in this study each infrastructure's—i.e., Resolute Bay, Cambridge, etc. in Table 1, relative value is solely based on how well its airfield's location is able to support operations within the context of a MAJMAR response.

With this scope in mind, this Scientific Report describes the approach designed and implemented by the authors in response to the third objective. This work's main contribution is a methodology that provides insights into the impact of Canadian Arctic infrastructure investment/divestment decisions on the CAF's ability to respond to a MAJMAR scenario within Canada's Arctic. It accomplishes this by: first, identifying exisitng geospatial gaps in the CAF's ability to respond as well as expected scenario outcomes; and second, by comparing these results with those in which an infrastructure investment/divestment is implemented. Whereas the former provides a baseline assessment, the latter explores the impact of a decision in terms of changes in both geospatial gaps and regions in which the CAF may still respond, but the scenario's outcomes differ. While the methodology is presented in the context of a MAJMAR, it is applicable to a range of scenarios involving transportation or evacuation of people, including major air disasters, natural disasters, and humanitarian crises.

The remainder of this report is organized as follows. section 2 describes the methodology used in the study; in particular, it describes the MAJMAR scenario in which the methodology is demonstrated, how the scenario's evacuees' medical state and the CAF's response are modelled, and how the impact of infrastructure investment/divestments are quantified. Next, section 3 contains technical details of the implementation of the method and three applications: First, an evaluation of the expected CAF response to the scenario given current infrastructure. This provides insight into the strengths and weaknesses of the CAF response capability based on airfield location in terms of access and redundancy. The second part of this section is an analysis of the effect of infrastructure investment to create a new airfield with forward-deployed fuel or SAR helicopters. This is provides a working example of how extending the model can provide a concrete measure of the impact of specific infrastructure decisions on mission outcomes. Lastly, section 4 summarizes this study and provides direction for future work.

Additionally, while not in the Canadian Arctic, a response to a MAJMAR scenario Canada's Pacific Search and Rescue (SAR) region has been studied (Eisler and Dobias 2015, 2017).

2 Methodology

This section describes the methods used in this study and the reasoning for those choices. Subsection 2.1 describes the scenario. In subsection 2.2 we describe the translation of the scenario to an mathematical model. The approach to apply this model across the Canadian Arctic is found in subsection 2.3.

Before proceeding, we define some terminology. (Chan and Rempel 2017) define the “Northern AoR” as the region of Canadian territory north of 55°N. They also define infrastructure as “the permanent installations required for military purposes” or “the resources (such as buildings or equipment) required for an activity.” We will limit this to the subset of infrastructure which may be used to support air, land and/or sea force projection and sustainment in the Northern AoR. We further define “Canadian Arctic waters” in accordance with the region used in the 2014 Fall Report to Parliament of the Commissioner of the Environment and Sustainable Development, Chapter 3—Marine Navigation in the Canadian Arctic (Office of the Auditor General 2014), as reproduced in Figure 1.

2.1 Scenario

The scenario selected for this work is a MAJMAR in the Canadian Arctic waters involving a cruise ship. Although it is fictitious, the idea of a large cruise ship sailing across the NWP in the Canadian Arctic Archipelago is not (CBC News 2014). Even in warm waters, significant maritime accidents have happened and called for a mass evacuation with heavy casualties. A notable example is the case of the *Costa Concordia* in 2012 (The Guardian 2012, Wikipedia 2019a). When a large cruise ship encounters an accident in the Arctic region (High North News 2017), it becomes more dangerous and challenging to mount a rescue and evacuation operation, as was the case with the *Viking Sky* off the coast of Norway in 2019 (CBC News 2019b, Vertical 2019). Hydrographic data for the Canadian Arctic is inadequate across most of the region, as indicated in Figure 2 (Office of the Auditor General 2014). That a cruise ship venturing off the main shipping lanes to avoid an iceberg or sea ice could experience some sort of mishap is well within the realm of the possible. This work depicts such a scenario, which was approved by Deputy Chief of Staff Operations - Continental (DCOS Ops Contl) prior to beginning modelling efforts (Hunter et al. 2018).

In the scenario, the *Gemstone Tranquility*, a cruise ship travelling through the NWP during the summer, suffers a catastrophic incident that renders the ship uninhabitable, forcing the evacuation of the ship. Possible causes for such an event are running aground or striking ice, which causes the ship to take on water and lose power. Given the size and capacity of Gemstone Tranquility, the Canadian Coast Guard (CCG) maintains a constant communication with its crew (Marine Safety and Security, Transport Canada 2017). It is assumed that the Joint Rescue Coordination Centre (JRCC) is contacted almost immediately after the evacuation decision was made, either via the CCG or directly by Gemstone Tranquility.

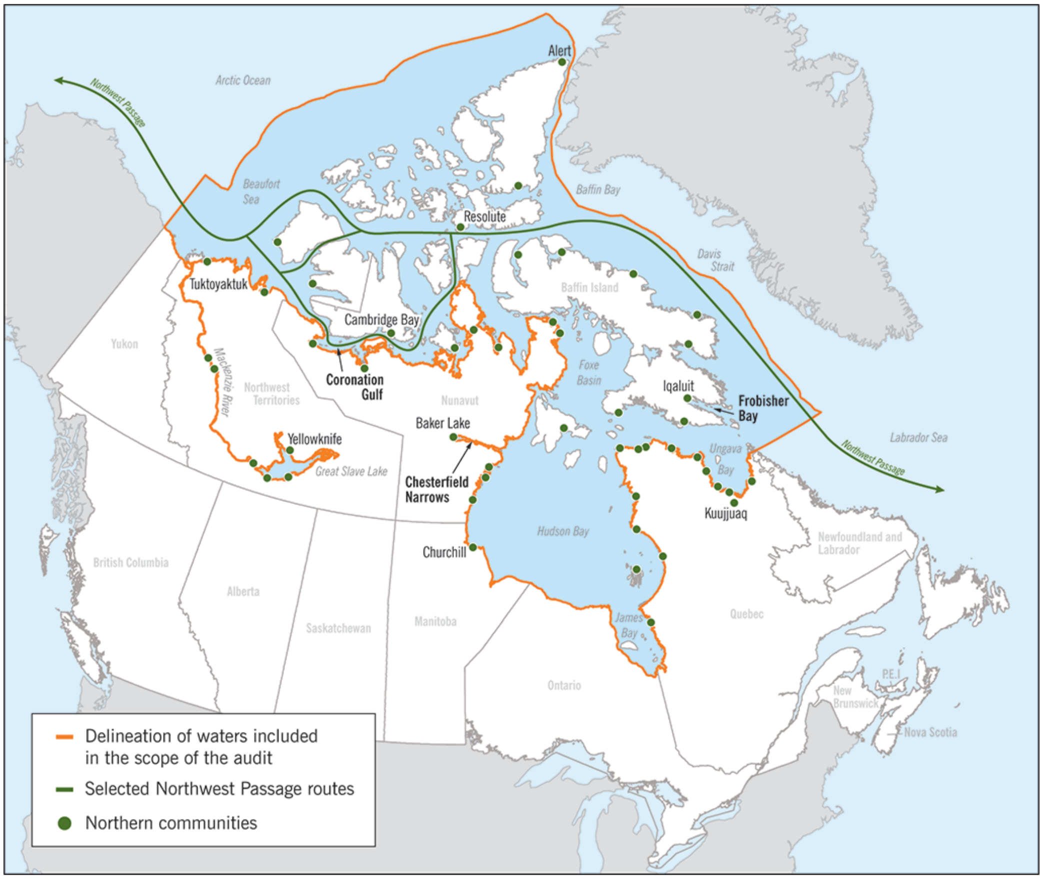

Figure 1: *This map delineates which Canadian Arctic and Northern bodies of water are included in the scope of the study. It also depicts selected Northwest Passage routes for marine transportation of goods through Canada's Arctic, as well as where the Northern communities are situated. Source: 2014 Fall Report to Parliament of the Commissioner of the Environment and Sustainable Development. Note: Not all northern communities are represented on the map.*

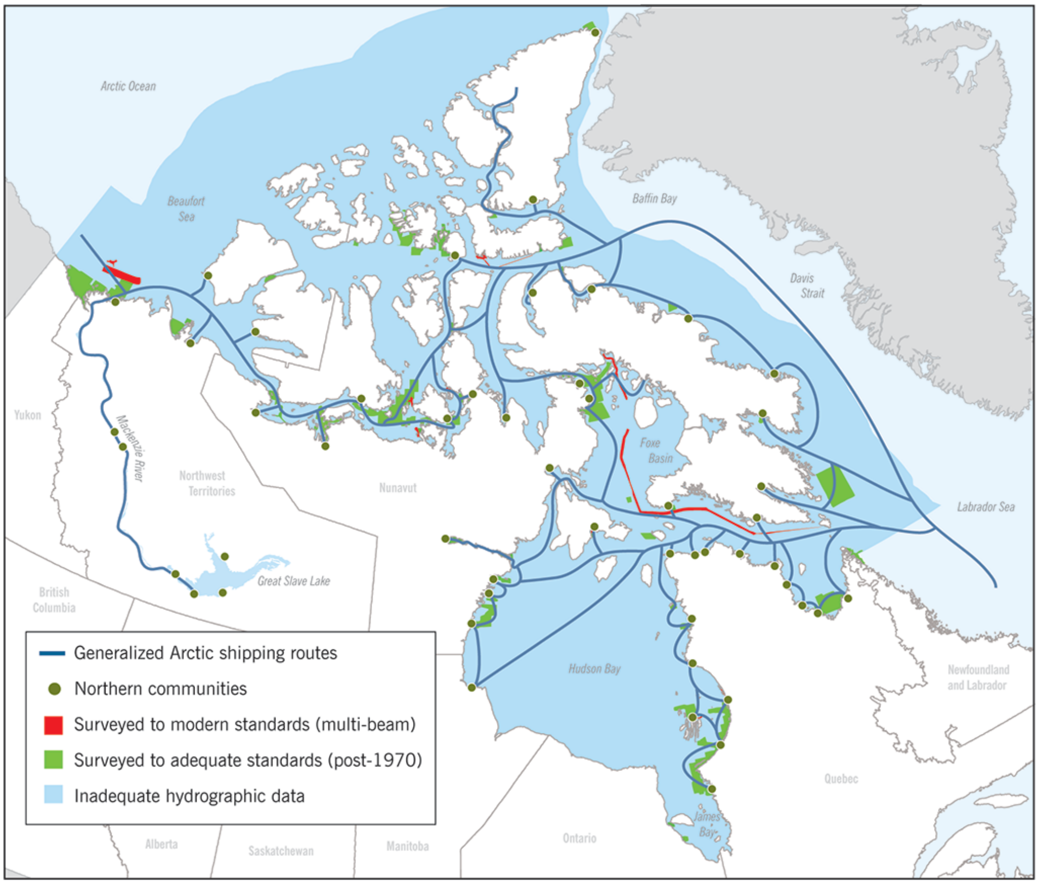

Figure 2: *This map depicts the generalized Arctic and Northern shipping routes as well as the routes that have inadequate hydrographic data. It also shows the routes that were surveyed to modern standards through multi-beam sonar technology and those that were surveyed to adequate standards (post-1970). Source: Adapted from Fisheries and Oceans Canada via the (Office of the Auditor General 2014). Note: Not all northern communities are represented on the map.*

The following is a list of assumptions for the scenario that are used to build the models and conduct the analysis in the remainder of this report.

Assumption 1 Although the CCG is the lead agency for the response to maritime disasters (Department of National Defence and Fisheries and Oceans Canada 2017), the CCG and JRCC will ask the CAF to assist due to the magnitude of the event;

Assumption 2 The baseline accident location is in the vicinity of 71.9°N, 96.0°W in Franklin Strait as shown in Figure 3. The diagram shows this location along the NWP (red line). This point was used for computing distances and travel times for model development and testing. We then extrapolate by placing the accident at many different points across the Arctic and North;

Assumption 3 The scenario takes place during the summer in August. In general, this is the month with the greatest freedom of navigation due to ice melt. The length of daylight at the reference position in mid August is 19 hours (TimeAndDate.com 2018)[7] and the temperature is between 0°C and 5°C (timeanddate.com 2019)[8];

Assumption 4 The total number of passengers and crew aboard the ship is 2000. All persons aboard are present and accounted for—that is, there are no missing persons;

Assumption 5 The CCG's Search and Rescue Units (SRUs) are too far away from the accident location (CBC News (2019a)) and do not have the capacity to carry 2000 people. The CAF are asked to support the rescue and evacuation of the passengers.

Assumption 6 The distress signal is sent at midnight. Everybody on the ship starts the evacuation process at that time, and the CAF starts mounting the rescue and evacuation operation at the same time;

Assumption 7 Per existing CCG planning, the evacuees move from the accident location to an evacuation location on a nearby shoreline by lifeboat within the first 24 h, whence they will require extraction. CCG elements may or may not be directly involved in this process, but the CCG is assumed to be performing coordination functions at minimum;

Assumption 8 Northern communities are assumed to be able to assist the evacuees from the accident location to an evacuation location (also called an evacuation *node*), on shore and provide some care at the latter, only CAF assets and resources are used to transport the evacuees from the evacuation node;

Assumption 9 One location with an airfield suitable for a CC177 Globemaster III (CC177) or CC130J Hercules (CC130J) and within the operational range of the chosen rotary-wing (RW) aircraft is selected to act as a Forward Operating Location (FOL). The FOL will function as a logistical hub and temporary shelter point for the evacuees.

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[7] The number of daylight hours affects the maximum duration of operations under visual flight rules (VFR).

[8] The weather conditions will strongly influence the rate at which the evacuees' health degrades.

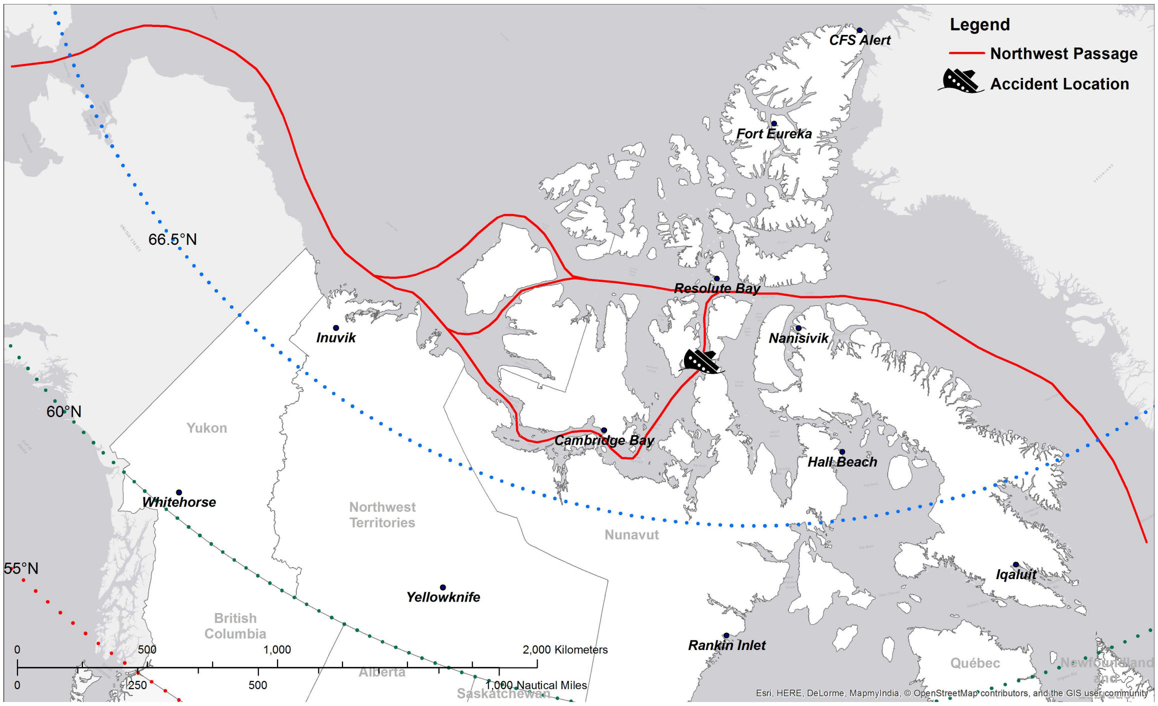

Figure 3: *Northern Canada and the Northwest Passage (NWP). The reference location of the accident is shown with an stricken ship icon.*

RW aircraft are used to bring the evacuees from the evacuation node to the FOL, and fixed-wing (FW) aircraft will take them from the FOL to a location in the South; and

Assumption 10 Because the distance between the FOL and the evacuation node is often very large, and because only the CH149 has a hoist capability, all helicopters will land to load and unload.[9]

Assumption 11 For reasons that will be made clear below, we have assumed no significant aircraft breakdowns. Time has been built into the model to allow minor corrective maintenance procedures, but major failures are not considered.

Assumption 12 The weather is assumed to be for the duration of the operation at and between all points where aircraft must travel.

Assumptions 11 and 12 are very optimistic and improbable but necessary. As such, all results should be considered very optimistic.

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[9] Early modelling quickly showed that hoisting evacuees off a stricken ship quickly enough to avoid mass casualties is impractical unless all helicopters have a hoisting capability, and the FOL is very close to the ship. This result is supported by the actual results seen for the attempted evacuation of the *Viking Sky* (Vertical 2019).

2.2 Problem definition and modelling

For the CAF, this scenario immediately becomes an problem of logistics: 2000 persons must be evacuated from a very difficult situation far from the bases of the most relevant CAF assets. To do this, the CAF must first deploy RW aircraft from their Main Operating Bases (MOBs) to a suitable FOL within range of the evacuation location. These helicopters will require a large quantity of fuel for the evacuation operation, which must be assumed to be unavailable at the FOL unless otherwise specified. This must be transported to the FOL by Royal Canadian Air Force (RCAF) FW transports, principally CC130J Hercules. The evacuees that are moved from the accident location to the FOL must then be moved to southern Canada for medical care and repatriation. At the same time, CAF personnel are required to operate and maintain the RW aircraft at the FOL, to assist and care for the evacuees, and to co-ordinate the operation. Both the evacuees and the military personnel will require additional supplies of all sorts. These personnel and supplies must also be moved to the FOL on the same FW transports that are moving the fuel and the evacuees. All the while, the victims that have not yet been evacuated are exposed to the difficult conditions of the Arctic without adequate sustenance, housing or sanitation, which will inevitably lead to illness and generally declining health among them. Thus, the most crucial aspects of this problem are

- the deployment of RW aircraft to the FOL;
- the modelling of the logistic network that moves all of these persons and supplies; and
- the representation of the medical condition of the evacuees over time.

We consider each of these aspects below. As the point of scenario is to save lives, the measures of performance for a given CAF response and infrastructure configuration will be based on or incorporate the number of survivors. The measures of performance (MOPs) are discussed in subsection 2.4.

2.2.1 Canadian Armed Forces response

Following the approval of the scenario, the authors presented it to CJOC J5 North. J5 North consulted RCAF 1 Canadian Air Division and the Joint Forces Air Component Command (JFACC), which holds the primary responsibility for air asset tasking, to create an estimate of the military personnel and assets that would be allocated to deal with this scenario. The authors then requested additional technical and operational information on the capabilities of these assets from those entities. This information is found in Annex A. The maximal response, as laid out by 1 Canadian Air Division, would involve 2 CH149 Cormorants (CH149s), 8 CH147 Chinooks (CH147s), either 2 CC130J *or* 1 CC177, plus 500 CAF personnel drawn from the IRU, RCAF and supporting units.[10] If this scenario were to actually occur, it may not be possible to allocate this many aircraft. It is very unlikely that more aircraft could be assigned to this operation.

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[10] In practice, the CC130Js can land at more locations than the CC177 and so are used more often in the following analysis (Chan and Rempel 2017).

2.2.2 Deploying helicopters to forward operating locations

The deployment of CH147s from 1 Wing Petawawa and CH149s from 9 Wing Gander or 19 Wing Comox to an arbitrary point requires a consideration of several factors: a) the range of the helicopter, b) the location of airports to act as waypoints between the origin and the destination, c) the availability of necessary services at the waypoints, fuel being the most important, and d) the requirement to obey crew rest rules and flight regulations in the Flight Operations Manual (1 Canadian Air Division 2018).This problem is a Shortest Path Problem (SPP). In a SPP we have a set of N locations, with every two locations linked by a travel cost. We wish to determine the path from one given location to another given location which minimizes the travel cost. The costs may be in time or some other measure, and are not necessarily directly proportional to the distances. The specific SPP used is described in full in Annex B. It has been solved separately for each helicopter type and FOL used in this report. The resulting deployment times were used as input parameters to the mathematical model described in the following section.

2.2.3 Modelling the logistic network

Based on the concept of a Northern Infrastructure Cluster (IC) defined in the infrastructure database (Chan and Rempel 2017) and the assumptions in subsection 2.1, we define a logistic network that provides the conceptual framework of the problem. A diagram of the network is shown in Figure 4. The IC becomes the FOL for the evacuation operation.[11] Regions are colour-coded; southern Canada is green, the FOL is blue, and the evacuation location is red. The accident location is not shown as the evacuees have moved from there by lifeboat per Figure 2.1.

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[11] From this point onward, the term FOL will be used in the place of IC.

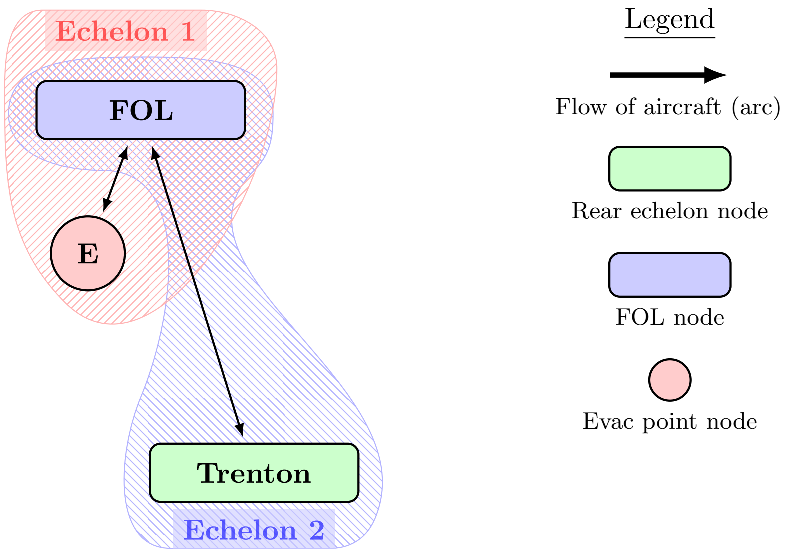

Figure 4: *Schematic diagram of the logistic network, identifying the first and second echelons.*

The arcs in Figure 4 indicate the allowed movement paths between nodes of the network and the arrowheads point in the direction of movement.[12] Arcs have associated lengths that prohibit aircraft from using them if distance exceeds the aircraft's range. The arcs and nodes are grouped into echelons based on their proximity to the evacuation node. We define echelon 1 as the evacuation node, the FOL node, and the arc between these nodes. It is covered in the red shaded area in Figure 4. Echelon 2 contains the FOL node, the rear echelon node and the arc that connects them. Thus, the FOL node is a member of both echelons; forming the interface between the echelons for all trans-shipments.

Two logistic models were developed to represent the operation of the logistic network, a time-stepped simulation model and an optimization model. Each of them describes the imagined CAF response to the scenario, including:

- the variations of evacuation location, chosen FOLs and the rear echelon location(s) in southern Canada (principally Canadian Forces Base (CFB) Trenton);
- the RCAF RW and FW aircraft assigned, accounting for the speed, range, fuel consumption rate and capacity of each aircraft to carry fuel, supply and persons in various medical states;
- the movement of evacuees southward on those aircraft and the transportation of supplies and CAF personnel northward; and
- the need for fuel to be present at the FOL for helicopter operations and the consumption of that fuel by operations.

The simulation model is described in full in (Chan 2019). The mathematical specification of the optimization model is contained in (Hunter 2019a), with a brief description of its characteristics in Annex C. They were developed concurrently at the beginning of the study, using the single accident location of Assumption 2, with Resolute Bay as the FOL. The simulation model provided a means to verify the results of the optimization model and to test assumptions. Once the optimization model was assessed to be working correctly by producing results consistent with the simulation model, the optimization model was then applied across all feasible combinations of selected FOLs and a grid of evacuation locations. The optimization model is quicker to execute and also is able to minimize fatalities by optimizing the evacuee loading decisions. This is discussed in subsection 2.3.

Assumptions 11 and 12 on page 10, which rule out aircraft breakdowns and weather delays, exist to reduce the computational burden of the optimization model. Each possible breakdown or weather change in the scenario creates a new and different model to be solved. A large number of variations is required for each feasible FOL-evacuation location pair. This would increase the total computation time per scenario by several orders of magnitude, which is

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[12] We use the term "arc" in the graph notation sense, as a directed edge connecting two nodes. Arcs with arrowheads at both ends actually represent two unidirectional arcs travelling in opposite directions in the model code.

impractical given CJOC OR&A's current computational resources. This may be considered for future work if additional computing power becomes available.

2.2.4 Representation of the medical state of evacuees

Because the quality of CAF response to the scenario is measured in terms of the number of survivors, their medical condition must be considered to make an assessment of an infrastructure's impact on operations. This section discusses the medical condition of the evacuees and how it is affected and represented in the model.

For the purposes of the study, an evacuee's medical condition affects only their life expectancy from that point in time and the amount of space they will require on an aircraft. An evacuation triage system similar to the Simple Triage and Evacuation (START) system (Wikipedia 2019b) is adopted in this study. It divides the evacuees into five categories, listed in Table 2, from the uninjured, colour-coded as white, to the terminally injured or deceased who were colour-coded as black.[13] The other three categories are for those who required immediate treatment (red), early treatment (yellow), and only routine treatment (green). The CAF triage system (Department of National Defence and Fisheries and Oceans Canada 2017) is substantially similar to the START system, with the addition of a sixth category, grey, for missing persons. Since Assumption 4 above precludes the existence of missing persons in this analysis,[14] we ignore this category. The triage state in which one is in dictates his or her evacuation priority. Under standard operating procedure (SOP) the patients in the red triage state have the highest priority followed in order by yellow, green and white triage states. This SOP is relaxed in the optimization model to allow the optimization software to find the best possible results. The SOP of the air SRU leaves those in the black triage state at the scene. We further assume that patients in the red and yellow triage states are on stretchers.

Initial conditions and triage states

The medical state modelling assumes that the condition of the evacuees deteriorates only gradually over time and only before being airlifted to a southern city with adequate medical facilities. As a result, their corresponding triage state moves one level from white to green, or green to yellow, and so on. Patients in the yellow triage state may only change to the red triage state and may not go directly to the black triage state. However, the time required to do so can be less than the time scale of the optimization model, with the result that some evacuees appear to jump directly from one state to a non-adjacent state in the output.

At the start of the evacuation, 100 people are injured with different treatment requirements. The study assumes that 30 of them required immediate treatment (i.e. in the red triage

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[13] An evacuee's medical condition is not modelled in detail because it involves numerous factors such as cause of injury, severity, first aid, age, medical history, etc., that are not knowable or desirable to know at the chosen level of resolution.

[14] Given the environmental conditions of the region, anyone who goes missing during the evacuation of a ship is effectively already dead.

Table 2: *Properties of the five triage states.*

Triage State	Required Treatment	Initial Count	On Stretcher?
White	None (Uninjured)	1,900	No
Green	Routine	40	No
Yellow	Early	30	Yes
Red	Immediate	30	Yes
Black	None (Deceased)	0	Yes

state), another 30 require early treatment (yellow triage state) and the last 40 injured evacuees are in the green triage state. The initial counts are tabulated in Table 2. The initial number of injured evacuees is inspired by the Costa Concordia disaster that happened 140 km from Rome, Italy in 2012 (Wikipedia 2019a). The ship, which had 4252 people on board (over three thousand were passengers), ended up having 32 death and 64 people injured (Reuters 2012). Hence, an initial set of 100 injured people was deemed reasonable for a MAJMAR in a cold, remote and isolated environment.

Medical state transition rates

As stated above, individual evacuees' medical conditions are not modelled in detail. It is still necessary to have some way of determining how many persons there are in each triage state for the purposes of solving the transport space allocation problem and to evaluate response effectiveness. In order to model the effects of exposure on victims that have not yet been evacuated, a medical professional was consulted for some rule-of-thumb estimates of how long a person would stay in a particular triage state under various environmental conditions and levels of care (Chan 2017). As there is a wide range of potential injuries and maladies that could conceivably exist at the beginning of the modelled time period, they suggested some representative medical conditions to set the mean times in the yellow and red triage states. These are discussed in this section.

All times are found in Table 3. In accordance with our assumptions, these are the mean times that a person would spend in the indicated state before progressing (deteriorating) to the next worse state. If there is no intervention, a person will always eventually transition from white to green, green to yellow, yellow to red and finally red to black. The means define exponential distributions[15] in a Monte Carlo simulation that builds a medical state transition matrix. The distributions are broad enough to plausibly incorporate a wide range of ailments if the means are set properly.

The red triage state at the evacuation node is modelled after a person having a heart attack.[16] The 8 h average transition period for the yellow triage state patients at the scene is

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[15] The standard deviation of an exponential distribution is equal to the mean.

[16] The American Heart Association recommends fewer than 90 minutes from the symptoms begin to the opening of the blocked artery (Antman, E.M. *et al.* 2004).

Table 3: *Mean times spent in medical (triage) states as a function of evacuee location.*

	Mean time in state [h]			
Location	White	Green	Yellow	Red
Evacuation node	120	48	8	1.5
FOL node	160	64	10.67	2

a rule-of-thumb approximation based on the time windows from the onset of symptoms for treating stroke patients[17] and pneumonia patients.[18] Finally, it is assumed that the healthy evacuees would catch a common cold or influenza in five days because they stayed close to one another in a confined area at the evacuation node in poor living conditions. The other average transition times at the FOL node and onboard of an aircraft are simply multiples of the baseline averages at the evacuation node.

The values in Table 3 are almost certainly the greatest source of uncertainty in the absolute accuracy of results for this study. Thus, these times should be validated prior to using this study's results, particularly for decisions related to triage, medical care, and evacuation procedures. However, so long as all evacuees at all nodes follow the same medical transition process, the mortality rate for evacuation node-FOL pairs may be used to evaluate the evacuation response quality.

Medical state transition matrices

The optimization model requires a medical state transition matrix that is applied to evacuees at evacuation and FOL nodes at the end of every day. The transition matrix is calculated by simulating the progression of 10 000 000 evacuees through the colour-coded triage states. The data in Table 3 are used as the inverse rates (i.e., means) of exponential distributions in this simulation. The simulation must be used once for each node type. The results are used to determine the population distribution across end states at the end of a 24 h time window, given their initial state at the beginning of the time window. The resulting transition matrices that are used for the optimization model runs are found in Table 4. It has been assumed that every evacuee has spent 24 h at their location at the end of each day for the purposes of the population state update. This is clearly not true, but the model formulation does not distinguish individuals, making this assumption necessary even if it does not reflect individual situations.

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[17] Per (Musuka et al. 2015), 4.5 h is the recommended time within which recombinant tissue plasminogen activator (rtPA) can be effectively used, and the time window for treating ST-segment elevation myocardial infarction (STEMI) patients using endovascular thrombolysis is 12 h.

[18] Within two days after the start of symptoms, neuraminidase inhibitor as a treatment is recommended to the viral pneumonia patients by (Ruuskanen et al. 2011).

Table 4: *Medical state transition matrices used for the optimization model. Rows give the initial state, columns the end state. The values in a row are the probabilities of ending in the corresponding end state given that the evacuee began in the row's state.*

Evacuation node transition matrix

	End state				
Initial state	White	Green	Yellow	Red	Black
White	0.819	0.141	0.0173	0.003	0.0195
Green	0.0	0.606	0.111	0.0212	0.261
Yellow	0.0	0.0	0.0498	0.0115	0.939
Red	0.0	0.0	0.0	0.0	1.0
Black	0.0	0.0	0.0	0.0	1.0

FOL node transition matrix

	End state				
Initial state	White	Green	Yellow	Red	Black
White	0.861	0.116	0.0124	0.00110	0.0103
Green	0.0	0.687	0.116	0.0110	0.185
Yellow	0.0	0.0	0.105	0.0109	0.884
Red	0.0	0.0	0.0	0.0	1.0
Black	0.0	0.0	0.0	0.0	1.0

2.3 Generalizing over Canadian Arctic waters

As discussed in subsubsection 2.2.3, the optimization model was developed and tested using the same reference scenario as the simulation model. The models were compared and aligned during this process to ensure that they achieved comparable results. Exact alignment of results was not expected due to the differences between the models detailed in Annex C.1.

In order to apply the optimization model beyond the reference location, we discretize space using a grid of representative locations (nodes) that cover Canadian Arctic Waters as represented by the Area of Interest (AoI) defined in subsubsection 2.3.1. These are subdivided by whether or not an evacuation can occur at the location. We also create a list of the CC130J and CC177-capable airfields in the AoI that can use used as FOLs. The optimization model is solved for all feasible pairs of evacuation nodes and FOLs. An evacuation node-FOL pair is feasible if the evacuation node's location is within the operational range of at least one of the modelled RW aircraft from the FOL in question.

2.3.1 Geographic scope and representation of space

The area around the NWP and Hudson's Bay, corresponding approximately with the Canadian Arctic waters definition shown in Figure 1, is discretized into hexagonal regions projected onto the Earth's surface using a geodesic Discrete Global Grid (DGG) system. Per (Sahr 2018),

> A Discrete Global Grid (DGG) consists of a set of regions that form a partition of the Earth's surface, where each region has a single point contained in the region associated with it. Each region/point combination is a called a cell. Depending on the application, data objects or values may be associated with the regions, points, or cells of a DGG. A Discrete Global Grid System (DGGS) is a series of discrete global grids, usually consisting of increasingly finer resolution grids (though the term DGG is often used interchangeably with the term DGGS).

A DGG using an icosahedral Snyder equal area (ISEA) projection (Snyder 1992) with hexagonal cells, aperture 3 and resolution 8 (hereafter referred to as ISEA3H8) was created with `dggridR` (Barnes 2018). `dggridR` itself implements the version 6.2b of the DGGRID software package, based on (Sahr et al. 2003). The DGGRID software and links to relevant articles are available at (Sahr 2018). A DGG has many advantages for representing the surface of the Earth. For this study, the most useful attribute is the avoidance of irregular shapes and/or areas that arise with grids based on latitude and longitude.

Any icosahedral DGG projection tiles the Earth in a variable number of hexagons and 12 pentagons. For the ISEA3H8 DGG used here, a complete tiling of the WGS84 ellipsoid results in 65 600 hexagons and 12 pentagons. The pentagons are exactly $^5/_6$ the area of a hexagon. By careful orientation of the projection, the pentagons have been placed outside the area of interest. Because of the shape of the WGS84 ellipsoid, there is some variation in the shape of the cells in order to keep the area constant. The area of a hexagon is $7774.2\,\mathrm{km}^2$, which is equivalent to a circle with a diameter of 99.5 km. The minimum, mean, and maximum spacings between cell centres are 82.3 km, 95.3 km, and 104.5 km.

The worldwide grid has been cropped to the Canadian Arctic Waters south of 77° N, such that all cells included have their centres and at least 50% of their area within Canadian territory. Cells that represent 100% land area have been removed due to the maritime nature of the scenario. This leaves 558 of the original 65 612 cells. The result, shown in Figure 5, is henceforth referred to as the Area of Interest (AoI). Each of the cells is referenced by a unique identifier and modelled using the location of its centre. They have been categorized as either coastal cells that contain at least some coastline, or all-water ocean cells.[19] There are 359 coastal cells and 199 ocean cells. We distinguish between coastal and water cells because while the original maritime disaster can theoretically occur in any cell, our assumptions mean than evacuation operations take place only in coastal cells. Also shown in Figure 5 are the locations of the 25 FOLs used in the initial analysis. Their names and exact locations are listed in Table 5, starting with Inuvik in the far west and continuing in ascending order of longitude. Their locations are *not* moved to the nearest cell centre, since these are well known and there is little to be gained by doing so.

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[19] The problem of ice coverage is ignored for now. Current climate trends suggest that this will likely be irrelevant for this scenario's summer time frame in the near future.

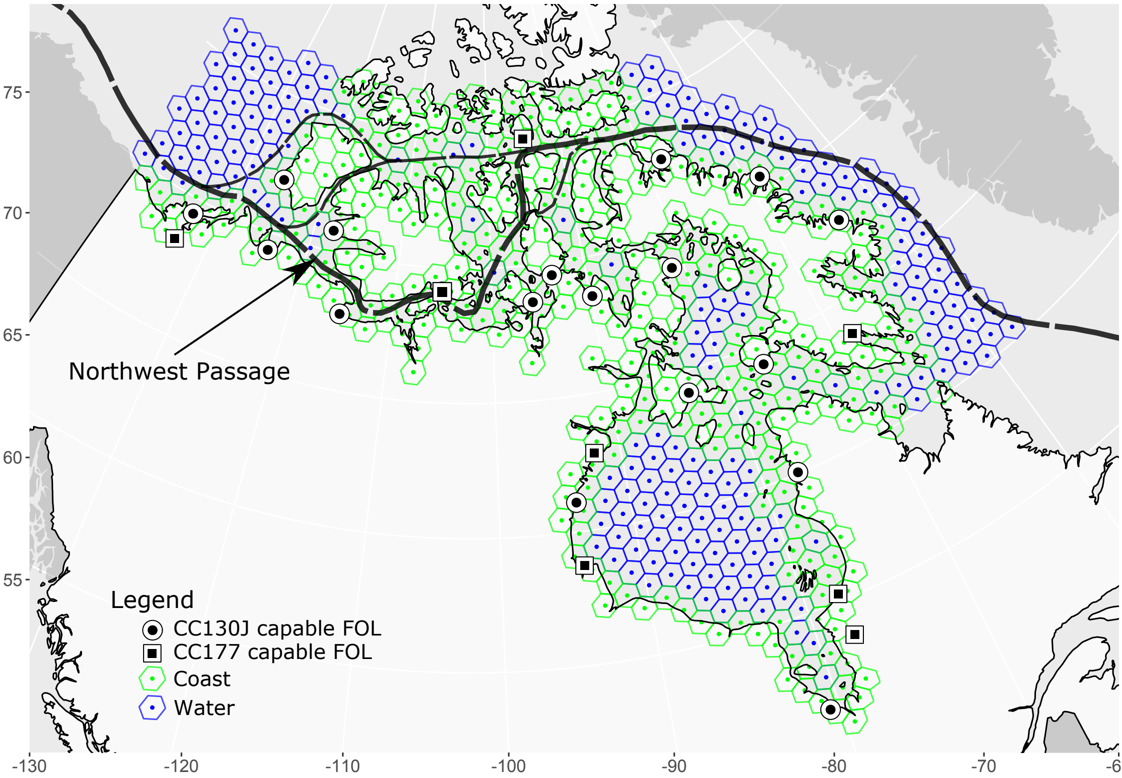

Figure 5: *The ISEA3H8 grid used to cover the AoI. The colour of the dots in the centres of the cells indicates whether it is a coastal or all-ocean cell.Cells that are all land have been removed. The cell boundaries are coloured according to the classification of both cells that touch the boundary. The locations of the FOLs included in the study are indicated as in the legend: Those with circular markers are usable by CC130J. Those with square markers may be used by CC177 and CC130J aircraft. The Northwest Passage is shown as a dark grey dashed line.*

Table 5: *List of Forward Operating Locations*

FOL	Location	Latitude	Longitude
Inuvik	Northwest Territories	68.36	-133.72
Tuktoyaktuk	Northwest Territories	69.45	-133.03
Sachs Harbour	Banks Island, Northwest Territories	71.99	-125.25
Paulatuk	Northwest Territories	69.35	-124.07
Ulukhaktok	Victoria Island, Northwest Territories	70.74	-117.77
Kugluktuk	Nunavut	67.83	-115.10
Cambridge Bay	Victoria Island, Nunavut	69.12	-105.06
Gjoa Haven	King William Island, Nunavut	68.64	-95.85
Resolute Bay	Cornwallis Island, Nunavut	74.70	-94.83
Arviat	Nunavut	61.11	-94.06
Churchill	Manitoba	58.75	-94.13
Taloyoak	Nunavut	69.54	-93.53
Rankin Inlet	Nunavut	62.81	-92.09
Kugaaruk	Nunavut	68.53	-89.81
Coral Harbour	Southampton Island, Nunavut	64.14	-83.17
Hall Beach	Nunavut	68.77	-81.24
Moosonee	Ontario	51.29	-80.61
Pond Inlet	Baffin Island, Nunavut	72.70	-77.96
Kuujjuarapik	Quebec	55.28	-77.76
Radisson/La Grande Rivière	Quebec	53.63	-77.70
Puvirnituq	Quebec	60.05	-77.26
Cape Dorset	Baffin Island, Nunavut	64.23	-76.54
Iqaluit	Baffin Island, Nunavut	63.75	-68.52
Clyde River	Baffin Island, Nunavut	70.48	-68.60
Qikiqtarjuaq	Baffin Island, Nunavut	67.56	-64.03

2.3.2 Model sweep algorithm

An `R` script was written to apply the model to all feasible evacuation node-FOL pairs (R Core Team 2018). The algorithm given below does this in a specific order so that the result of previous evacuation node-FOL pair is used as a starting point for the next pair to reduce the time required to find solutions of acceptable quality. The exact run time of the solver depends on the details of the problem, mainly the number of aircraft included and the distances between nodes. A full discussion of the complexity of the problem is found in (Hunter 2019a).

1. For each FOL, do the following:
    - (a) Look up the helicopter deployment times to this FOL that was found using the SPP in Annex B;
    - (b) Find all map cells within the operational range of the helicopter types given in subsubsection 2.2.1.
    - (c) Sort the in-range cells for this FOL in order of increasing distance from the FOL;
    - (d) In this sort order, do the following for each cell:
        - i. Create an instance of the optimization model that incorporates the FOL-cell combination-specific data in `.mps` format by doing the following:
            - A. Create an MPS file from the base optimization model file incorporating the modified input data using `glpsol.exe`;
        - ii. Within `R`, call Gurobi to solve the model in the MPS file;
            - A. If this is the first cell processed for this FOL, do a cold start of the solver;
            - B. Otherwise, use the best solution for the previous cell as the starting point for the solver.

          Acceptable stopping conditions are:
            - A. The relative Mixed Integer Program (MIP) gap is at or below a specified lower level;
            - B. The maximum time limit was reached;
        - iii. Save the current solution as a starting point for the next cell;
        - iv. Write the output to a Gurobi solution file and a `R` data file.
2. After completing all FOL-cell combinations, another `R` script was run to read through all of the folders created, read the `R` data files and read the results of interest into a single `R` data frame that will be used as input for further analysis.

2.3.3 Local community response assumptions

Although most communities in the region are small and have limited resources, they nonetheless have some capability to provide assistance. However, (Chan and Rempel 2017) found a lack of data to make a detailed assessment of each community's capabilities and concluded that contacting each community was required. Given the time and resources required to do this, we instead implemented a mathematical approximation. The capabilities of Northern communities and governments have been treated as an abstract function of each community's population and distance to a coastal evacuation cell. For this we use all of the 84 communities found in the infrastructure database (Chan and Rempel 2017) plus another 23 located in the neighbouring provinces of Manitoba, Ontario, Quebec, and Newfoundland and Labrador, not just the 25 FOLs in Table 5.

Community response is represented as a multiplier function w_c that reduces the number of fatalities in the CAF-only response. We use a generalized logistic function that increases with distance from a community and decreases with its population. This is a very subjective representation of the ideas that there is some inherent capability of communities to provide assistance in their neighbourhoods, and that larger communities are more capable than smaller ones. Equation 1 is used to model the effects of community assistance capacity as a function of population and proximity to an evacuation node:

$$w_c(x,p) = A + \frac{K - A}{(1 + Q\exp(-B(x - x_0)))^{1/\nu}}, \tag{1}$$

where x is the distance of the cell from the community in km, p is the population of that community. The other parameters are

A, the lower asymptote;

K, the upper asymptote;

B, the growth rate;

ν, a parameter which controls near to which asymptote maximum growth occurs. By definition, $\nu > 0$;

x_0, the starting distance in km for the growth of the curve;

Q, a parameter which specifies that value of $w_c(x,p)$ at $x = x_0$.

The values of these parameters are

$$A = \frac{1}{1 + \log_{10}(p)}, \qquad K = 1, \qquad B = \frac{1}{50},$$
$$\nu = 0.5, \qquad x_0 = 30\log_{10}(p), \qquad Q = 3\log_{10}(p).$$

These values are of course quite arbitrary. They have been selected such that the effect is greater close to the community and decreases with distance, with almost all effect being lost by about 400 km away regardless of community size. This is intentional; current regulations require lifeboats for ships travelling north to carry 24 h of fuel. An approximate speed of 10 kn would allow them to cover 444 km in that time. The difference in w_c between three communities is shown in Figure 6. The communities shown have been selected to show the effect of population size. Iqaluit is the largest community inside the scenario AoI and has the strongest effect. For example, using this model, Iqaluit multiplies the optimization model fatalities by 0.28 (a 72% reduction) at a distance of 100 km and by 0.47 (a 53% reduction) at a range of 200 km. Eureka has no permanent population and so has no effect whatsoever beyond the availability of its airfield . Qikiqtarjuaq, with a population of 515, is close to the median size of northern communities. Note that no community eliminates fatalities, even at a distance of zero. This is by design, as the ability of most Northern communities to shelter and support 2000 evacuees is limited at best. Equation 1 was calculated for every combination of community and cell regardless of distance. Only the result for the community exerting greatest influence was kept for each cell. Since many of these communities are inland far from the coast, their calculated fatality reduction factor is very close to 1, and they have no influence on the outcomes.[20] The resulting map of community-based multiplicative fatality reduction factors is shown in Figure 7. The communities used are also shown in this figure.

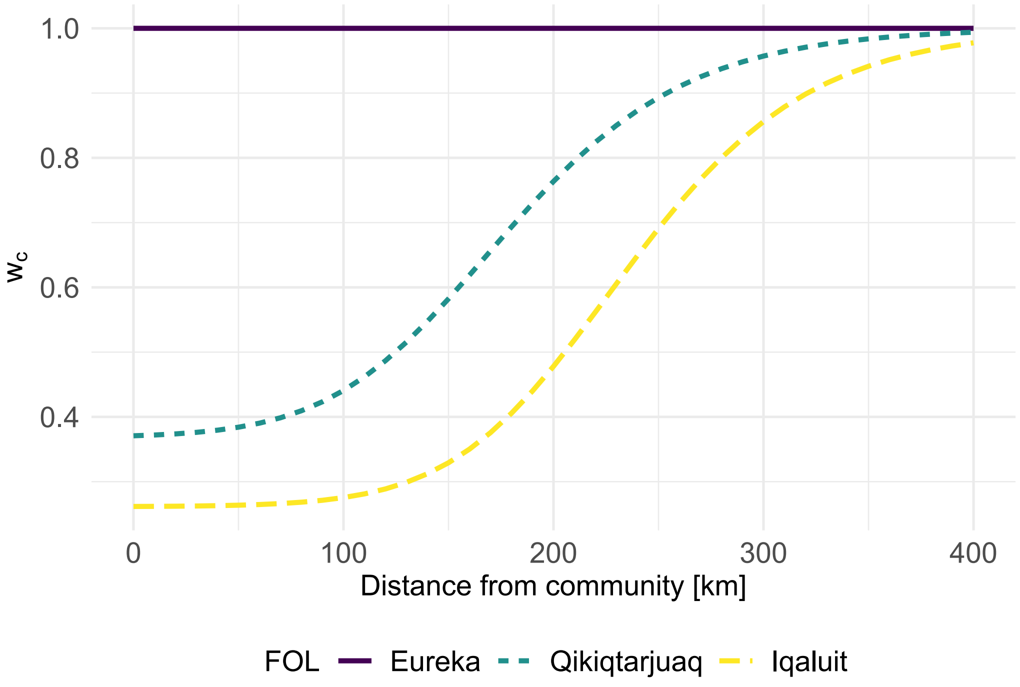

Figure 6: *The community multiplicative fatality reduction factor w_c as a function of distance for three communities.*

2.3.4 Relative likelihood of an evacuation by cell

Not all cells are equally important for this analysis for two reasons. First, the chance of cruise liner traffic varies across the region as some cells are simply not accessible due to prevalent ice conditions. Second, under the assumptions of this study, the evacuees are assumed to

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[20] In a different scenario, such as an airliner crash, these communities would exert a strong influence on the outcomes.

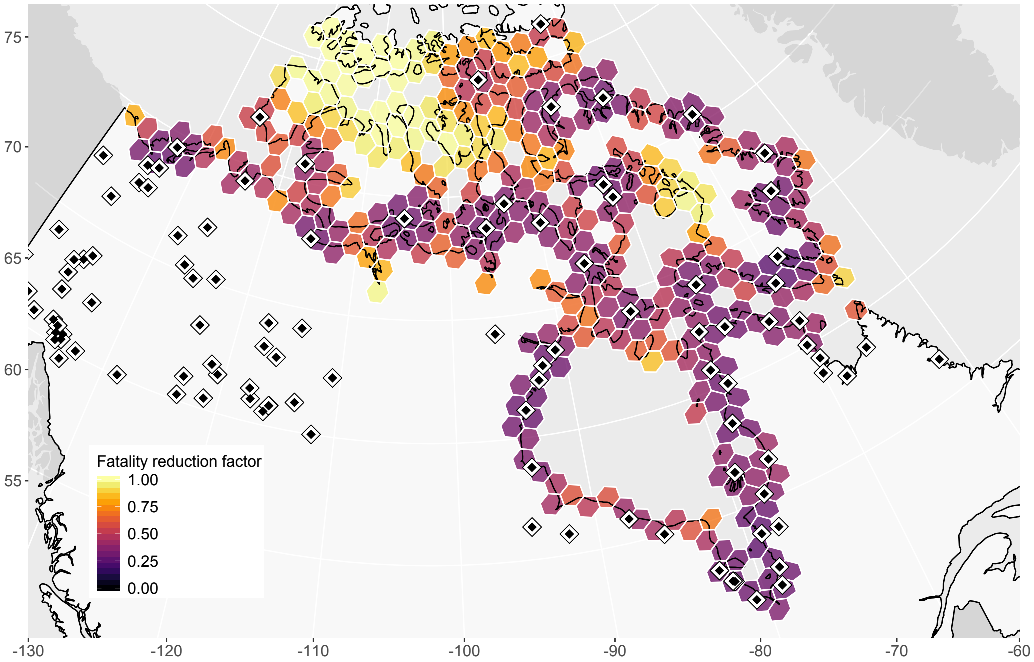

Figure 7: *Multiplicative fatality reduction factor by cell, based on the assumed proximity to and size of communities in the region. The communities considered are indicated with diamond shapes.*

move from the ship to the nearest coastal cell(s), which are the only places where CAF evacuation operations are permitted. We assess the relative likelihood of evacuation by cell by making assumptions about these two factors.

At the present time, there is insufficient cruise ship traffic in the Canadian Arctic to produce a useful traffic density map. From 1853 up to the end of 2019, there had been 12 transits of the NWP by cruise ships (Headland 2020), all of which took place in 2013 or later. Data on the numbers and route data of cruise ships that entered the AoI but did not complete a NWP transit has not been found by the authors. We create a hypothetical traffic density based on the assumptions that

- on average, large cruise ships will travel along the NWP path as shown in Figures 1, 3 and 5; and
- ships will make deviations around this path to visit local communities and sites of interest.

Both of these assumptions were true in the case of the *Crystal Serenity* (CBC News 2014). We implement them using a traffic density weight function $w_t(x)$ based on the distance between the cell in question and the nearest point on the NWP line as seen in Figure 5. First, the distance between all cells in the ISEA3H8 DGG is calculated. Next, the NWP lines seen in Figure 5 are mapped on the ISEA3H8 grid. Then, for each cell in that line, a weight is calculated for every cell in the grid using a half-Cauchy function[21] to create a relative weight. The half-Cauchy function is used because it has a general bell-shaped curve but has fat tails, ensuring that cells continue to have significant weight for hundreds of kilometres from the NWP line given an appropriate scale factor. The specific function is

$$w_t(x, s) = \frac{1}{1 + (x/s)^2}, \tag{2}$$

where x is the distance in km and s is a scale factor.[22] For comparison, this function is plotted in Figure 8 along with two other choices for the scale factor. The NWP line has been treated as though it passes through the centre point of cell it enters, guaranteeing a distance x of 0 and a weight of 1 in the traffic density weight function.

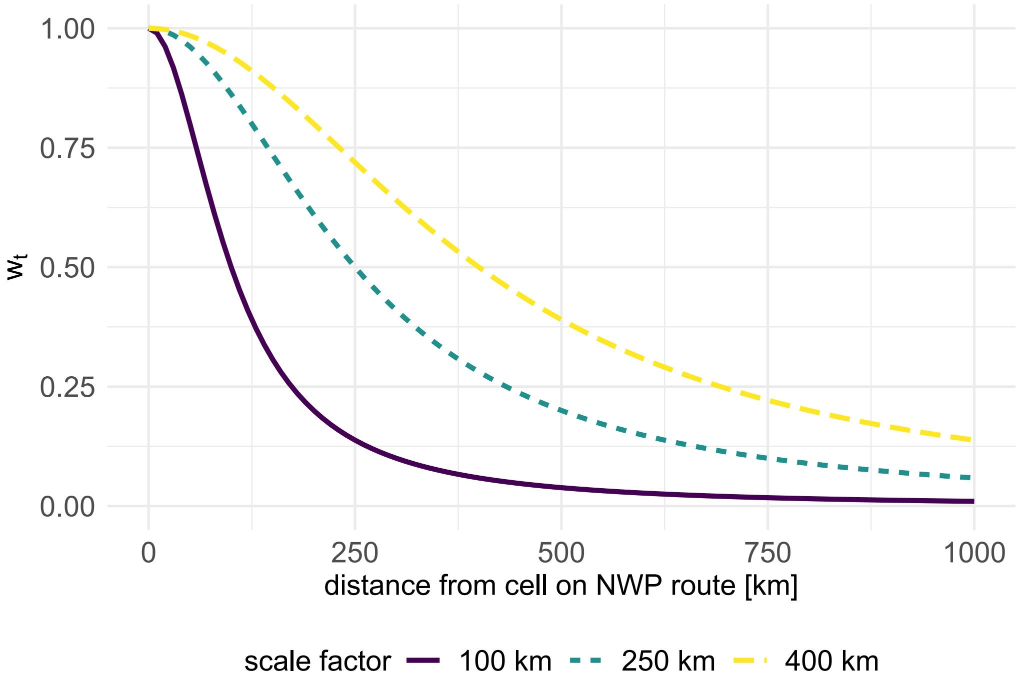

Figure 8: *Three examples of the traffic density weight function as a function of centre-to-centre distance from a cell on the NWP and the chosen scale factor. Each function is rescaled to a maximum value of 1 at a distance of zero. A scale factor of* 250 km *is used for this study.*

The resulting traffic density weights using a that was set equal to 250 km are shown on the map in Figure 9. This creates substantial traffic density out to 500–600 km (6–7 cells) around the main NWP line. Choosing a smaller scale factor concentrates the weights around the cells directly on the NWP route. A larger value spreads the weight farther from the route lines, such that it no longer is a significant factor. If this is the desired outcome then

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[21] It is a half-Cauchy function because only values of x greater than or equal to 0 are permitted.

[22] This function has been rescaled to a maximum value of 1 by dropping the normalization constant of $^1/_{\pi s}$.

$w_t(x, s)$ should be set equal to 1 for all cells. The weights generated by the thinner NWP lines in Figure 9 are multiplied by 0.5 to account for the lower likelihood of traffic along those paths.

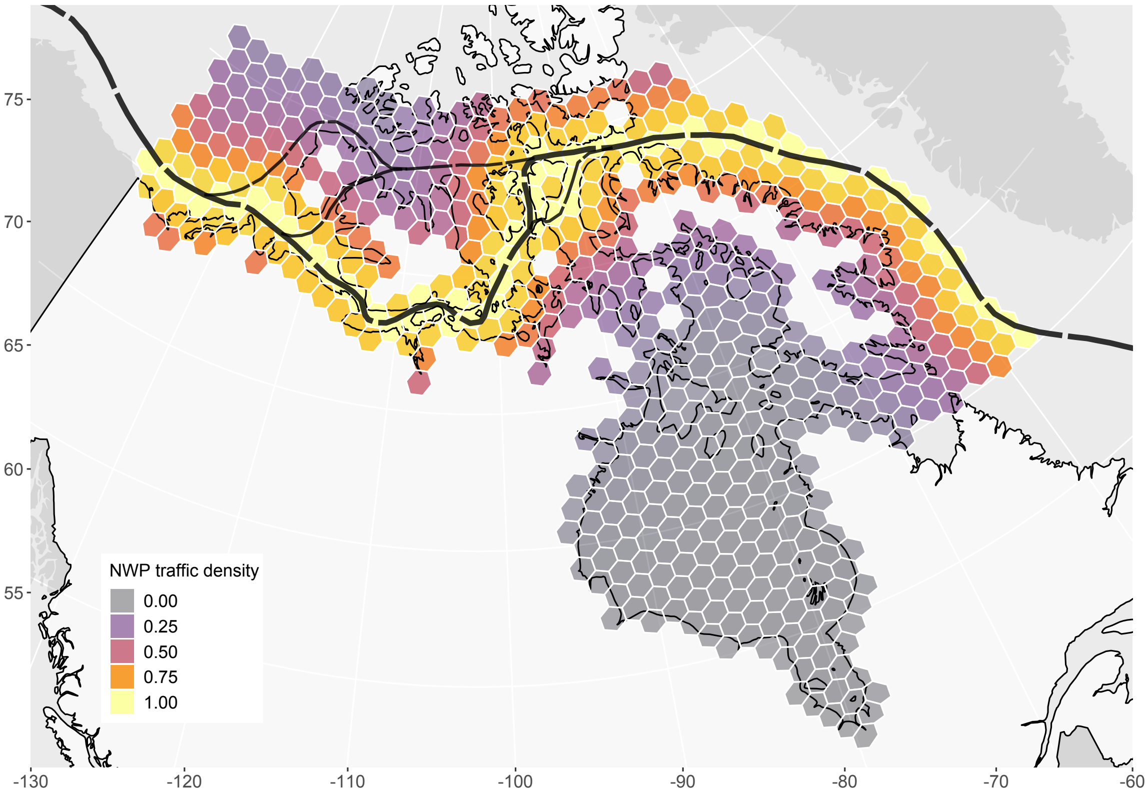

Figure 9: *Representation of the hypothetical traffic density around the NWP on the ISEA3H8 DGG system.*

Next recall that we have assumed that all evacuees have been transported to a suitable shoreline—cells indicated by green centres in Figure 5—by the ship's crew (see Assumption 7 on page 9).[23] Thus we need to determine where evacuees from incidents in the all-water cells of our traffic density map in Figure 9 end up. We do this by transferring the traffic density value of each all-water cell to one or more coastline cells. For each all-water cell with index k, we find the nearest coastal cell on a centre-to-centre basis. Next find the set of all other coastal cells that are no more than a fixed Δx_{max} farther away than the closest. We use a value of 100 km for Δx_{max} on the assumption that the evacuation coordinators will not have the lifeboats travel for more than a few hours longer than necessary to reach a suitable shoreline. The all-water cell k's traffic density weight is spread between these coastal cells. If the cell k's traffic density weight is w_t and Δx_i is the difference in distance between the closest coastal cell and the i^{th} one, then the traffic density weight that is transferred from

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[23] CCG support for this step may be direct or indirect.

cell k to the i^{th} coastal cell is given by

$$w_t^{ki} = w_t \left(\frac{\Delta x_{max} - \Delta x_i}{\sum_j \left(\Delta x_{max} - \Delta x_j \right)} \right) . \tag{3}$$

After transferring all ocean cell traffic density to nearby shores, we cap the maximum value that can accumulate in any coastal cell at 1 for two reasons. First, because cells that are outside of the AoI are excluded from consideration, weight cannot be spread to them. This means that there is no chance that evacuees can end up in Greenland or Labrador, which inflates the weight transferred into the remaining cells. Second, because of the combination of the form of Canada's coastline, the happenstance centres of the cells and the simple weight transfer equation, a few promontories tend to accumulate a very high proportion of the total weight to a degree that is unrealistic. Figure 10 shows the resulting relative evacuation likelihood. These value are taken as the assumed relative likelihood of an evacuation by cell in the following analysis.

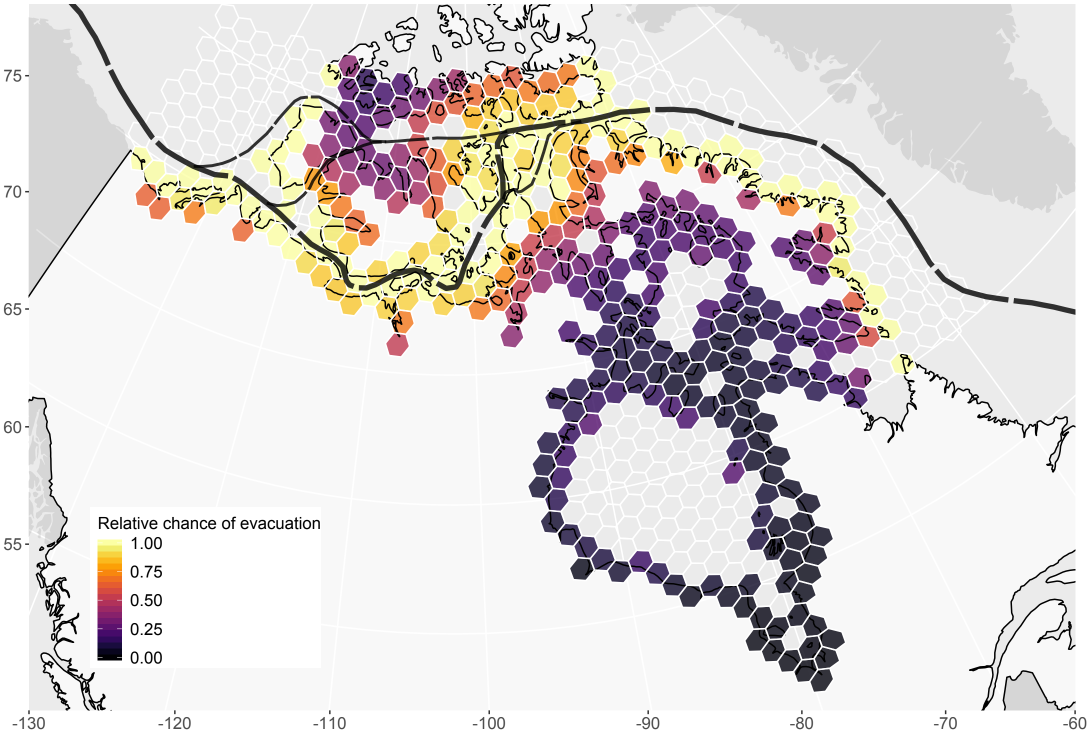


Figure 10: *The relative likelihood of an evacuation by cell, as based on the traffic density model and assumptions concerning movement from ocean to coastal cells.*

2.4 Measures of performance

Solving the optimization model across the DGG for all FOLs results in a large quantity of data. Detailed solution data exists for each feasible FOL and evacuation cell combination. It is possible to drill down into any one of these to examine the details. Available information includes aircraft movements, the locations and medical states of all evacuees at the beginning of each day, loads carried by each aircraft on each leg of each trip and fuel consumption. For each flight leg, the quantity of evacuees by medical state, fuel, military personnel, and other cargo is known. The operational impact of infrastructure can be measured in terms of many of these factors, but a key measure is how many evacuees die.

The most basic MOP for a given DGG cell is the number of fatalities. Clearly the smaller the value of this MOP, the better. This measures the quality of the CAF response (only) to this geographic location without consideration for other responding organizations or the likelihood of an evacuation in the cell in question. It is useful for assessing CAF projection capability, particularly as a starting point for considering different scenarios.

The *adjusted* fatalities by cell, created by multiplying number of fatalities by the value of the local response function (defined in Equation 1), attempts to capture the combined efforts of the CAF and local governments. This is an assessment of the projected quality of the response without consideration of the *likelihood* of a response in the cell.

Next we weight the adjusted fatalities by cell according to the relative likelihood of an evacuation in that cell, as estimated in subsubsection 2.3.4. This measure now no longer describes pure fatalities, but is a risk measure in the sense that it combines the relative likelihood of evacuation for a cell with the projected evacuation quality: a large value of this MOP indicates that this cell has both a high chance of an evacuation and a high number of fatalities in the event of an evacuation.

Because the MOP for each cell is associated to an FOL, we can roll up by FOL. Multiple values of each measure may exist for each evacuation cell, as the algorithm models a CAF response from all FOLs within operating range of the helicopters modelled. We have filtered the results by evacuation cell such that only the FOL associated with the lowest number of fatalities for each cell is presented as the best FOL for that cell. However, all results are saved, as this allows us to evaluate the effect of removing an FOL from consideration. We present rolled-up weighted adjusted fatalities by FOL in section 3, but it is possible to do so with any of the MOPs. By accumulating the weighted adjusted fatalities by FOL, we can see which FOLs are exposed to the greatest risk of fatalities in the event of a MAJMAR.

Finally, the weighted adjusted fatalities may be summed over the entire DGG to obtain a measure of effectiveness (MOE) for a given instance of infrastructure and response inputs. When comparing two different instances, we look at the difference in the MOE to assess the value of the changes. Examining the individual cell and FOL MOP differences provides insight into the reasons for the higher level effects.

3 Results and discussion

In this section we discuss the modelling results and the metrics we have used to evaluate them. Subsection 3.1 describes the implementation and execution of the models. Subsection 3.2 looks at the modelling results using the current infrastructure and the baseline scenario parameters. Two examples of a potential infrastructure improvement are described in subsection 3.3. Other results that are not directly relevant to this study but nonetheless interesting are briefly discussed in subsection 3.4.

3.1 Model execution

The model was solved on an HP Z840 dual-processor workstation, with an Intel® Xeon® E5-2650 v4 motherboard and 16 GB of RAM. This motherboard has two processors, each with 12 cores and 24 threads. Total execution time is between 144 and 192 h, that is, 6-8 days. The exact time depends on the number of decision variables to be decided; cases with poorer response characteristics solve more quickly because the number of fatalities is greater and therefore the number of decisions to be made within the model is smaller. The model is intensive in CPU usage but not memory; only a few GB are needed by the solver. At the time that this study was initiated and modelling began, the only solver to which the authors had access was GNU Linear Programming Kit (GLPK), which does not possess a warm-start capability. Part way through the study, the team acquired a Gurobi solver, but licences for the desired intermediary software, AMPL, could not be purchased. This meant that GLPK remained in the tool chain to read the model file, load the input data for the combination, and write an MPS file containing both.

Computations are kept to an acceptable completion time of 6–8 days per complete scenario evaluation by use of the Gurobi control parameters and controlling the order in which cells are evaluated. The Gurobi `TimeLimit` parameter is set to 3600 s to place an upper bound on execution time spent per FOL-cell combination. The (relative) `MIPGap` parameter is set to 0.01 to force the solver to stop at a point of diminishing returns and move to the next combination.

For each FOL, the evacuation location cells within helicopter range are solved in order of increasing distance from the FOL. Cells that are closer to the FOL are in general easier to solve than more distant ones, because the fuel consumption constraints are the most limiting for this model, and cells close to the FOL use fuel more slowly than it is delivered. For each cell after the first for an FOL, the solution for the previous cell is added to the model data as a warm start solution. In practice, this solution is almost never actually feasible, as it will violate the fuel requirement constraints, but it is almost always close enough that Gurobi is able to find a very good starting point nearby.

By solving in order, it was possible to find solutions to almost all FOL-cell combinations with MIP gaps between 0.01 and 0.02. This represents a marked improvement to solving each FOL-cell *ab initio*, which resulted in MIP gaps between 0.03 and 0.05 in the same approximate length of computation time. For reference, the variation between solutions with MIP gaps of 0.05 and 0.02 could represent a difference of 50-100 evacuees' lives.

3.2 Baseline response and infrastructure scenario

Figure 11 shows the number of fatalities projected by solving the MIP, which considers CAF assets only. It exhibits several trends. First, the number of fatalities increases as the distance between the evacuation cell and the FOL increases, as is expected.

Second, the number of fatalities is higher in the north-west portion of the AoI. This is a result of the added time required to deploy CH147s to this area. For responses on the western side of the AoI, the CH149 helicopters come from CFB Comox. However all CH147s are based at CFB Petawawa, and an extra day of travel is required for them to reach the northwestern part of the AoI.

Third, the projected number of deaths is high across the entire AoI. The lowest observed number of deaths is 607 and occurs at the most easterly FOL examined: Qikiqtarjuaq on the east coast of Baffin Island. In this particular case, the FOL is located almost exactly at the

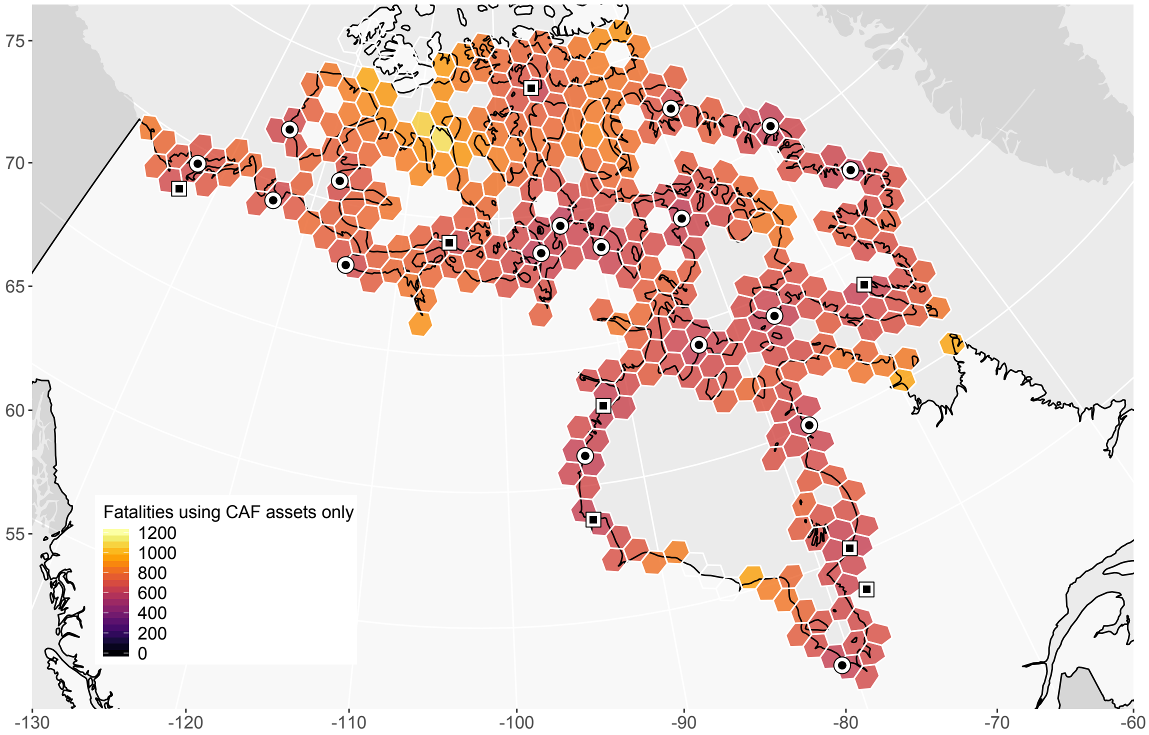


Figure 11: *Map of fatalities for the baseline response and infrastructure scenario as a function of the evacuation location when only CAF assets are used. The value shown for a cell is the lowest achieved among all FOLs in range of the cell. Empty cells are out of helicopter range.*

centre of the evacuation cell in question. Thus the travel time for the RW aircraft between the FOL and the assumed point of evacuation is very small and almost all of the helicopters' time is spent loading, unloading and in between-flight service. The worst results occurs in the two bright yellow cells in the north-west of the map, with deaths numbering 1093 and 1058. These cells are at the very limit of the effective range of the modelled RW aircraft from the best available FOLs, Cambridge Bay and Ulukhaktok. Helicopters operating from those FOLs spend much more time in transit to these evacuation locations reducing the number of trips per day.

There are two parts of the map that show uncoloured cells—the very farthest northwest and the centre of the south shore of Hudson Bay. These cells are out of RW range using the FOLs considered here. In that sense, the fatality rate here would be 100%. A different response plan than what is modelled is needed for these cells. In order not to skew the results for the rest of the DGG, we have left them blank instead.

It is very important that these numbers not be taken out of context or as a exact projection of the number of fatalities. There are many factors that will affect this result, not the least of which is the fact that, due to time considerations, the model was not solved to optimality, but a relative MIP gap between 1% and 2%. (See subsubsection 2.3.2.) This means that better solutions could exist for all of the cells, and cells have not been solved to exactly the same level of accuracy. Many other factors also affect the absolute accuracy of the result. Prominent among these are assumptions of no aircraft breakdowns, clear flying weather and the selected medical transition rates, and this list is by no means exhaustive. With that in mind, we use the results for relative comparison between cells.

Figure 12 shows the adjusted fatalities MOP, as defined in subsection 2.4. As a reminder, this MOP is derived from the results shown in Figure 11 which are then multiplied by the fatality reduction factor based on the local community assistance calculation in subsubsection 2.3.3 and shown in Figure 7. This is the measure of evacuation *quality* by cell. There are several items of note in this figure. First, the overall situation is much improved, with the number of fatalities being much lower for most cells. Second, there are some notable areas of exception where the fatalities remain high: on the western shore of Baffin Island facing Foxe Basin, and in the northwest of the map. These areas remain high because there simply are no people living in these areas, and since the set of FOLs is a subset of the set of communities, there are no FOLs available either. If an evacuation were required in these regions, the expected outcome is poor.

Figure 13 shows the weighted adjusted fatalities MOP as defined in subsection 2.4. Figure 13a shows the adjusted fatalities the entire AoI. The colour mapping of the weighted adjusted fatalities MOP reaches it peak value in two places: on the west coast of Prince of Wales Island on the line between Cambridge Bay and Resolute Bay, and on the McClure Strait shore of Banks Island to the north of Sachs Harbour. The latter location's high MOP value is an isolated result, due to the weight applied to the alternate NWP route through the Parry Channel. Given that this path is not yet consistently ice-free enough to be navigable in all years, this weight may be excessive. As such we will not discuss it further at the

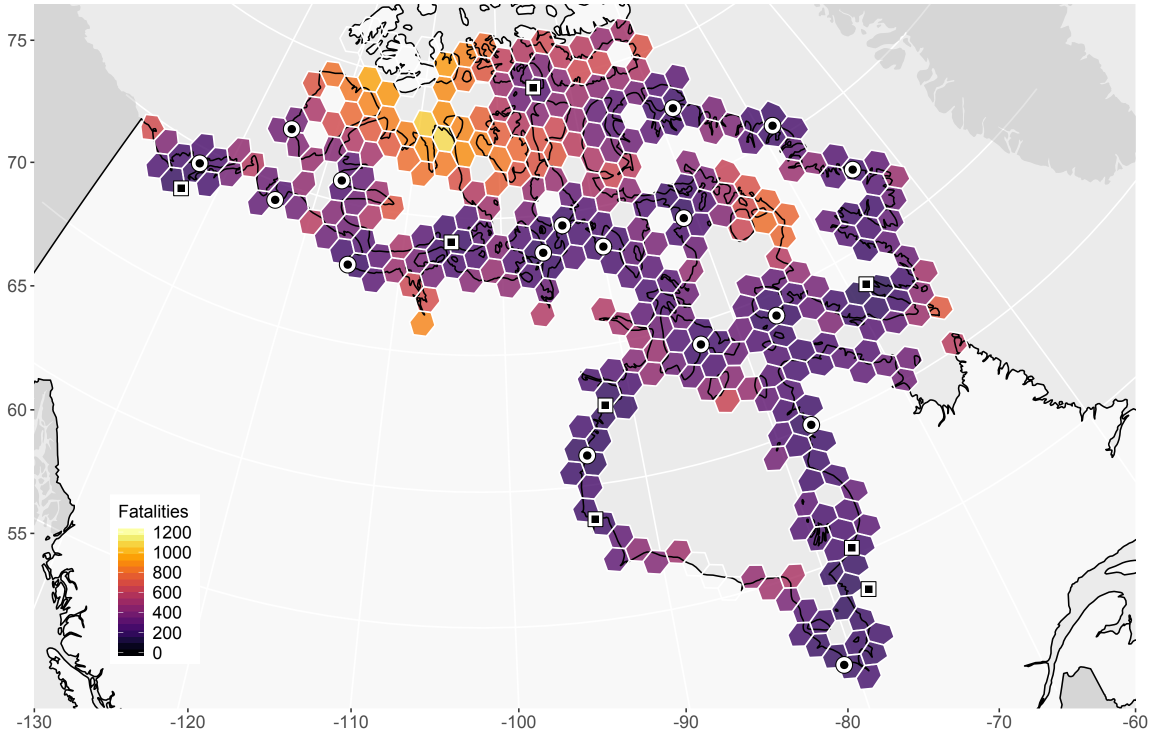


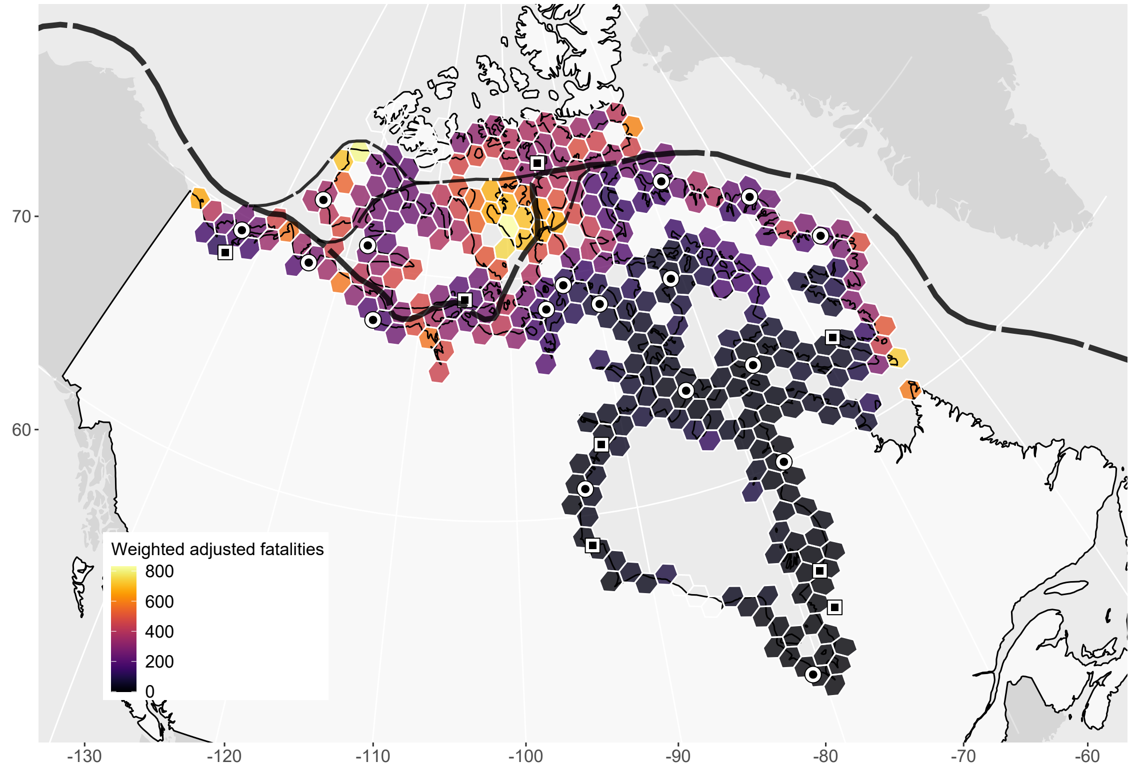
Figure 12: *Map of adjusted fatalities for the baseline response and infrastructure scenario as a function of the evacuation location. The value shown for a cell is the lowest achieved among all FOLs in range of the cell.*

present time.

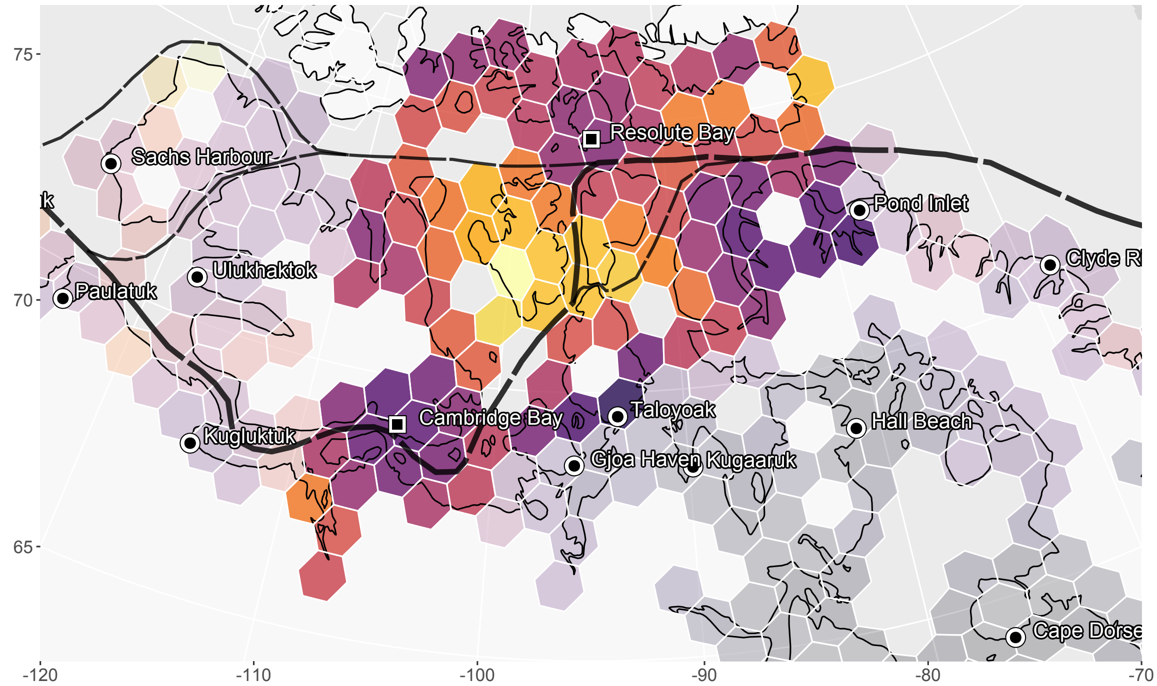
The peak MOP value on Prince of Wales Island on the other hand is just the largest value in a region of high MOP values. The coastal regions around the NWP between Cambridge Bay and Pond Inlet are consistently higher than average for the AoI. This area, highlighted in Figure 13b, is the region of greatest concern due to the confluence of three factors:

1. The relatively high expected traffic density;
2. The dearth and tiny size of local communities; and
3. The lack of suitable FOLs that results from item 2 above.

That is, cruise ships will need to pass through this area, but almost no-one lives here so there is little hope of local assistance, and the lack of FOLs means that the modelled CAF response is poor.



(a) *The entire area of interest.*



(b) *Highlighting the region of greatest concern*

Figure 13: *Map of weighted adjusted fatalities by evacuation location.*

Summing the weighted adjusted fatalities MOP by best FOL, we arrive at a single value per FOL that expresses the MAJMAR risk associated with each FOL. These are plotted in descending order in Figure 14. In this figure, the top three FOLs by this MOP are Resolute Bay, Taloyoak, and Cambridge Bay—the three FOLs within the highlighted region in Figure 13b, emphasizing the conclusion that this is the region of greatest concern.

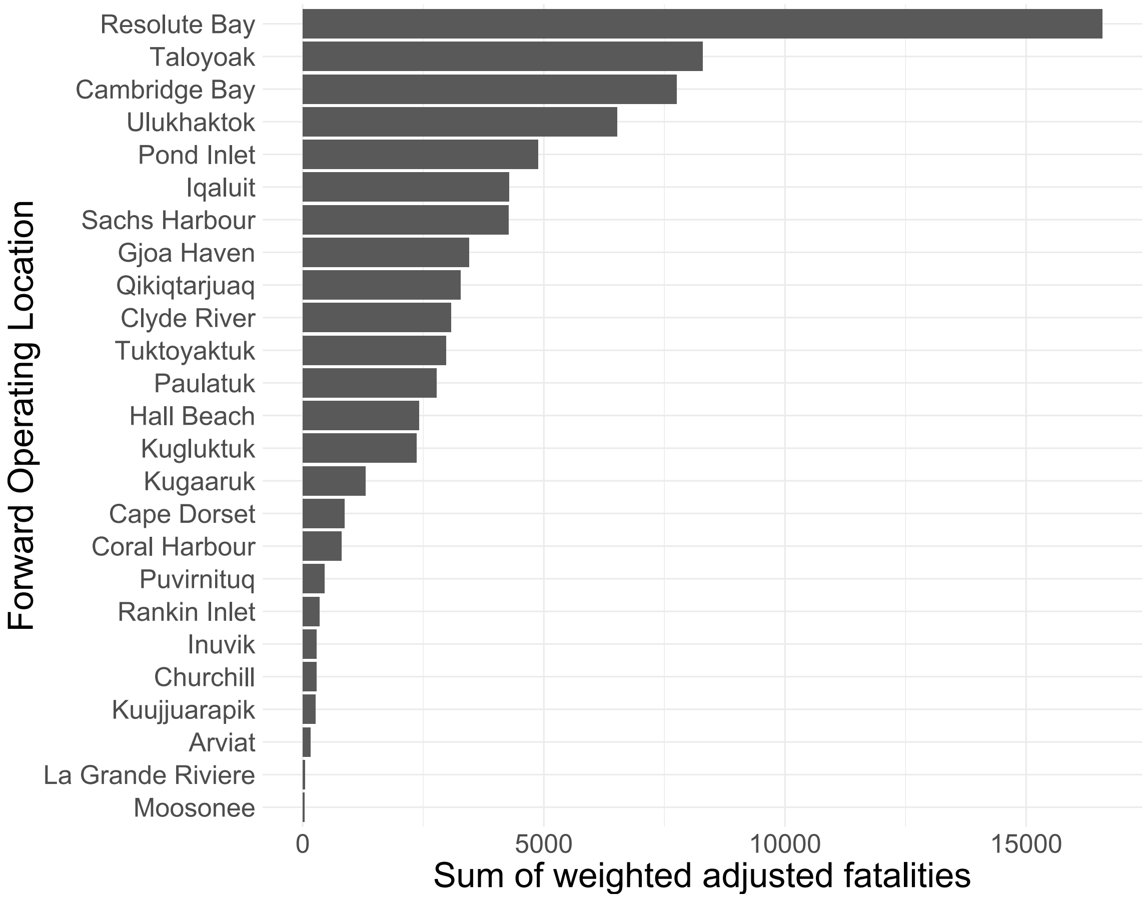


Figure 14: *Sum of weighted adjusted fatalities by FOL in the baseline scenario, in descending order.*

Figure 15 shows the mean weighted adjusted fatalities versus the number of cells served for each FOL. “Cells served” means the number of evacuation location cells for which the indicated FOL is the best one; saying that the cell is best served from an FOL does not indicate the quality of service is. It is possible for an FOL to be the best for a given evacuation location and yet still have poor results in an absolute sense. Since the cells are equal in area, the horizontal axis is proportional to area. Taking the product of the horizontal and vertical axes values by FOL in Figure 15 gives the by-FOL values seen in Figure 14. This graph partially explains the ordering seen in Figure 14. Resolute Bay is the most at-risk location because of the synergistic combination of

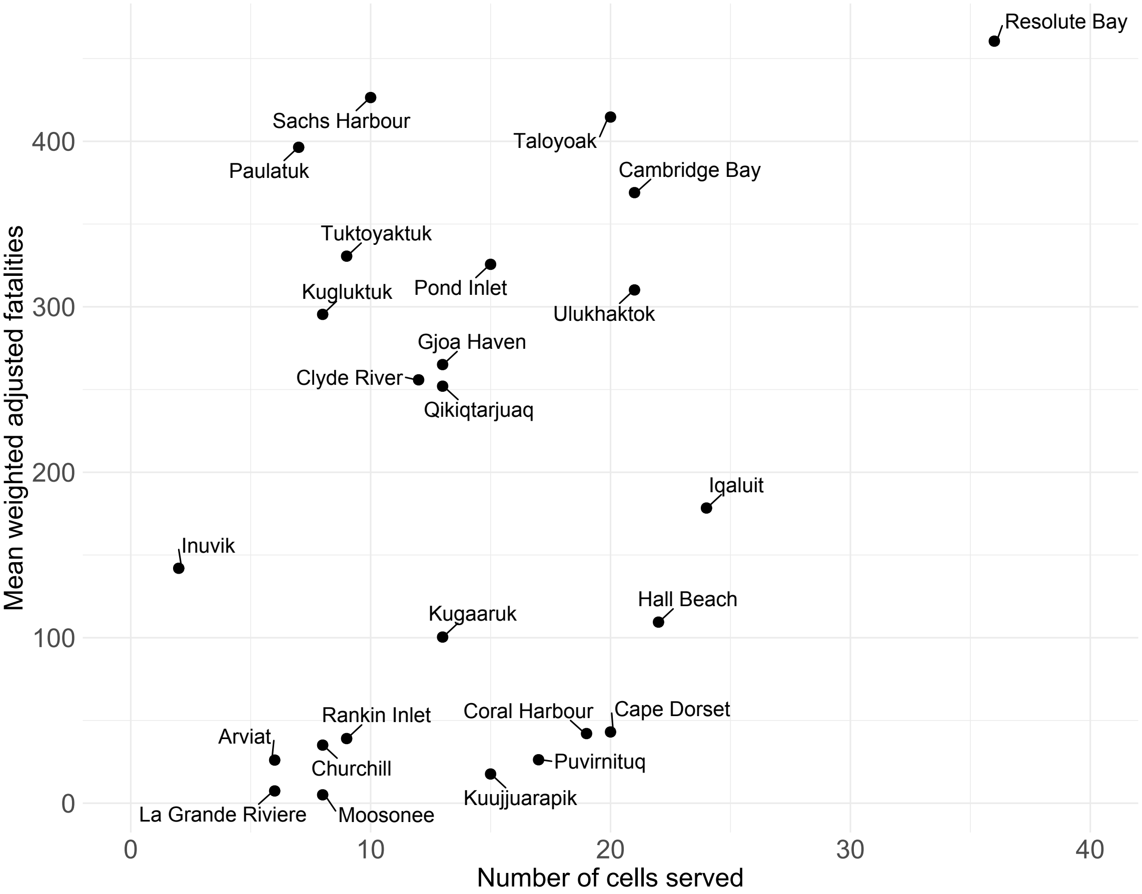


Figure 15: *The mean weighted adjusted fatalities by FOL as a function of the number of evacuation cells for which that FOL results in the lowest number of fatalities.*

1. being one of the most remote FOLs, thus requiring the greatest time to reach from southern Canada, and also causing the greatest transportation delays for injured evacuees, resulting in more deaths;
2. being the best and in many cases only FOL from which to reach a large area (number of cells); and
3. having many served cells far from the FOL, which reduces the number of trips and evacuees transported per day in the first echelon.

Items 1 and 3 increase the number of fatalities per cell (the y-axis of Figure 15), and item 2 is the x-axis of the figure. Cambridge Bay and Taloyoak also have high mean weighted adjusted fatalities, but respectively serve 42% and 44% fewer cells.

Beyond this, there are two broad groupings of FOLs seen in Figure 15, roughly divided along the 200 mean weighted adjusted fatalities line of the y-axis. This division corresponds approximately to the travel time to and from southern Canada. The FOLs above the line are remote than those below.

FOLs that are on the left side of the graph are used to reach fewer cells. This is often a result of restricting operations to coastal cells only. For example, places such as Arviat, La Grande Rivière, Churchill, Moosonee and Rankin Inlet all border on Hudson Bay, but the relative lack of coastal cells compared to places such Resolute Bay, Iqaluit, Hall Beach, Cambridge Bay and Ulukhaktok. Another consideration for this parameter is the relative density of communities. For example, Inuvik is the best FOL for only two cells under the give assumptions because Tuktoyaktuk is closer to most of the cells in the vicinity.

Taken together with the mean weighted adjusted fatalities per cell, this explains the rankings seen in Figure 14. The low amount of coastline covered by Inuvik is the primary reason for its low rank. The Arviat, Churchill, La Grande Rivière, Moosonee and Rankin Inlet FOLs all cover small lengths of coastline and that coastline is of relatively little importance under the traffic density assumptions, lowering the mean weight adjusted fatalities per cell. As a result they make up five of the seven lowest-ranked FOLs in this study.

In summary, the results for a MAJMAR scenario using the baseline infrastructures and the stated assumptions about evacuations, local assistance and traffic density indicate a clear region of elevated risk along and around the NWP between Cambridge Bay and Clyde River (see Figure 13b). Ships transiting the NWP must pass through this region but there are few communities or suitable FOLs from which to support an evacuation.

3.2.1 Sensitivity to loss or unavailability of a forward operating location

It is quite conceivable that, whether due to a governmental decision, poor weather conditions, or some other cause, the most useful FOL to respond to a MAJMAR in a given cell is not available. Should this be the case, then the next best FOL would be used, if one exists. The effect of this on the MOPs is easily computed from the model outputs. The increase in weighted adjusted fatalities when the best FOL is not available is shown in Figure 16. The evacuation locations that have no back-up FOL are indicated with wtith a heavy black border. We previously saw that the region highlighted in Figure 13b had the poorest current coverage of the NWP, but in combination with Figure 16 it is clear that it is also the region with the lowest redundancy of coverage.

Figure 17 shows the mean change in weighted adjusted fatalities per affected cell when the best FOL cannot be used. For example, removing Resolute Bay affects the results for 21 cells. The mean change in the weighted adjusted fatalities for these 21 cells is an increase of 510. Not all of the FOLs included in the study are seen in this figure. The removal of any unlisted FOL does not create any increase in weighted adjusted fatalities. This figure clearly shows the potential severity of the lack of redundancy in the Cambridge Bay-Resolute Bay-Clyde River portion of the NWP.

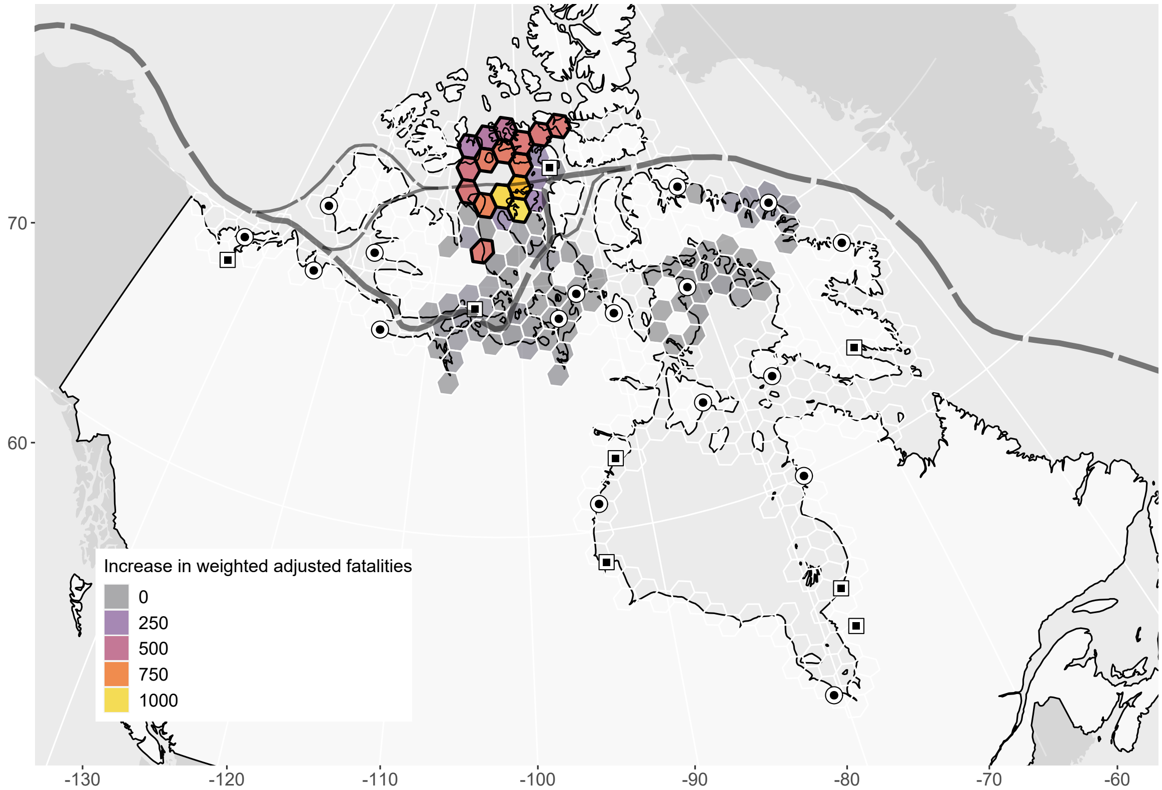


Figure 16: *Increase in weighted adjusted fatalities when the best FOL is unavailable. Untinted cells are equally well served from at least one other FOL. Cells with black borders have no back-up FOL.*

3.2.2 Sensitivity to the weighting scheme

The assumptions about community assistance in subsubsection 2.3.3 and about traffic density and evacuation to the coast in subsubsection 2.3.4 are of course quite arbitrary. Any number of arguments could be made for changing them or even leaving them out. It is important to keep in mind that the primary objective this study is the demonstration of a method. The challenging part of this analysis, computationally, is the solution of the transportation optimization model for all of the FOL-evacuation location combinations. This is completely independent of the traffic density and community effect weights and the evacuation mapping of the traffic density to the shorelines. Indeed, all of the FOL-evacuation location combinations are solved before any weights are considered and the results are stored separately. It is possible to change any or all of the weights and mapping relatively easily to support different analytical objectives.

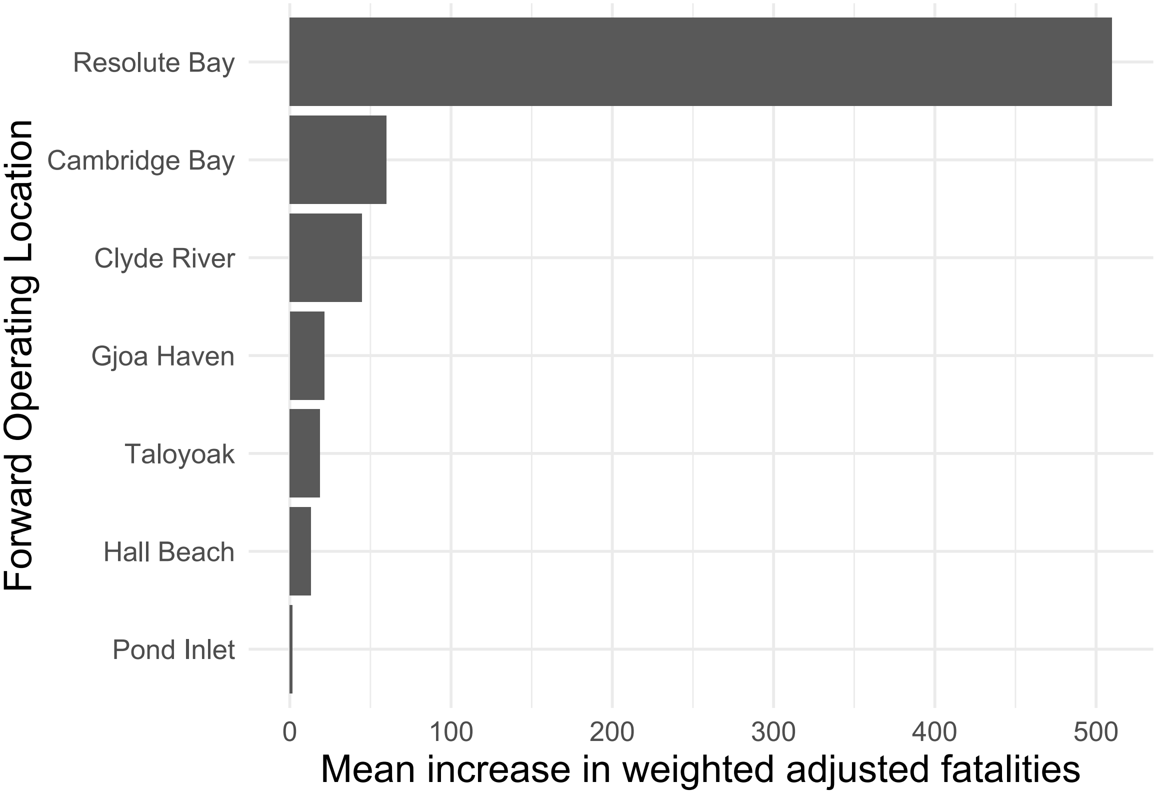


Figure 17: *Mean change in weighted adjusted fatalities per cell by removed FOL, in descending order. Removing any FOLs not shown does not create an increase in weighted adjusted fatalities.*

3.3 Infrastructure investment example – Nanisivik

As a demonstration of the proposed methodology, we examine two variations on a hypothetical infrastructure investment at Nanisivik Naval Facility (NNF). NNF is a deep-water harbour and presently has a concrete jetty and a fuel storage tank farm. Formerly this was an access point for a mine locating some 20 km inland. At the mine site, there used to be a functioning air strip 1951 m (6400 ft) long, enough to allow a CC177 to land. It is well known that the weather conditions at this site, with an elevation of 642 m, are frequently so poor as to preclude flying under VFR. For the purposes of this study, we will ignore this since we have already assumed that the weather is clear. We shall assume that this problem can be solved by installing appropriate equipment to allow operation under Instrument Flight Rules (IFR).

The first variation assumes the following:

- The existing airfield is repaired and improved for IFR operations as described above;
- Enough fuel storage can be converted or additional storage built to make the aviation

fuel capacity at Nanisivik effectively infinite. In terms of the modelling, we have set the quantity of fuel available at 1000 pallets equivalent, or 2.592 million kg. At the lowest density of JP-8 fuel (0.775 kg/l), this amounts to 3345 m^3.[24] This removes the need to move fuel forward to this FOL and the constraint that this delivery places on RW flight operations; and

- Some means exists to move fuel from NNF to the airfield in quantities such that the transfer rate is not a limitation to operations. This may be tanker trucks or it may be a pipeline.

The second variation extends the first by assuming that the airfield is sufficiently improved with additional buildings and facilities to permit extended forward deployments to the FOL. For this sub-scenario we assume that a detachment with a single CH149 and one air crew is located at Nanisivik, along with maintenance and airfield ground crew for a deployment of one to two months. This detachment is at a typical SAR posture, being at 30 minutes notice to move during on-call hours and at 2 hours notice otherwise. Thus one CH149 is available to respond on the first day of the scenario instances using Nanisivik as the FOL.

Figure 18 shows the change in the number of weighted adjusted fatalities MOP for the first Nanisivik variation. The mean reduction in the weighted adjusted fatalities is 25.2. The largest reduction is 54.

Figure 19 shows the change in the number of weighted adjusted fatalities MOP for the second Nanisivik variation. This change is more pronounced: First, a larger number of cells show a decrease in weighted adjusted fatalities when supported from the hypothetical Nanisivik FOL, to the point that in this model it is marginally better to support the regions around Resolute Bay and Pond Inlet from Nanisivik than from those FOLs. This is not likely to be true in reality but it does show the improvement to operational effectiveness if even one RW asset is forward deployed with adequate fuel and support.

Second, the degree of improvement (reduction in weighted adjusted fatalities) relative to the baseline is much greater than for the first variation. The mean and median reductions in weighted adjusted fatalities are both 62.6. Large improvements are seen to the north around Devon Island and to the west southwest around Prince Regent Inlet, between the northwestern part of Baffin Island, Somerset Island and the Boothia Peninsula. The largest reduction is 120.

The results for the second variation shows that prepositioned fuel is somewhat useful, but that the combination of prepositioned fuel and even a single forward-based RW aircraft can improve the outcomes significantly, potentially saving many lives. This bolsters the case for creating some sort of Northern operations hub and is worthy of further investigation.

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[24] The actual fuel consumption estimate is discussed later in Section 3.4.

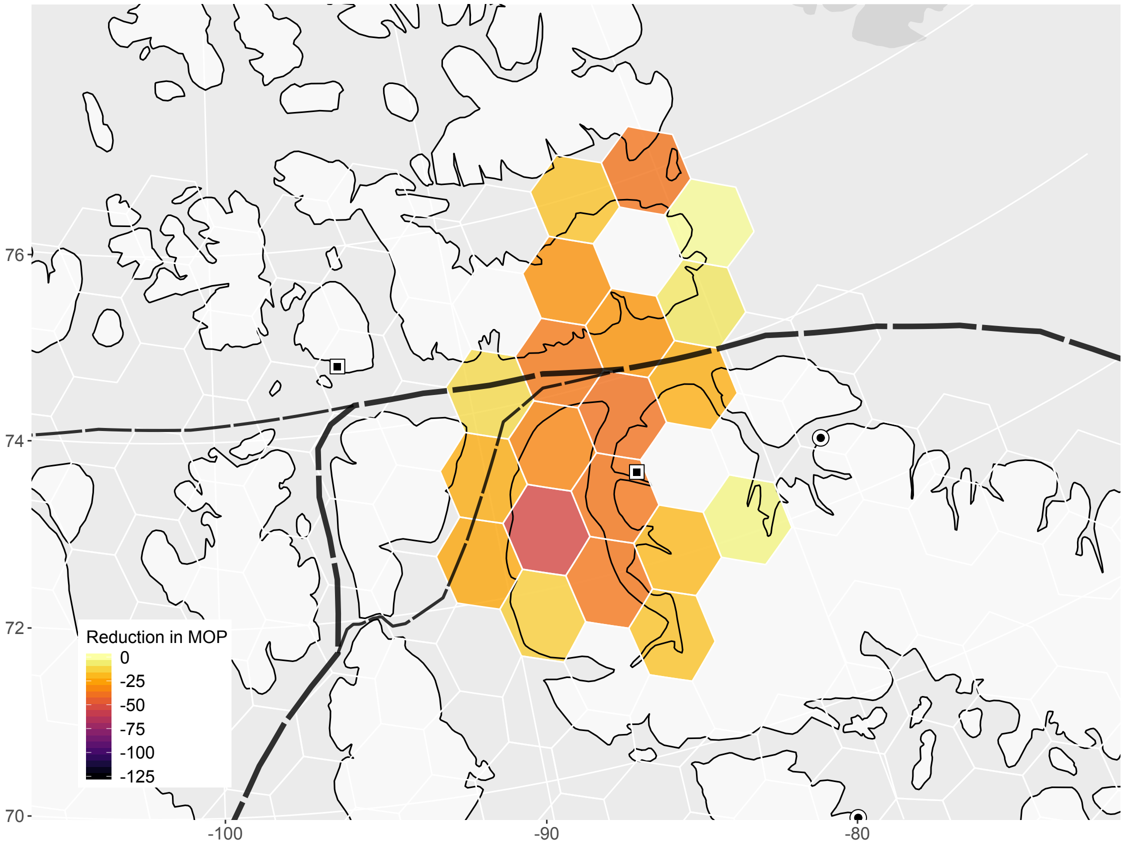

Figure 18: *Change in weighted adjusted fatalities with unlimited fuel available for the Nanisivik FOL. Nanisivik is indicated by the square FOL indicated located at 84.6°W, 73°N.*

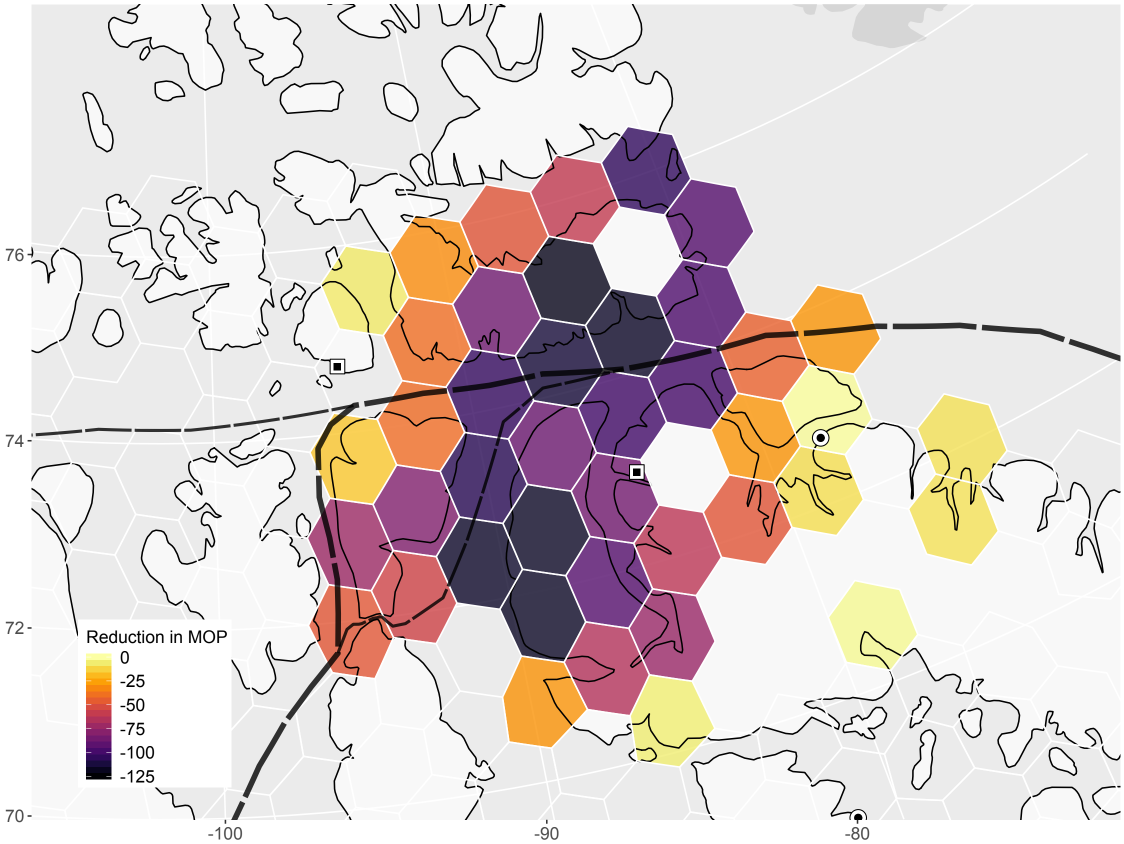

Figure 19: *Change in weighted adjusted fatalities with unlimited fuel available and 1 CH149 deployed at the Nanisivik FOL.*

3.4 Additional results

In this subsection we present two results that were not foreseen when planning the study. The first is a discussion of potential improvements to triage policy for MAJMAR scenarios in the Arctic and North. The second is a derived analysis of fuel consumption for the results described above.

3.4.1 Triage policy

The simulation and optimization models select persons for evacuation differently. This is discussed in more depth in Annex C.1. Examination of the difference in results between the two models suggest that the current SOP could be improved in this situation. In particular, the optimization model evacuates the healthy and lightly injured persons first. This is because the combination of travel times with the medical transition rates means that the more severely injured and ill evacuees cannot be moved to a safe location soon enough to save their lives. Furthermore, patients that are moved on stretchers occupy the same space as several healthier evacuees. Moving the healthier persons first ensures that they remain so instead of joining the pool of sick and injured as they wait for evacuation. This observation agrees with some tests using the simulation model. A more definitive statement on this subject would require more investigation.

3.4.2 Fuel consumption

The quantity of aviation fuel required to support RW operations is a necessary intermediate product of this logistical model. To illustrate the size of the logistical problem, we show the fuel required to achieve the results described above in Figure 20. This figure shows the quantity of aviation fuel consumed by RW aircraft from the time at which they begin operations from the FOL.[25] Summary statistics are tabulated in Table 6. These do not include fuel used by

- RW units during their travel to the FOL. This is assumed to have been procured from airports along the way;
- FW aircraft. These are assumed to refuel at other locations to reduce the logistical burden at the FOL; or
- Power generation at the FOL.

Figure 20a shows the fuel used by evacuation location for the baseline scenario considered in subsection 3.2. The values range from a minimum of 20 t to a maximum of 187 t, with a mean of 97 t and a median of 102 t. As expected, fuel consumption increases with distance from an FOL, but the number of survivors also decreases with this distance, as seen in

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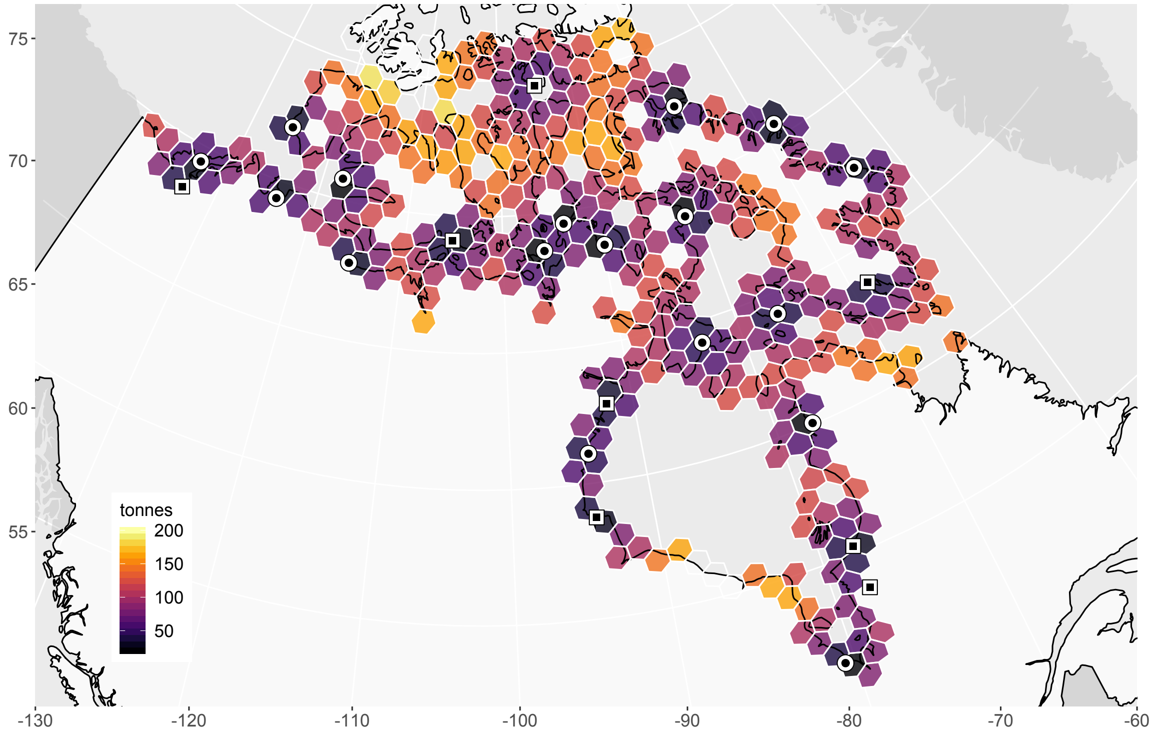
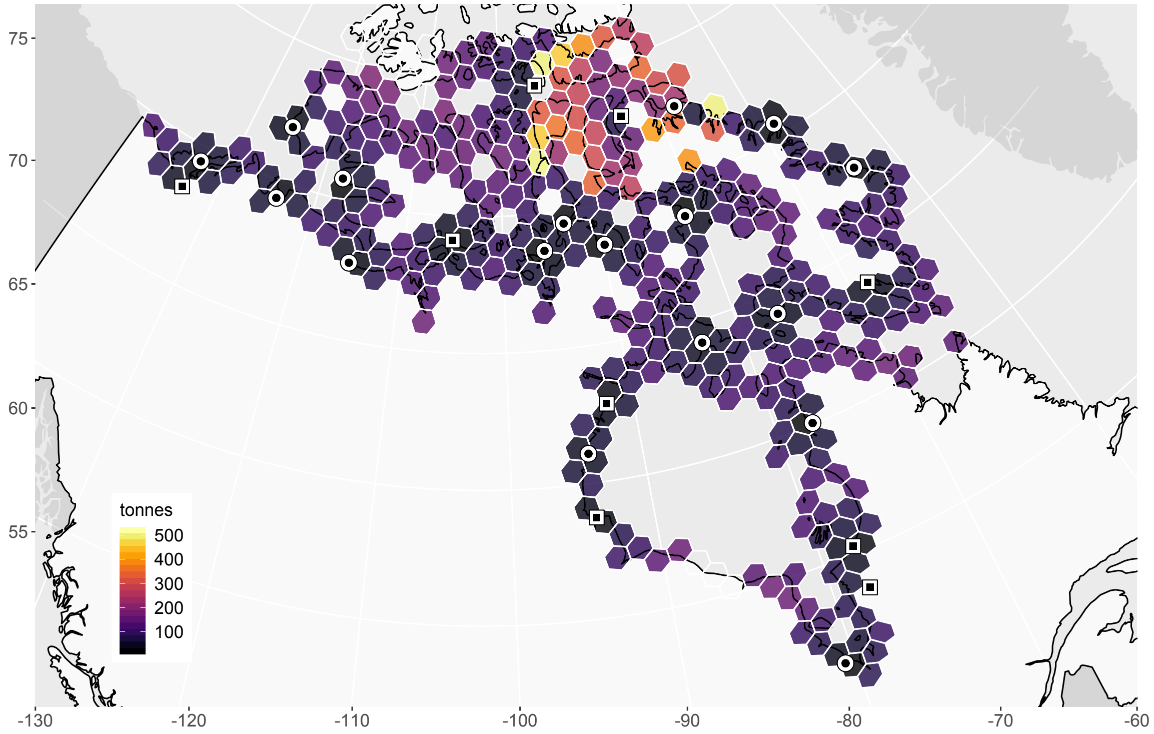
[25] Specifically, the fuel consumption shown is that used to achieve the best possible result, which is the set of routings and loads that ensure the greatest number of evacuees survive for the longest possible time. All potential FOLs were examined for each cell. The fuel used for suboptimal results is not shown.



(a) Baseline scenario



(b) Nanisivik investment scenario with unlimited fuel and 1×CH149.

Figure 20: *Rotary wing fuel consumption by evacuation location for two scenarios. Note the different scales on the maps.*

Table 6: *Fuel consumption summary statistics by scenario across all locations or a subset of locations. All values are in units of tonnes.*

Case	Minimum	Maximum	Mean	Median
Baseline	20	187	97	102
Nanisivik (full map)	20	501	118	102
Nanisivik-served locations only	79	501	292	288

Figure 12, meaning that the increasingly large quantities of fuel are used to save a smaller number of people.

Figure 20b shows the fuel used by evacuation location for the second Nanisivik investment scenario described in subsection 3.3, with effectively unlimited available fuel and one CH149 already deployed and available at Nanisivik. There is a large increase in fuel consumption for locations around Nanisivik. The median fuel consumption for the map is still 102 t, but the mean increases to 118 t and the maximum to 501 t. For the subset of locations that are best served from Nanisivik, the minimum, maximum, mean and median fuel consumption are 79 t, 501 t, 292 t and 288 t respectively.

The large increase in fuel consumption around Nanisivik when the fuel constraint was removed indicates that fuel availability and the time needed to deliver the fuel alongside the other categories of supply is a constraining factor for RW operations in the baseline scenario. Forward-positioning fuel for aircraft operations would improve outcomes across the board for this MAJMAR scenario.

4 Conclusion

This study's objective was to develop a methodology to assist with rationalizing current and future DND/CAF Arctic infrastructure investment and divestment decisions. To do so requires an analysis of each infrastructure's value—roughly 2600 locations in total—to each applicable CONPLAN, and while doing so provides a comprehensive view of each infrastructure's impact it also requires a significant effort in terms of both data collection and computing. Given these challenges, this study focused on designing a methodology applicable to a range of CONPLANs and demonstrated its applicability within a single CONPLAN—LENTUS, and more specifically a MAJMAR scenario. This scenario was selected for two reasons: it is a high logistical demand scenario and thus helps to identify gaps with respect to the CAF's ability to conduct operations in the Arctic; and second the CAF's response to a MAJMAR in Canada's Arctic has not been studied in detail and thus such an analysis may be beneficial beyond this study's scope.

We applied the methodology, which at its core is based on two mathematical programming models, to three Arctic infrastructure configurations within the MAJMAR scenario. Given the scenario's objective is to transport evacuees to southern Canada, we only considered infrastructure locations in Canada's Arctic with a CC130J or CC177 capable airfield. The current infrastructure analysis on its own is limited to informing discussion of the value of an airfield's location, as their only modelled characteristic as FOLs is their ability to accept CC130J only or both CC130J and CC177. Resolving differences between the FOLs based on specific local constraints will require model extension. The configurations analysed are:

1. Current infrastructure;
2. Current infrastructure plus an investment at the Nanisivik Naval Facility to improve its airfield for IFR operations with additional aviation fuel storage; and
3. A further extension to include infrastructure upgrades necessary to support a single forward deployment CH149 for one to two months during the summer.

Within each configuration we determined the value of each airfield using a risk measure that incorporates three components: the likelihood that a cruise ship will visit an area; the ability of local communities to provide assistance; and the ability of the CAF to evacuate survivors. Regarding the current infrastructure configuration our methodology showed:

- Resolute Bay covers a large geographic region, and in many cases, is the only FOL from which to evacuate survivors;
- Resolute Bay, Cambridge Bay and Taloyoak provide coverage to a vast area in Canada's central Arctic region, and thus divestment or degradation of the ability to stage a FOL from these locations would represent a significant decrease in the effectiveness of the CAF's response; and

- Beyond these three locations, the remaining infrastructure that was assessed may be grouped into two clusters roughly based on travel time to and from southern Canada (see Figure 15)—the further cluster consisting of Sachs Harbour, Pond Inlet, Tuktoyaktuk, etc. and the closer cluster consisting of Rankin Inlet, Churchill, Cape Dorset, etc.—where loss of infrastructure within the further cluster would represent a larger decrease in CAF effectiveness.

Regarding infrastructure investment configurations analysed in comparison to the current infrastructure, we demonstrated that our methodology was able to quantify the operational impact of various upgrades; in particular, our results showed that forward deployment of a CH149, along with required infrastructure upgrades and forward positioned fuel, to Nanisivik not only improves the CAF ability to respond within the immediate area, but also marginally improves the response as far away as Resolute Bay and Pond Inlet.

Lastly, although the goal of this study was not to compare infrastructure investment or divestment options in support of a specific decision, the ability of this methodology to do so, as well as support a variety of operational decisions—forward deployment of assets, evaluation of triage policies, assessing fuel requirements—is evident. For example, possible future options for extending this methodology or applying it to specific decisions include:

1. Adding greater fidelity to the models, such as
   (a) representation of the effect of runway characteristics on aircraft cargo capacity,
   (b) adding runway ramp space and heated indoor space to the model with explicit effects on maximum aircraft on ground and the ability to maintain them,
   (c) including local fuel storage and airfield landing aids as enablers of operations,
   (d) modelling the effects of military personnel and goods on actual outcomes such as evacuee survival and RW aircraft availability at the FOL, and
   (e) incorporate explicit modelling of Royal Canadian Navy (RCN), CCG and local and territorial government units and support;
2. Analysing the effect within an evacuation scenario of proposed infrastructure investments or divestments, such as airfield upgrades, adding operational support hubs, enhanced infrastructure or capability at communities, etc. using the current model;
3. Analysing the impact within an evacuation scenario of forward deploying fuel at a variety of locations across Canada’s Arctic. This would include a model extension to allow the transfer of fuel from the depot to the FOLs;
4. Transforming the underlying models from deterministic to stochastic and modelling decision making under uncertainty. This would enable the use of stochastic models of evacuee health, weather and aircraft reliability, and explicit representation of the flow of resources and information; and
5. Modifying and/or extending the model to represent other scenarios.

Of these, the first item regarding model fidelity improvements is the most important, as it adds explicit modelling of the FOL facilities that may be changed by infrastructure spending decisions. Should any of these analytical options be undertaken, additional computational power will be needed, such as cloud computing and an internal computing cluster. It currently takes a week to solve one instance of the model across Canada's Arctic region. A new instance is required for each proposed infrastructure or operational change. Expansion of the area for different scenarios or significant increases to model complexity will extend this time.

Finally, analysis of the RW aircraft deployment times to the various FOLs suggests that improvements to Northern operational capability may be achieved by making changes to postures and infrastructure in southern Canada independent of changes in the North. The effects of such changes can be examined using the same models. Although it is outside the current study's scope, we recommend that this be pursued as well.

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Annex A Royal Canadian Air Force response data

Additional information on RCAF response, in terms of assigned assets and their capabilities, was required to create and run the two models used in this report. Much of that information that was obtained from the JFACC, 1 Canadian Air Division and a CJOC Health Care Administrator via CJOC J5 Continental North (Hunter 2018). The proposed response in assets has been incorporated into the assumptions of the study.

Table A.1: *Additional input data and assumptions*

Assumption type	Assumption
Scenario settings	2 × CH149 + 8 × CH147 2 × CC130J *or* 1 × CC177 Daytime: 04:00 – 23:00 Nighttime: 23:00 – 04:00 Scenario started at 24:00 Resolute Bay could have at most 6 FW parked
Helicopter capabilities	CH147 average speed is 315 $\mathrm{km\,h^{-1}}$ CH147 range is 1100 km CH147 has 42 seats for passengers or 16 stretchers CH147 fuel capacity is 6200 kg CH149 average speed is 278 $\mathrm{km\,h^{-1}}$ CH149 range is 1018 km CH149 has 13 seats for passengers or 2 stretchers CH149 fuel capacity is 4100 kg
Helicopter availability	2 × CH149 available on day 0 of modelling 1 × CH147 available on day 2 of modelling +2 × CH147 available on day 4 of modelling remainder of CH147 available on day 5 of modelling Travel limited to maximum of 80% of total range (fuel reserve) 3 hours allocated for each fuel stop during deployment to FOL
Helicopter operations at FOL	CH147 turnaround at FOL between 1.0 h and 2 h, likely 1.5 h CH149 turnaround at FOL between 1.0 h and 2 h, likely 1.5 h Max operating day of 18 hours from first takeoff to landing; Last service time can occur partially or completely after this window
Helicopter ops at evacuation location	CH147 loading time between 30 min and 60 min ; likely 45 min CH149 loading time between 10 min and 20 min; likely 15 min
Fixed-wing capabilities and operations	At the start of operation, 2 CC130Js were ready to leave CFB Trenton in 8 h on average. At the start of operation, 2 CC130Js were ready to leave CFB Winnipeg in 10 h on average. At the start of operation, 1 CC177 was ready to leave CFB Trenton in 16 h on average.

Assumption type	Assumption
	CC130J turnaround time at CFB Trenton is between 4 h and 10 h. CC177 turnaround time at CFB Trenton is between 7 h and 11 h. CC130J cargo capacity is 8 pallets. CC177 cargo capacity is 18 pallets. CC130J turnaround time at FOL is between 2.5 h and 4 h; most likely 3 h. CC177 turnaround time at FOL is between 3.5 h and 5.5 h; most likely 4 h.
Evacuee and cargo characteristics	Evacuees in White and Green triage states are considered walking wounded and use the seated space consumption rate on aircraft. Evacuees in Yellow and Red triage states use the stretcher case space consumption rate on aircraft. Evacuees in the Black triage category are not moved by helicopter. Each cargo pallet can holds 16 drums of fuel for a total of 2592 kg.

Annex B Helicopter deployment routing

This annex describes the Shortest Path Problem (SPP) used to find the path with the shortest deployment time from a helicopter's MOB to each of the FOLs considered in the study, the sources of input data use, and the implementation of the model in practice. SPP definitions can be found in many texts on graph theory and mathematical programming. For but one example, see (Bradley et al. 1977), Chapter 8.

The model considers the following factors and constraints:

- the range of the helicopter,
- the location of airports to act as waypoints between the origin and the destination,
- the availability of necessary services at the waypoints, fuel being the most important, and
- the requirement to obey crew rest rules and flight regulations in the Flight Operations Manual (1 Canadian Air Division 2018).

Table B.1 contains the set and parameter definitions for the SPP. Note that the notation used here is completely unrelated to that used for the evacuation optimization model and is applicable to this annex only.

The set V was populated with a list of military aerodromes and certified airports in Canada at which appropriate fuel for the helicopter type in question is available. This information was obtained by scraping the SkyVector website (SkyVector 2019)[26] using the `rvest` package in R (Wickham 2016, R Core Team 2018).

The definitions of aerodromes, registered aerodromes and certified airports are taken from the Canadian Aviation Regulations (Transport Canada 2019). Registered aerodromes were excluded as they are not always open or available at short notice. A list of the appropriate types of fuel for CH147 and CH149 helicopters were obtained from A4 Maintenance at 1 Canadian Air Division Headquarters (Hunter 2019b). For both the CH147 and the CH149, Jet-A and Jet-A-1 are the acceptable fuel types that are mostly commonly available at civilian airports in Canada. By cross-referencing the aerodromes with the availability of fuel, the size of set V was reduced prior to model solution.

The set A was populated with the arcs between the aerodromes in V. These were filtered to remove connections that exceed the maximum deployment range of the aircraft type to reduce the size of the search space.

The objective function for this SPP, denoted here by F, minimizes the total time required to move from the origin node to the destination node, subject to the constraints below. It

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[26] This information was originally taken the Canada Flight Supplement (CFS) (Nav Canada 2018) by SkyVector, but an electronic version of the CFS was not available to the authors.

Table B.1: *Notation used for objective function, sets, variables and parameters in the shortest path problem model for helicopter deployment.*

Objective	Description
F	Total time taken for transit between origin and destination vertices
Set	**Description**
V	set of vertices (nodes)
A	set of arcs; $A \in \{V \times V\}$
Variable	**Description**
x_{ij}	Binary decision variable: $= 1$ if path includes arc a_{ij} $= 0$ otherwise.
$Days$	Integer variable containing the number of days used for travel
Parameter	**Description**
o	Index of origin vertex of the helicopter; $o \in V$
t	Index of destination vertex for the helicopter; $t \in V$
d_{ij}	Distance from vertex i to vertex j [km];
s	Speed of helicopter [$\mathrm{km\,h^{-1}}$];
f	Refuelling time [h]
d	Crew duty day length [h];
p	Preparation time prior to first flight of the day [h]
r	Crew required rest time after a duty day [h]

is given by Equation B.1 in terms of the notation given in Table B.1. All parameters have fixed input values.

$$\min F = \frac{1}{s}\left(\sum_{(i,j)\in A} x_{ij}d_{ij}\right) + f\sum_{(i,j)\in A} x_{ij} + pDays + r(Days-1), \tag{B.1}$$

subject to:

$$\sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} = 1, \qquad i = o; \tag{B.2}$$

$$\sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} = -1, \qquad i = t; \tag{B.3}$$

$$\sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} = 0, \qquad i \in V \setminus \{s,t\}; \tag{B.4}$$

$$Days \geq \left(\underbrace{\frac{1}{s}\sum_{(i,j)\in A} x_{ij}d_{ij}}_{\text{Total travel time}} + \underbrace{f\left(-1+\sum_{(i,j)\in A} x_{ij}\right)}_{\text{Refuel at all stops but last}}\right) \Big/ \underbrace{(d-p)}_{\text{Usable duty day}} \tag{B.5}$$

$$Days \leq 0.9999999 + \left(\frac{1}{s}\sum_{(i,j)\in A} x_{ij}d_{ij} + f\left(-1+\sum_{(i,j)\in A} x_{ij}\right)\right)\Big/(d-p). \tag{B.6}$$

Equation B.2 requires that there be exactly one more departure from node $i = o$ than arrivals, enforcing its status as the origin of the path. Equation B.3 mandates that the number of arrivals at node $i = t$ be exactly one more than the number of departures, making it the terminus of the path. Equation B.4 says that the number of arrivals at any node $i \in V$ that is not o or t must be exactly equal to the number of departures; that is, the path cannot begin or terminate there. The first term of Equation B.1 and Equations B.2—B.4 form the basic definition of all SPPs.

The next two constraints extend the basic SPP to include the time required to account for the aircrew rest periods after each duty day. Inequality B.5 states that the total number of days taken for the deployment must be greater than or equal to the sum of the total travel time and the refueling time *before the destination vertex*, divided by the available duty day length. It could be argued that the first fueling of the day could be accomplished outside of the duty day or at the same time as the duty day preparation period. The implied assumption here is that the aircrew may be responsible for overseeing this process depending on the airfield in question.

Inequality B.6 ensures that the *Days* is no larger than necessary: *Days* may only take integer values, B.6 ensures that it is never more than . Together, inequalities B.5 and B.6 ensure that there is only ever one valid value of *Days*. Note that *Days* is *not* the transit time to the destination, but a parameter that is manipulated by the solver in the solution process. A base version of model was coded in the GNU MathProg modelling language (Makhorin 2018), which is a subset of the AMPL language (Fourer et al. 1993). Actual model solution was done with Gurobi 8.0.1 (Gurobi Optimization, LLC 2018b). An R script was written which cycled over all combinations of the aircraft types (with associated bases) and FOLs, modifying the base version of the model file, compiling it to an MPS file with the appropriate input data using the GLPK, version 4.54 (Makhorin 2018). The script then passed this MPS file to Gurobi using the `gurobiR` package (Gurobi Optimization, LLC 2018a). The resulting output from all aircraft and destination combinations was then collated by the script. The solutions are shown in Table B.3.

Table B.2: *Non-geographic parameter values used in rotary-wing aircraft deployment routing problem.*

Parameter	Description
o	Index of origin vertex of the helicopter; $o \in V$
t	Index of destination vertex for the helicopter; $t \in V$;
d_{ij}	Distance from vertex i to vertex j [km];
s	Speed of helicopter [$\mathrm{km\,h^{-1}}$];
f	Refuelling time [h];
d	Crew duty day length [h];
p	Preparation time prior to first flight of the day [h]
r	Crew required rest time after a duty day [h]

Having solved for the shortest possible path, this is now converted into the number of days lost in transit via manipulation in `R` using the `lubridate` package. In line with the assumption that the disaster takes place at midnight in subsection 2.1, the timeline for beginning helicopter deployment begins at 4 AM the following day. Taking this as the start time for the movement, the total transit time from the SPP solution was added to this as a datetime object. This is feasible because the solution already included crew rest time. The availability time of day was then compared to the amount of remaining daylight hours at the reference accident location; if a full duty day could be executed in the remaining daylight hours, the aircraft was marked available for that day. Otherwise, it became available on the next day. These transit delays were then used as inputs to the evacuation optimization model as offsets to the base helicopter availability times for the FOL under consideration.

Table B.3: *Time required deploy to each FOL from the indicated MOB. A specific helicopter type is associated with each MOB and is indicated in the column header.*

	Time to deploy to FOL from MOB [h]			
FOL	CYQX (CH149)	CYQQ (CH149)	CYCB (CH149)	CYWA (CH147)
CYRB	44.8	43.2	17.6	42.7
CYIO	42.9	45.5	19.9	41.5
CYCY	41.3	46.4	21.1	25.9
CYYH	43.1	42.3	16.6	27.0
CYCB	45.3	25.7	0.0	41.9
CYUX	26.9	43.5	18.4	25.1
CYHK	43.3	42.0	16.4	26.9
CYBB	42.4	42.5	17.2	25.6
CYCO	47.2	24.6	16.6	43.2
CYVM	25.3	46.9	22.0	25.2
CYTE	24.7	43.7	20.9	23.5
CYZS	25.7	42.5	20.0	23.6
CYFB	23.8	46.1	22.3	23.7
CYRT	41.1	25.8	18.3	24.0
CYEK	41.2	25.3	19.7	23.9
CYSY	49.3	26.2	17.9	45.4
CYHI	47.4	25.6	16.9	44.5
CYUB	50.6	25.6	20.0	46.3
CYPC	49.0	25.0	17.7	45.2
CYEV	50.8	25.3	20.1	46.1
CYPX	23.9	43.4	22.3	21.0
CYGW	22.2	44.1	24.5	19.3
CYYQ	27.0	25.0	20.7	23.3
CYGL	22.1	44.0	25.1	17.7
CYMO	22.7	43.28	26.0	17.0

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Annex C Relevant characteristics of the optimization and simulation models

A mixed-integer linear programming model, henceforth called the “optimization model,” was developed for this study in parallel with the simulation model described in (Chan 2019). In so far as it is possible, it replicates the functionality of the simulation model. Significant deviations are noted in C.1.

At its core this problem is a *capacitated vehicle routing problem* (CVRP). Generically, the *vehicle routing problem* (VRP) is defined as follows: given a set of transportation requests, a set of vehicles and an objective function, select the vehicles and routes to perform all feasible transportation requests with the given fleet such that the objective function is minimized. (Toth and Vigo 2014) A capacitated vehicle routing problem (CVRP) extends the problem by assigning a capacity to each vehicle and a capacity requirement to each transportation request. The instantiation of the CVRP described here is further complicated by the inclusion of two echelons of transport, heterogeneous vehicle fleets, requirement for cargo pick up and delivery, backhaul, and split deliveries. All of these subjects are discussed in (Toth and Vigo 2014).

Development of the optimization model has followed and evolved from (Mitrovic-Minic et al. 2017) in general structure and notation, based on discussion with one of the authors of that paper, a Defence Research and Development Canada (DRDC) Defence Scientist (Hunter 2017). As in (Mitrovic-Minic et al. 2017), we define the undermentioned problem characteristics. Due to its lengthiness, the full mathematical description of the model has been published separately as (Hunter 2019a). What follows is a brief description of the characteristics and limitations of the model as it currently exists.

- Transportation modes:
    - All transport of cargo is achieved using fleets of air vehicles at this time;
    - Fleets are heterogeneous. There is no limit on the number of vehicle types that may be created;
    - Vehicles are assigned to an echelon. They may travel to any node which is connected to their echelon by an arc. This is subject on the vehicle’s range, and requirements for infrastructure and refuelling at the nodes;
    - The deployment of vehicles from their bases to the selected FOL(s) is represented as a delay in their availability. This delay is calculated separately (see subsubsection 2.2.2) and the result used as an input to the optimization model;
    - All vehicles have capacities that are defined by vehicle type. Compatibility between vehicles and cargo types must be considered and restrictions to allowable cargo types will require vehicle-type-specific constraints;
    - Refuelling requirements. All vehicle requires fuel to function. This is modelled explicitly only for first echelon vehicles. Second echelon vehicles are refuelling

    implicitly because they travel to and from nodes where fuel is readily available; and
  - Restrictions may exist that prevent certain cargo types from travelling together on a vehicle;

- Arcs
  - Arcs are unidirectional and have length representing the distance between the nodes. Two opposing arcs are needed between two nodes if travel is possible in both directions.
  - Vehicles may travel along any arc between any two nodes provided range restrictions and infrastructure requirements are met.

- Cargo. There are four cargo types. Each has its own supply, demand and carriage characteristics, detailed in (Hunter 2019a);
  - Evacuees. These are the persons that must be moved from event nodes to rear echelon nodes. Their supply is created at the event node(s) during model initialization. Demand is implicitly created by the model's objective function;
    - ∗ Medical state update is performed once per day, based on the location of the evacuees at the end of the day. A state transition matrix must be supplied as part of the input to the model. The creation of this matrix is described in section 2.2.4 below.
  - Fuel. For the purposes of this study there is one type of fuel for all vehicles. The supply is created the primary rear echelon node during model initialization. Demand is generated within the model by the requirement of first echelon vehicles for fuel;
  - CAF personnel. This category includes all military personnel without distinction. The supply and demand for them are defined explicitly during initialization;
  - Supplies. This represents all non-fuel items that are needed, both durable and consumable. Their supply and demand are defined explicitly during initialization;
  - Return of unused supplies, CAF personnel, and the bodies of fatalities are excluded from this model;

- Travel times, service times and loading/unloading times are modelled deterministically.

C.1 Differences between the simulation and optimization models

There are a number of differences between the simulation and optimization models, such as the discretization of time into days in the optimization model as opposed to the five minute segments of the simulation model. This difference causes divergences in the aircraft routing and availability timings and in the update of evacuee medical states between the models. The optimization model deals with routing and availability by including departure time calculations and constraints, but this does not match the fidelity of the simulation model, which tracks the position of every entity at every time step. As a result of this, the exact time of pickup and delivery of evacuees is not tracked in the optimization model. They are effectively added to the inventory at the delivery node at the end of the day. In order to prevent evacuees from being picked up before they are delivered to a node, the optimization model limits the total persons (by triage state) picked up to the inventory at the beginning of the day. Because the simulation model tracks each evacuee's location every five minutes, it is possible for an evacuee to move all the way from an event node to a rear-echelon node in the span of that model's day.

The effect of these differences on the update of evacuee medical states is not easily managed. The simulation model tracks each individual's state separately and updates probabilistically every five minutes, with different rates depending on where the individual is located at that time. By contrast, the optimization model only considers the evacuees' location at the end of the day, and uses a deterministic state transition matrix on the group of evacuees at each node. This undoubtedly leads to additional predicted deaths in the optimization model relative to the simulation model.

However, the more interesting difference between the models is the lack of things such as a triage policy in the optimization model. That is, rather than follow a standard operating procedure for the selection of evacuees, the optimization model simply searches through the set of possible differing loads for each aircraft flight and selects that (or those) that give the best net effect on the objective function. This has advantages and disadvantages. An advantage of this is that the optimizer is not bound by existing policy and can search for the choices that are most effective. This has the potential to yield new insights and suggest possible improvements to existing policies. On the other hand, the fact that the selection is not made using a policy means that each decision is individual in nature, such that there may be no over-arching policy insight to be gleaned at all. This could be changed by using other methods, something which is addressed in the discussion of (Hunter 2019a) and in subsection 3.4.

Acronyms and abbreviations

AoI Area of Interest

AoR Area of Responsibility

CAF Canadian Armed Forces

CC130J CC130J Hercules

CC177 CC177 Globemaster III

CCG Canadian Coast Guard

CFB Canadian Forces Base

CFS Canada Flight Supplement

CH147 CH147 Chinook

CH149 CH149 Cormorant

CJOC Canadian Joint Operations Command

CONPLAN Contingency Plan

CORA Centre for Operational Research and Analysis

CVRP capacitated vehicle routing problem

DCOS Ops Contl Deputy Chief of Staff Operations - Continental

DGG Discrete Global Grid

DRDC Defence Research and Development Canada

DND Department of National Defence

FOL Forward Operating Location

FW fixed-wing

GLPK GNU Linear Programming Kit

IC Infrastructure Cluster

IFR Instrument Flight Rules

IRU Immediate Reaction Unit

ISEA icosahedral Snyder equal area

JFACC Joint Forces Air Component Command

JTFN Joint Task Force North

JRCC Joint Rescue Coordination Centre

MAJMAR Major Maritime Disaster

MIP Mixed Integer Program

MOB Main Operating Base

MOE measure of effectiveness

MOP measure of performance

NIS Northern Infrastructure Study

NNF Nanisivik Naval Facility

NWP Northwest Passage

OGDAs Other Government Departments and Agencies

OR&A Operational Research & Analysis

RCAF Royal Canadian Air Force

RCN Royal Canadian Navy

RW rotary-wing

SAR Search and Rescue

SME Subject Matter Expert

SOP standard operating procedure

SPP Shortest Path Problem

SRU Search and Rescue Unit

START Simple Triage and Evacuation

VFR visual flight rules

VRP vehicle routing problem

WAF weighted adjusted fatalities

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With the reduction of ice coverage in the Arctic, access to Canadian territorial waters such as the Northwest Passage is becoming feasible over a wider area and time span. As a result, maritime traffic through the area is expected to grow, increasing the likelihood of Canadian Armed Forces domestic operations in the region. We present analytical work on the effect of sparse logistical infrastructure on military operations in the Canadian Arctic region, whose purpose is to inform Department of National Defence and Canadian Armed Forces infrastructure investment decisions. We focus on a major maritime disaster scenario requiring the evacuation of a large cruise ship. We examine the transportation and logistics component of the problem using a mixed-integer programming capacitated vehicle routing model. Factors considered include the current Canadian Armed Forces force deployment and response posture, transit to forward operating locations, vehicle capacity, fuel requirements, the time-degradation of the medical state of the evacuees, and triage decisions at loading time. The model is applied over all feasible combinations of forward operating locations and a grid of accident locations to assess performance over the entire region and the impact of procedural and infrastructure changes.

Avec la réduction de la couverture de glace dans l’Arctique, l’accès aux eaux territoriales canadiennes telles que le passage du Nord-Ouest devient possible sur une zone et une période de temps plus large. Par conséquent, le trafic maritime dans la région devrait augmenter, ce qui augmentera la probabilité d’opérations nationales des Forces armées canadiennes dans la région. Nous présentons un travail analytique sur l’effet d’une infrastructure logistique clairsemée sur les opérations militaires dans la région de l’Arctique canadien, dont le but est d’éclairer les décisions d’investissement dans l’infrastructure du ministère de la Défense nationale et des Forces armées canadiennes. Nous nous concentrons sur un scénario de catastrophe maritime majeure nécessitant l’évacuation d’un grand navire de croisière. Nous examinons la composante transport et logistique du problème à l’aide d’un modèle de routage de véhicule capacitif à programmation en nombres entiers mixtes. Les facteurs pris en compte comprennent la posture actuelle de déploiement et d’intervention des Forces armées canadiennes, le transit vers les lieux d’opérations avancés, la capacité des véhicules, les besoins en carburant, la dégradation dans le temps de l’état médical des évacués et les décisions de triage au moment du chargement. Le modèle est appliqué à toutes les combinaisons possibles d’emplacements d’exploitation avancés et d’une grille d’emplacements d’accidents pour évaluer les performances dans toute la région et l’impact des changements de procédure et d’infrastructure.