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Evacuating isolated islands with marine resources: A Bowen Island case study

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ABSTRACT

Inhabited islands are susceptible to natural hazards, such as wildfires. To avoid disasters, preventative measures and guidelines need to be in place to strengthen community resilience. If these fail, evacuation is often the only choice. However, island evacuation is a vastly understudied problem in both research and practice, particularly for islands without permanent road connections to the mainland that require marine evacuation. Multiple vessel trips are necessary to evacuate the population from suitable access points, which previous studies did not entertain. Furthermore, most existing studies either focus on evacuations from an academic, or from a government perspective. Instead, this paper presents a collaborative approach. It applies a recently developed evacuation routing model that optimizes the evacuation plan for Bowen Island in Canada through minimizing the expected evacuation time across disaster scenarios. These were designed with the participation of a broad range of stakeholders, from local residents and volunteer groups to agencies from all levels of government and companies, which integrates both academic and practical perspectives to maximize solution quality. Different options for fleet sizes, staging locations and scenarios were considered. The results show that the optimized evacuation time for Bowen Island varies between 1 and 8 h, as it strongly depends on the disaster scenario, the evacuation fleet, and can be accelerated by temporary staging areas. The suitability of the approach for evacuation studies can be confirmed through the identification of key improvements for increased community resilience and the inclusion of the results in the official Bowen Island evacuation plan.

1. Introduction

1.1. Motivation

Science has frequently connected the increased occurrence of natural hazards to climate change [1–3]. In largely forested areas, such as the west coast of North America, communities are vulnerable to natural hazards that affect forests, particularly fires. The increased severity of wildfire events since the year 2000 confirms the increase of wildfire events [4]. The increased frequency of such natural hazards, combined with past failure to reduce the risk for disasters sufficiently leads to an increased risk for disasters to vulnerable socio-ecological systems [5,6]. Since wildfires are becoming an increasingly high threat [7] to societies, there is increased interest in providing solutions to make communities more resilient against wildfires [8]. Achieving community resilience is a complex

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task and many studies have investigated how to improve it, especially considering communities threatened by wildfires [6,8,9], such as preventative forest management and the design of community infrastructure and property layouts at the urban-wildland interface. Making communities more resilient and investing in disaster prevention is therefore the primary objective of disaster risk reduction and highly influences the effects on the community should a natural hazard occur. However, while the risk to the population can be reduced by appropriate resilience measures, a contingency plan is necessary as a last resort for the case that a disaster cannot be averted. Hence, an important aspect of a disaster contingency plan is to ensure the ability to evacuate the population quickly and efficiently [10]. Evacuations are particularly difficult in areas that have geographically challenging circumstances, such as a limited number of exit roads or no road access at all, as a recent geo-spatial data analysis by StreetLight Data showed for communities in the USA [11]. This particularly applies to marine communities, as recent disasters have shown: for example, during the 2020 Australia bushfires, a large part of the population of Mallacoota had to be evacuated using navy vessels after the fire front had cut off all exit routes [12], and during a wildfire in Greece in 2019, the population of beach villages had to be evacuated from the beach using boats [13]. The increased awareness of the risks of wildfires has motivated the Bowen Island Municipality (BIM) to review community preparedness plans and to prepare an evacuation plan for the heavily forested Bowen Island [14] as a last resort contingency. Bowen Island is located in Howe Sound, to the west of the Canadian west coast metropolis Vancouver in the Province of British Columbia (BC) and does not have a road connection to the mainland. Fig. 1 shows a schematic map of the area around Bowen Island. The Bowen Island community, including many of the over 3600 residents [15], local government staff and elected officials, identified the need for evacuation planning during the summer of 2015, when smoke from wildfires on the nearby Sunshine Coast was visible from Bowen Island, and residents awoke to an orange sky. This nearby wildfire event prompted a review of the outdated 2007 Bowen Island Emergency Management Plan and the subsequent formation of an Emergency Program for the community. Geographically, Bowen Island's topography and road networks mean that limited routes are available for evacuation, with most of the island's sub-communities served by single terminating roads. Further, limited modes of transportation off-island are available, with the ferry providing one primary point of access and egress. While the ferry is the most utilized and affordable choice for getting to and from Bowen Island, vehicles and equipment can alternatively be transported by private barge, and private vessels can access the island at multiple points for passenger pick up and drop off.

In addition to the geographical challenges and the heightened awareness of the risk in recent years, multiple community plans and assessments had indicated that planning was imperative to ensure an effective evacuation of the island as far back as 2007. The Bowen Island Municipality Community Wildfire Protection Plan (CWPP) notes the potential for a large interface fire and that "under this scenario, rapid evacuation of residents and safe escape or refuge for firefighters would be essential. At present, action is required to bring evacuation and emergency response planning to a level where this type of emergency is taken into account." [16][p. 21]. The CWPP also recommended "developing a contingency plan in the event that smoke requires complete evacuation of the island" [16][p. 31] and that "an evacuation plan should be developed and appropriate evacuation routes should be mapped. A large fire may require the evacuation of the entire island and egress could be very restricted. A contingency plan for water evacuation should be developed in the event that the ferry is unavailable." [16][p. 33].

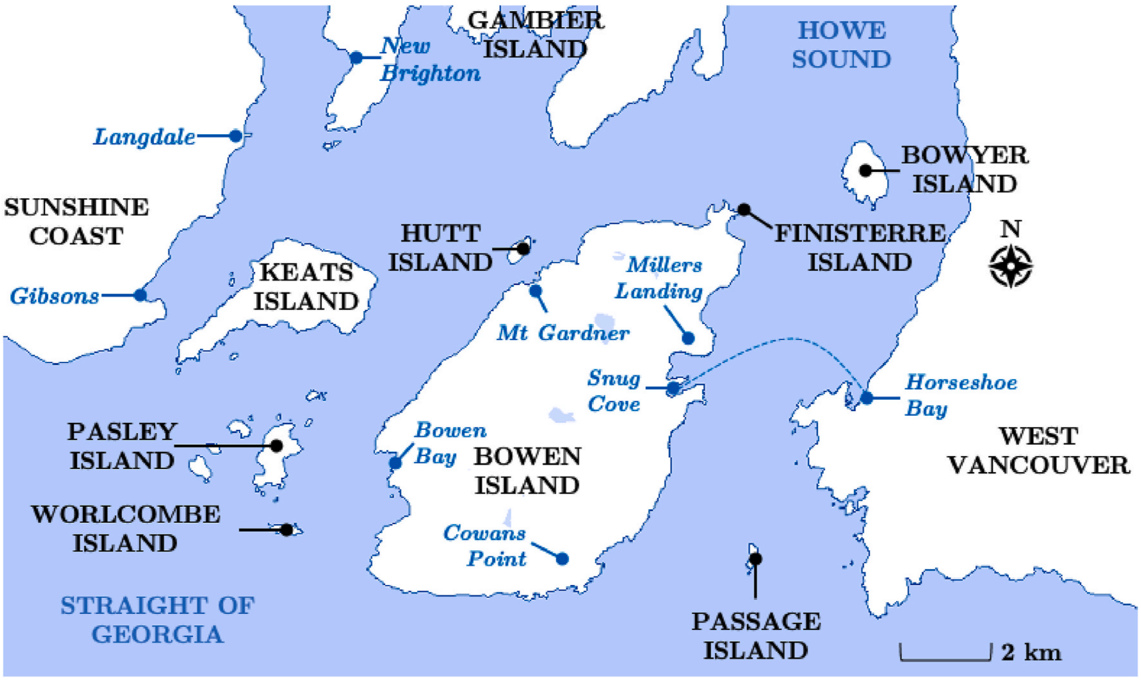


Fig. 1. Map of Southern Howe Sound including major settlements and islands.

The 2018 BIM Hazard Risk and Vulnerability Assessment (HRVA) also stresses the importance of evacuation planning as critical to the Municipality's ability to conduct a successful evacuation [17]. The HRVA highlights the reality that the presence of multiple terminating roads makes the potential for evacuation by water a distinct possibility, and that "the multiple challenges posed by an island-wide evacuation make evacuation planning important to emergency preparedness on Bowen Island" [17][p. 26]. The HRVA recommends that the Municipality engage in formal evacuation planning, and that this work could also prove useful in re-supplying the island in the event of a BC Ferry Services Inc. infrastructure failure, as well as in re-supplying sub communities that are not accessible by road post-disaster. The heightened awareness of the local risk of wildfire and the anticipated challenges associated with evacuating the island, combined with the availability of funding for local government evacuation planning through the Province of BC and the Union of British Columbia Municipalities (UBCM), led the community to formally address the issue of evacuation planning beginning in 2019. While modelling of land based (vehicle) traffic had been incorporated into earlier planning, modelling of marine vessel traffic was identified as necessary in order to better understand potential opportunities, challenges and timelines under a variety of realistic evacuation scenarios. The community well understood the capacity of the ferry [18][p. 48], but did not have any knowledge of what the fleet of local vessels could contribute to reduce total evacuation time, nor what capacity existed should the ferry be unavailable and how to select appropriate route plans for these evacuation resources. To fill these knowledge gaps and take advantage of sophisticated modeling skills the local government did not have access to, the local government emergency manager of Bowen Island entered into a collaboration with the research team of the Supply Chain Transportation and Logistics Center (SCTL) at the University of Washington. This collaboration was a result of a chance meeting at a workshop on marine transportation resilience in the scope of 'Shipping Resilience: Strategic Planning for Coastal Community Resilience to Marine Transportation Risk' (SIREN), highlighting the importance of opportunities for researchers and practitioners to connect and collaborate in this type of forum. While collaboration did increase the time and resources expended, the integration of carefully collected ground level data with sophisticated evacuation modeling techniques, led to invaluable insights regarding expected evacuation times under different scenarios. The research questions defined for this collaborative study were:

- How to evacuate an island, where road-based evacuation is not possible, and marine resources have to be used to evacuate the population?
- How long does it take to evacuate the island under a variety of conditions?
- How to use this information to plan and prepare for a real-world evacuation and reduce the evacuation time?

Other island communities with similar characteristics around the world face similar challenges, see for example [11] for similar places in the United States. This shows the wider relevance of this problem, which is why answering these research questions systematically and rooted in methodology can be used as a template for similar studies in other regions.

Before investigating ways on how to evacuate an island, it is important to consider what makes this problems special compared to other evacuation problems. At first, the lack of a permanent road-based connection to the mainland makes it impossible for the majority of an island population to leave the area with a private vehicles or on foot. Instead, they have to move to the shoreline and evacuate by marine resources. Since the majority of people do not own boats that are readily accessible to evacuate themselves, they are dependent on others. Since there may be multiple potential vessel access points in a community that cannot easily be overseen, this is where it becomes necessary to evacuate the island through a coordinated effort that includes the management of vessel routes and passenger assignment. However, these plans are sensitive to changes in the nature of the hazard and the size of the population that is affected and one-size-fits-all approaches to evacuation plans become impractical. Thus directing the population to appropriate vessel access points and coordinating a potentially heterogeneous vessel fleet while considering a variety of disaster realizations are the main challenges in island evacuation that are not comparable to regular road-based evacuation. This paper focuses on the latter of the two challenges.

1.2. Previous work

There are different ways of how evacuation planning can be approached. From a practical perspective, the Province of BC provides some guidance to communities with regards to evacuation planning. Relevant to the Bowen Island case study, Emergency Management British Columbia has published a 47 page guide, "Evacuation Operational Guide for First Nations and Local Authorities in British Columbia: A guide to managing evacuations during emergency response", which provides "a simplified reference tool for Emergency Operation Centres (EOC) or designated community contacts to follow when issuing an Evacuation Alert, Order, or Rescind." [19][p. 3]. The document serves as a quick reference guide for community leadership during an evacuation: "Intended for use during the response phase of an emergency, this guide provides advice, information, considerations, and templates for all stages of an evacuation. The recommendations provided are not prescriptive." [19][p. 8]. The guide is not an evacuation plan template, but provides relevant details that should be included in evacuation plans such as quick reference information, protocols and procedures, relevant legislation, definitions, roles and responsibilities, and factors for consideration by decision makers. Internationally, similar evacuation planning frameworks exist elsewhere, and notable examples include the mass evacuation planning guidelines from New Zealand [20] and from the United States by the Federal Emergency Management Agency (FEMA) [21]. While many communities in British Columbia have evacuation plans or plans under development [22], marine model-based evacuation plans specific to islands have not been publicly shared. Locally, the cities of Whistler and Squamish completed a multi-modal evacuation plan for the Sea to Sky corridor, but their evacuation analysis is rather based on infrastructure access points than on modeling [23]. Provincially, Cortes and Quadra Islands have evacuation plans that focus on land based evacuation to marine points, but do not model marine traffic [24]. While information on the marine evacuation of Manhattan during 9/11 is available and may have some relevance in terms of the potential availability of spontaneous volunteers, learnings from the evacuation of over half a million people by water in urban New York are not necessarily applicable to a rural community of under 4000 residents [25].

Reviewing evacuation frameworks from a research perspective, Tüydes [26] and Southworth [10] structure evacuation studies into five categories: (a) hazard analysis, (b) vulnerability analysis, (c) shelter analysis, (d) emergency response actions, and (e) behavior analysis. While all of these categories are relevant to the case study in this paper, the core of this exercise focuses on the planning for and execution of emergency response actions, including the coordination of resources and evacuation flows. Modeling the emergency response for evacuations is a popular topic, particularly in emergency research and mathematical modeling. The large number of surveys on evacuation studies demonstrate the large body of existing research, see for example [27–29,29–35]. We therefore refrain from restating details on the extensive literature available and refer the interested reader to these reviews. In general the used methodologies range from systematic survey techniques over simulations to mathematical optimization. As the reviews show, a lot of research has been presented on how to plan for the emergency response action component of evacuations for areas that can rely on a solid road infrastructure. For that, emergency planners can mostly rely on the ability of the population to evacuate using private vehicles. Naturally, this assumption can not be made for the evacuation of islands without permanent road connections. While there are some studies that have investigated the resilience of island communities to hazards that can lead to evacuations, such as Putra and Mutmainah [36], Wilkinson et al. [37], these have not considered the systematic creation of a resource-based evacuation routing plan, but were rather based in hazard analysis [37], and spatial analysis [36]. In fact, the systematic and model-based evacuation of islands is a massively understudied problem, as not much previous work has been published on this topic.

While there are many evacuation models [38], only one methodological study by Krutein and Goodchild [39] has focused specifically on modeling the evacuation of isolated communities, such as islands. Krutein and Goodchild presented an optimization model that calculates the optimal route plan to evacuate an isolated community through the use of a coordinated set of resources. They further provide a version of the model that allows for scenario-based evacuation planning. The paper also presents related models from previous research for other application areas. However, the paper used synthetic data to test the model and did not provide a case study. Because the objective of this paper focuses on evacuating an island as quickly as possible, optimization is the natural choice. Krutein's and Goodchild's model therefore can be considered a reasonable model to answer the questions this paper poses, and at the same time fill a knowledge gap by providing a case study for this type of model.

1.3. Contributions

Previous work from both academic research and practice does not provide sufficient answers in terms of how to consider the special circumstances of island evacuation. Furthermore, the only model identified as capable to consider these circumstances was not yet applied to a real-world example. The challenge, not frequently mentioned in academic modeling research, is that a successful evacuation planning study based on modeling techniques such as optimization requires substantial data collection efforts at the local and regional level and a close collaboration with other stakeholders, in order for the model to provide insights that are actually valuable for emergency management and first responders [40,41]. If inaccurate assumptions on data are made by modelers, the results of the model can be drastically different and wrong conclusions can be drawn. This creates a need to conduct interdisciplinary research to validate data and modeling assumptions with communities itself and to investigate perceived risk levels and concerns within the communities.

While evacuation plans based on mathematical models can not predict what exactly what will happen during a disaster, especially considering hazard uncertainty and evacuation behavior, not taking advantage of modeling techniques can result in not fully leveraging the available data and therefore missing important learnings that can be derived from the collected information. Therefore, mathematical modeling in combination with thorough stakeholder management and data collection provides and important tool for disaster risk reduction. Given that the authors of this study had access to local and regional expertise as well as modeling expertise, this study takes advantage of these interactions to take an end-to-end collaborative approach to this problem. It should be mentioned here that previous research has identified Indigenous communities as highly knowledgeable about how to effectively evacuate their own communities based on experience [42], which poses a conflict between scientific and Indigenous approaches to evacuation that can cause misunderstandings in resilience planning and communication and ultimately result in disasters [40]. When evaluating the effects of this topic, the well researched topic of evacuation behavior [43,44] plays a large role. However, attempting to resolve this problem entirely is beyond the scope of this paper.

This research focuses on a substantial data collection and knowledge acquisition, which is then used to inform the aforementioned optimization model to produce an evacuation planning model that considers a wide variety of inputs from different stakeholders. With that, this case study fills an important research gap. At the same time, this work delivers a valuable contribution to the generation of an evacuation plan for Bowen Island itself. The contributions of the study presented in this paper are therefore the following:

- This study represents the first reported attempt to systematically plan the evacuation of an island by marine resources beyond regular ferry operations based on an integrated approach of data collection, surveying, stakeholder management, and mathematical modeling. The strength of this data-backed approach is the end-to-end collaboration and integration of knowledge from the modeling expertise of academic researchers with the data and experience of emergency authorities and the process knowledge of municipal emergency managers to revise a model version that reflects the challenges on the ground and provides insight that can be used by emergency authorities.
- The model used in this case study further contributes to local evacuation planning on Bowen Island in multiple ways. Primarily, it helps emergency planners to better understand the amount of time potentially required to evacuate residents from the island. Modeling informed the community evacuation plan, specifically the alternate marine evacuation timetable: for Bowen Island, in evacuations involving population sizes of 1000 or more where ferry access is cut off, additional services from more distant locations

with higher capacity vessels are likely to be critical to reducing evacuation times. Finally, the concept of using locations less ideal for long term sheltering (e.g. smaller islands) as temporary staging areas had never been entertained prior to this work; but was found to drastically reduce evacuation times and is now incorporated into the Evacuation Plan [18].

- The process followed in the presented study can be used as a template for future evacuation studies and for planning for the evacuation of similarly geographically challenged communities. This tool thus delivers a significant contribution to interdisciplinary research around evacuation that helps to reduce the impact of disasters caused by natural hazards not only in theory but also in practice.

The remainder of this paper is structured as follows. Section 3 presents the materials and methods that were used to complete the case study and reviews in detail the accessed and collected data sources that were used to gather the model inputs. Furthermore, Section 4 introduces considerations with regard to the scenario design, different options for shelter locations and evacuation fleet sizes. Section 5 concisely presents the results of the model and Section 6 discusses the implications of these results and finishes with a summary and a research outlook. The structure of the study is presented in Fig. 2 and considers iterative approaches to both the Data Collection and the Modeling steps with stakeholders to maximize the insight delivered by the study.

2. Material and methods

2.1. Data sources and data collection

2.1.1. Data requirements

To run the study using the Isolated Community Evacuation Problem (ICEP) model [39], a substantial data set validated by multiple stakeholders was required to maximize the value of the study for both research and practice. The following inputs were needed:

- The population size on the island and its fluctuation on different days and at different times;
- The distribution of residents around the different sub-communities of Bowen Island;
- The willingness and ability of the population to self-evacuate with private vessels;
- Potential docking points and shelter locations for recovery vessels;
- Realistic scenarios for wildfire emergencies on Bowen Island including weather information;
- Information on the existence, usual location, capabilities and limitations of potential recovery vessels, including cost parameters for vessel contracting and operating cost.

To gather all the information listed above, a multitude of sources was used, ranging from publicly available data to ground-level data collection through surveys and interviews with subject matter experts. The required data were collected collaboratively by both the research team and local government staff: dividing labor in this way overcame issues of staff capacity and ensured that relevant data was collected in a timely manner. In some cases, the local government was better positioned to collect or request relevant data (e.g. the resident survey), which resulted in more robust modeling results, acceptable by the local population. The following sub sections describe the information obtained from the corresponding sources, and further outline the challenges in obtaining this data. As illustrated in Fig. 2, an approval loop with stakeholders after the completion of the data collection was worth the effort to ensure stakeholder acceptance of the modeling results.

2.1.2. Insurance Corporation of BC

In late 2019, data on the number of vehicles registered on Bowen Island (by postal code) were requested from the Insurance

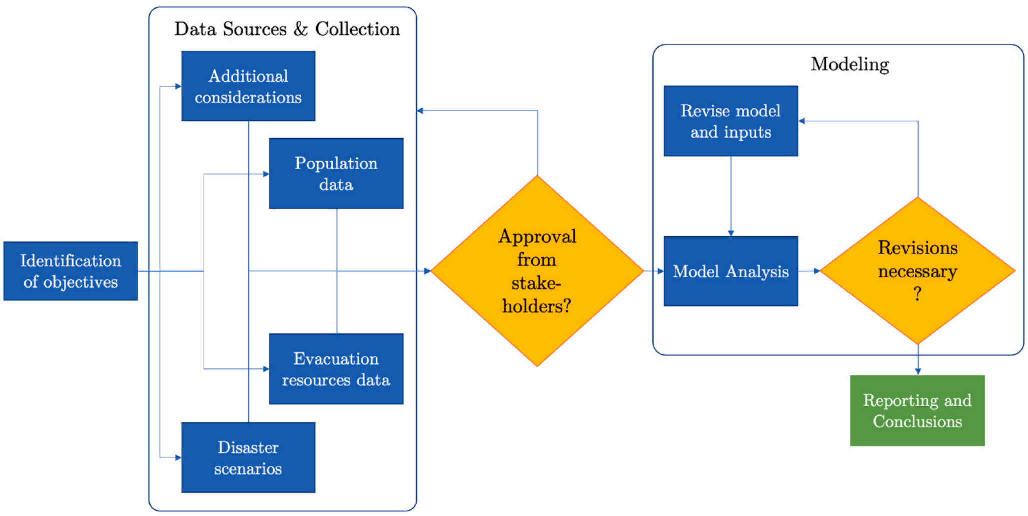


Fig. 2. Case study process template.

Corporation of British Columbia (ICBC) in order to estimate rates of vehicle ownership and potential capacity to self-evacuate (i.e. the ability for an occupant to exit an evacuation area without transportation assistance). The number of vehicles registered to Bowen Island addresses as of January 13, 2019, including temporary and storage policies, was provided to the Bowen Island Municipality by ICBC for a variety of vehicles categories including passenger, commercial, commercial trailer, utility trailer, motorcycle/moped and motor home. ICBC reported upon request that the total number of passenger and commercial vehicles and motorcycles/mopeds (no trailers) registered to postal codes on Bowen Island was over 3030. Given population estimates obtained from census data, rates of household vehicle ownership are estimated at over 90% [18][p. 32].

2.1.3. Population data

Government of Canada 2016 census data [15] was used to obtain population figures and thus inform estimates of how many people are on Bowen Island at any given time. According to the census, the total population of Bowen Island is 3680, of that, 640 are 0–14 years old [15]. According to census data, approximately 420 dwellings are utilized as seasonal or temporary homes, and anecdotally it is believed that the population increases by at least 1500 people in the summer months [45]. Additionally, day-trip and overnight tourists are anticipated to increase the population during the tourist season in particular. Further, the municipality of Bowen Island maintains estimates of household numbers at the sub-community or neighborhood level based on the number of dwellings in each area. This information is illustrated in Fig. 3. The evacuation zones illustrated on the map are based on traffic control points and population size. Together with the assumption of 2.5 residents per household [15], this allowed to estimate the number of residents in, and thus potential evacuation demand from, each neighborhood.

2.1.4. Tourism and BC Ferry Services Inc. Ridership data

BC Ferry Services Inc., which operates the only regularly scheduled ferry service between Bowen Island and the mainland, compiles ridership statistics that can be used to estimate the fluctuation in the number of residents and visitors across seasons, months, days and time of day, and that can be received upon request. Ridership data from 2015 to 2019 was requested from BC Ferry Services Inc. and subsequently reviewed and analyzed in order to estimate the number of people on the island at any given time. BC Ferry Services Inc. offers an "Experience Card", which provides a discount to ferry riders and requires users to pre-load funds. Ridership by payment method was reviewed in an effort to determine tourist vs resident travel, based on the assumption that generally, those travelling without the use of an Experience Card were tourists. Analysis found that "the population of Bowen Island varies significantly based on

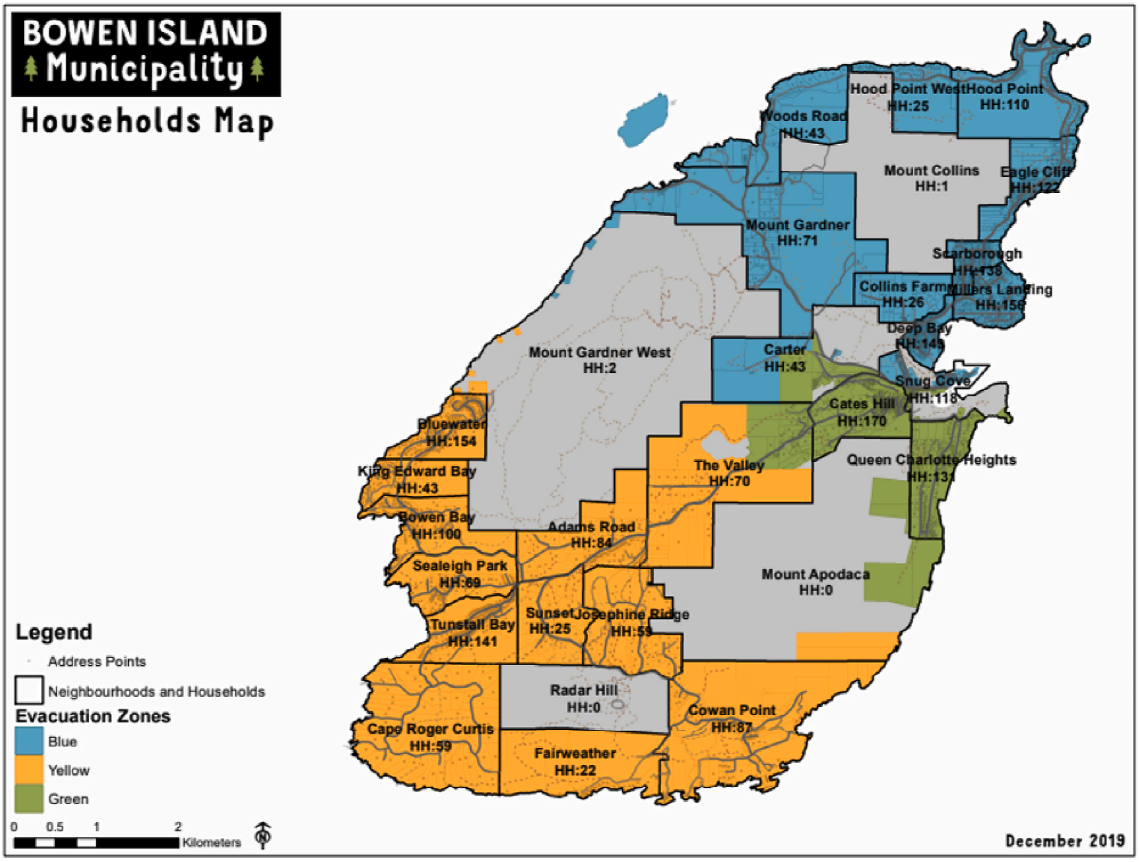


Fig. 3. Household map of Bowen island. Source: Bowen island municipality [18][p. 52].

the season, weather, and time of day due to visitors, commuters, and part time residents" [18][p. 53]. The Evacuation Plan lists factors for emergency operations centre staff to consider when estimating the population during an evacuation, and provides the reader with averages, to assist in adjusting the current number of people on the island according to the season, day of the week and time of day [18].

2.1.5. *Island survey 2019 data*

"The Island Survey 2019 was intended for Bowen Island residents and property owners and asked 51 questions in seven sections: Quality of Island Life, About your Household, Municipal Services, Transportation, Emergency Preparedness, Housing, and the Local Economy. It took about 15 min to complete online. The survey launched early September 2019 and was open for five weeks, until mid October. The survey was available online through the municipal website and in paper copy from Municipal Hall. It was advertised on the municipal website, in the local newspaper (the Bowen Island Undercurrent), in a mail drop to all Bowen Island mailboxes, in the weekly municipal e-newsletter and through the municipal social media channels (Facebook, Twitter, Instagram). […] A total of 523 responses were collected, which represents 18% of the adult population of Bowen Island according to the 2016 Government of Canada Census [15]. The responses indicated an 88% completion rate." [46][p. 2] Two evacuation specific questions were asked as part of this survey, and the answers were used to inform marine evacuation modelling demand estimates. When asked, "In the event of an evacuation order, are you able to self-evacuate the island by private boat," approximately 19% of respondents answered yes, and just over 80% said no: 488 responses were received. Respondents were then asked, "If you are not able to self-evacuate the island by private boat, how are you most likely to access the ferry": response rates by answer choice appear in Table 1.

2.1.6. *Bowen Island fire rescue expertise*

Local stakeholders such as Bowen Island Fire Rescue were engaged to provide data in order to ensure the model is as accurate as possible. Realistic scenarios that could trigger an evacuation were developed in partnership with the Bowen Island Fire Rescue Chief and the Bowen Island Municipality Emergency Program Coordinator: the scenarios were chosen based on historical events as well as near misses, where a fire with the potential to get out of control had occurred previously, and in many cases could have easily escalated given slightly different circumstances. As well, wildfire risk factors identified in the 2018 Hazard, Risk and Vulnerability Assessment [17], such as steep slopes or areas known for high levels of seasonal human recreational activity, were incorporated. Scenarios developed were also verified with the Fire Chief prior to running the model to ensure accuracy and legitimacy.

2.1.7. *Marine vessel operators*

Vessel fleet availability, capacity, and capability information was obtained from regional vessel operators with ownership of appropriate vessels to perform evacuations, including multiple local water taxi operators [47–51], the Canadian Coast Guard [52], Royal Canadian Marine Search and Rescue [53], BC Ferry Services Inc. [54], and others.

Regarding the use of cost parameters for recovery vessels, in British Columbia, costs associated with an evacuation are generally recoverable from the Provincial government and thus, costs are not likely to be a major factor in local government evacuation calculations [19,55]. As per the BC Provincial Government's Evacuation Operational Guide for First Nations and Local Authorities in British Columbia, "Emergency Management BC can provide financial reimbursement to First Nations and Local Authorities for eligible expenses related to evacuations." [19][p. 8]. While cost was not a significant planning factor in this scenario, in other jurisdictions, including remote communities and those in which the costs of evacuation borne by local government may not be recoverable, this could be a decisive factor.

2.1.8. *Weather reporting services*

Season and weather are critical components of wildfire behaviour and can be the difference between a fire being contained or getting out of control. Weather information (in particular wind speed and direction) for scenarios was chosen based on realistic parameters on record [56] as well as scenarios that have been observed by local first responders in the past to cover a variety of possibilities. Analysis found that due to tourism, the island's population varies based on weather [18], and this was incorporated into modelling by increasing the anticipated number of evacuees on hot sunny days.

2.1.9. *Workshop with first responders and Local Authorities*

A table-top exercise, based on a wildfire evacuation scenario, was held in early 2020 in order to test the preliminary evacuation plan for Bowen Island. Participants included BIM staff and representatives from BC Ferry Services Inc., North Shore Emergency

Table 1
Summary of answers to Island Survey 2019 question: "If you are not able to self-evacuate the island by private boat, how are you most likely to access the ferry".

Answer Choices	Responses	
	Percentage	*Total Answers*
By foot	25.00%	117
By bicycle	1.92%	9
By scooter or motorcycle	1.50%	7
with a vehicle	66.03%	309
I can self-evacuate the island by private boat	5.56%	26
	Total Answered	468
	Skipped	55

Management, Metro Vancouver Regional District, Cormorant Marine, Metro Vancouver, First Bus Company, the University of Washington and others. The input data for the modeling approach was subsequently revised to incorporate feedback from participants and observers of this exercise.

2.1.10. Workshop with government, agencies, and non-governmental organizations

Furthermore, on February 28, 2020, the preliminary modeling approach was presented at a SIREN workshop with representatives from the Royal Canadian Coast Guard, the Canadian Red Cross, the Bowen Island Emergency Program, Emergency Management BC, the BC Ministry of Transportation and Infrastructure (MOTI), and Qathet Regional District. Additional input on potential shelter locations, potential recovery vessel sources, recovery vessel availability times, and was gathered and incorporated into modeling considerations.

2.1.11. Marine dock inventory development

To identify the location of all useable docks, and what challenge they posed in terms of access from land (i.e. are they suitable for evacuations? Are there any obstacles like stairs?), their size, and the depth of the surrounding water at different tides (i.e. what vessel size they could be used by), and inventory of marine docks was collected. This information was collected by a local community volunteer and confirmed with marine vessel operators and local stakeholders during the table-top exercise.

2.1.12. Nautical charts

Nautical distances in between the docks on the island and the ports on the mainland are necessary to obtain since they determine the travel times in between these locations. Point-to-point distances are not realistic distance measures, because the direct distance might be obstructed by landmarks or flat water, and thus routes had to be generated that take the shortest nautical distance. This data was collected from a nautical chart tool [57].

2.1.13. Data collection challenges and learnings

During the acquisition of the required data mentioned above, multiple challenges and difficulties were identified that should be considered in any comparable study.

- It can be challenging to approximate population number fluctuations and distributions over time, even with available census data. On islands without permanent road connections, ferry ridership data is helpful to estimate fluctuation, but high uncertainty remains over the distribution. It can be helpful to gather data on lodging and seasonal residents through surveys.
- When using surveys to collect data, it is critical to achieve a representative sample of the entire population both in demographics and spatial distribution to make sure that the data is useable. Especially for disaster preparation, this is crucial to ensure that the right conclusions are drawn.
- While mapping out inventories of possible access points for emergency resources, it is important to remain attentive to potential access points that do not immediately appear suitable but that require more disaster preparation, e.g. docks that are not in good shape, or decommissioned ferry access points.
- The creation of realistic scenarios needs to draw from multiple sources. The primary source should be an entity with fire rescue expertise, such as a fire department, secondary considerations can come from other participants, such as other first responders, evacuation resource providers, and weather services. Every entity will consider different elements of scenarios challenging and it is important to make sure the selected scenarios cover all of these concerns. The task of the research team is to compile all of these concerns into a set of scenarios that all parties can agree on before the model is run to ensure that the results are accepted and understood as relevant for the community. An iterative approach of presenting proposed scenarios to stakeholders and collecting feedback through workshops is an approach to accomplish this.

It is important for a research team to consider the aforementioned challenges to ensure a smooth data collection process and analysis.

2.2. Modeling methodology

2.2.1. Model functionality

Krutein's and Goodchild's model is a two-stage stochastic recourse programming formulation [58] that allows for the scenario-based planning of the evacuation of an isolated community, such as an island. The main difference between their model and other evacuation models (e.g. Ref. [38]) is the use of external resources. Almost all other models used in evacuation planning assume road-based evacuation routes and thus assume that a population primarily leaves the area by personal vehicle. This allows the models to evaluate individual vehicles as flow variables since every vehicle only leaves the affected area once. If like in an island case however, the evacuation needs to be executed by a coordinated set of vessels, these vessels may have to do multiple trips and go to different locations after another to evacuate the area, thus creating a multi-trip problem that results in a routing problem. While there are similar models for homogeneous vehicle type evacuation, such as the Bus Evacuation Problem (BEP) [59], the use of heterogeneous vessel fleets and the lack of an existing road infrastructure further complicates the problem as trips between resources are not interchangeable, which this model considers. The model therefore fits the objective of this case study well, and has been revised based on feedback from the emergency management team, the response team, and through resident surveys to make sure that model assumptions accurately reflect population concerns. To introduce the reader to the functionality of the revised model, the key elements of the model inputs and outputs are restated here and explained at the example of the case study presented in this paper. For details over the mathematical model structure we refer the reader to the original paper [39]. The model takes the following inputs:

- The set of shelter locations with respective docks that can be accessed by marine vessels;
- The set of evacuation areas, where the evacuee populations are located;
- The set of evacuation pick-up docks, that can be accessed by marine vessels and are allocated to exactly one evacuation area;
- A fleet of potential recovery vessels including the vessel capacity, the vessel travel speed in loaded and unloaded condition, impacts of weather on vessel travel speed, loading time, unloading time, the vessel storage location, the time to availability of the vessel, variable operating cost, and fixed cost for contracting;
- A compatibility matrix indicating which vessel is compatible with which evacuation pick-up dock;
- A distance matrix providing travel distances between shelter locations and potential docking locations on the island;
- A set of disaster scenarios that cover a realistic range of disaster possibilities. These include the relative probability of the scenario compared to the other scenario, the number of evacuees at each affected evacuation area, the percentage of the population that is able to self-evacuate, and weather information;
- A maximum allowed evacuation time. This ensures that evacuation plans remain timely;
- A penalty cost assigned to each evacuee that could not be evacuated. This ensures that the model attempts to generate a plan that evacuates as many evacuees as possible within the maximum allowed evacuation time.

After optimizing the evacuation plan considering all the inputs listed above, the model outputs are the following:

- A vessel fleet that is optimal across the investigated scenarios;
- Optimal route plans for each individual scenario using the vessel fleet from above.

The functionality of S-ICEP is illustrated in Fig. 4, which takes the inputs explained above. The model consists of two decision stages, which are divided by a probabilistic event, a scenario-independent first stage and a scenario-dependent second stage. The first stage optimizes a fleet of vessels that causes a low expected evacuation time and cost across all scenarios. It obtains the information of how a vessel fleet performs in different scenarios from the second stage, which makes an optimal evacuation routing decision for each scenario. For each two-stage stochastic model with recourse, there exists a deterministic equivalent that sums up all scenario decisions multiplied by their respective probabilities into one large problem. The objective functions are structured in a way that the goal of minimizing the evacuation time dominates the goal of minimizing cost. Thus, if multiple evacuation time-minimal solutions are available, the solution that results in the lowest cost is chosen. Depending on how well the selected scenario set represents possible real world disasters, the resulting vessel fleet will be the best solution to tackle the real world disaster, once it occurs.

This way, the emergency planner receives information on which vessels to rely on in case of an emergency, and agreements between emergency management and the vessel providers can be put in place. As an additional benefit, the optimal route plans for each scenario can reveal which areas of the island are particularly vulnerable to disasters that require evacuation. Through running multiple iterations with different configurations on shelter locations, planners can investigate the effect of considering additional shelter locations on evacuation time and assess the vulnerability of a location to a particular disaster scenario.

2.2.2. *Objective function selection*

Krutein and Goodchild further provide alternative objective functions [39]. As previously mentioned in Section 3, for this case study cost considerations were not necessary. Therefore, it was decided to use the simpler conservative objective function that solely

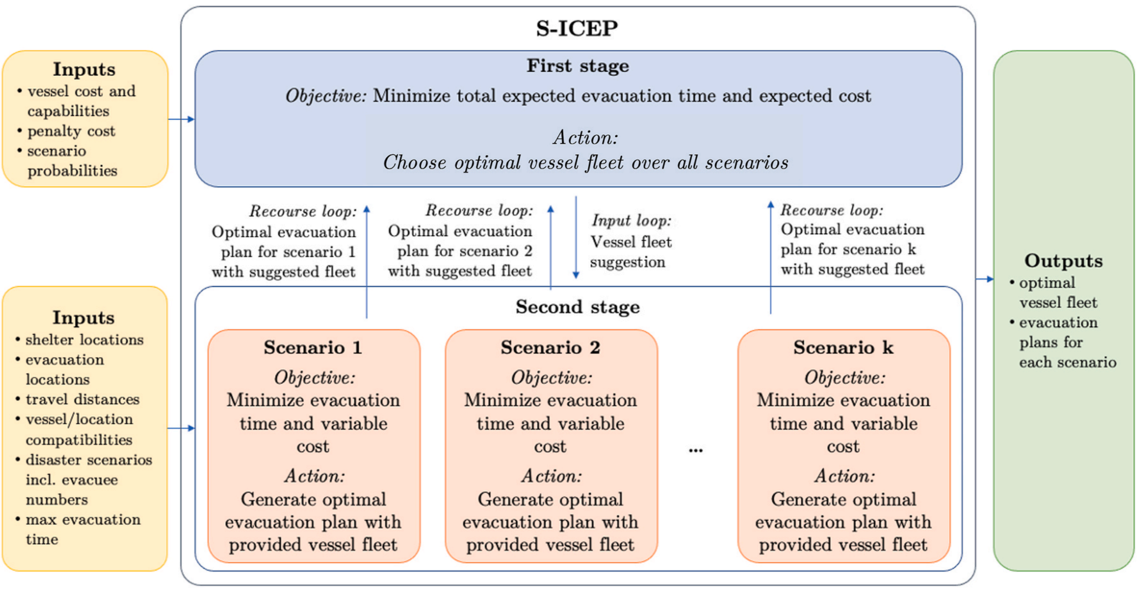


Fig. 4. Illustration of the two-stage model structure of S-ICEP.

focuses on minimizing the expected evacuation time over all scenarios. For the readers convenience, this conservative objective by Krutein and Goodchild [39] is presented in equation (1) in terms of the case study of this paper.

$$\min \quad comp(\zeta) + P\sum_{a\in A} fl_{an}(\zeta) \tag{1}$$

$comp(\zeta)$ represents the expected total evacuation time of the route plan across all disaster scenarios. P represents a penalty value that is assigned to every evacuee that is expected not to be evacuated (fl_{an}) with the route plan. This way, the model automatically penalizes not evacuating the entire population and forces the solution algorithm to try to avoid leaving anyone behind, unless there is no other option. In practice, this problem can be solved using efficient solution approaches that take advantage of the mathematical structure of the model. This can be done through either minimizing a deterministic equivalent, which can be generated through discretizing the objective function, using acceleration techniques in commercial solvers, or through near-optimal heuristic solution approaches, as discussed by Krutein and Goodchild [39]. Since this case study receives a collection of deterministic disaster scenarios with relative occurrence probabilities, the stochastic objective function can be discretized into a deterministic equivalent, as equation (2) shows for k scenarios, where the sum of all relative probabilities equals 1, as equation (3) shows.

$$\min\, p_1\left(comp_1 + P\sum_{a\in A} fl_{an1}\right) + p_2\left(comp_2 + P\sum_{a\in A} fl_{an2}\right) + \cdots + p_k\left(comp_k + P\sum_{a\in A} fl_{ank}\right) \tag{2}$$

$$\sum\nolimits_{i=1}^{k} p_i = 1 \tag{3}$$

As mentioned previously, it is imperative during the modeling process to take the special properties and considerations of the data set on hand into account and to consider the interactions between the data and the model this causes. For the Bowen Island case, it can be valuable to consider alternative shelter locations, and make these decisions part of the model itself. It is possible to alter the model framework to include variables that account for the optimal selection of shelter locations and include a corresponding cost term in the objective function. However, Krutein and Goodchild provide some guidance that the computational effort to run the model to an exact solution is already pretty high [39], and with exponentially increasing complexity, it is reasonable to run the model multiple times for different shelter location configurations, since the number of options in for the presented case study is relatively small.

3. Data model interactions

3.1. Shelter locations

It is important to consider whether using additional shelter locations that are not default choices would significantly reduce evacuation time and costs. In the area around Bowen Island default shelter locations would be areas that have a larger accessible port or marina and that have a good connection to additional infrastructure for first response and evacuee support. For this case study, Horseshoe Bay, Fisherman's Cove and Gibsons were selected as the default shelter locations. Fig. 5 shows the map of the case study

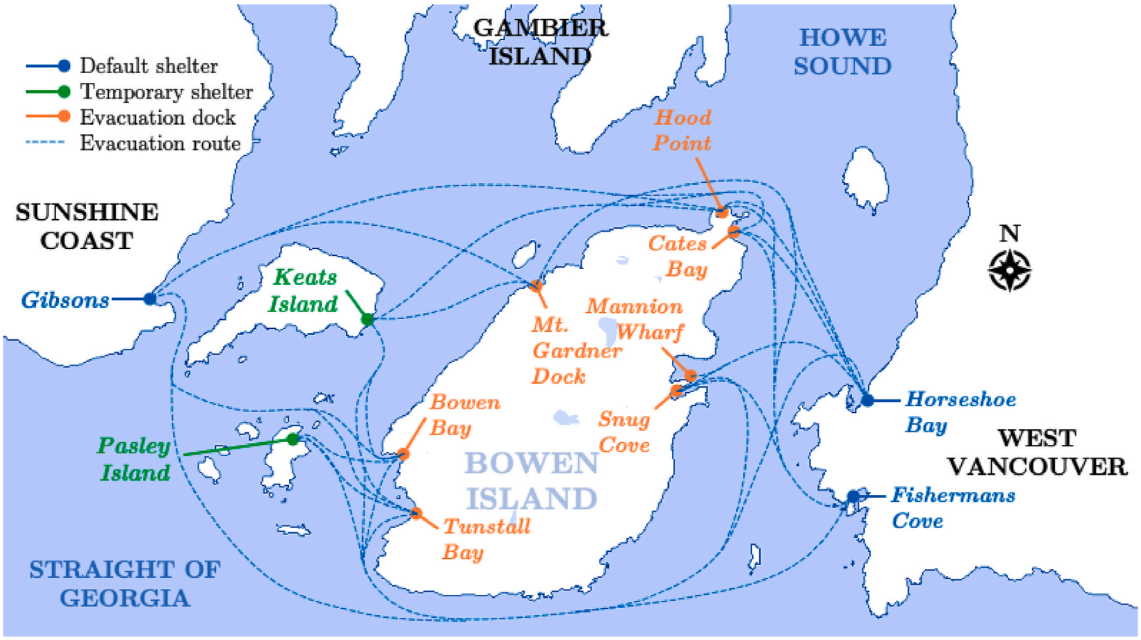


Fig. 5. Map of Southern Howe Sound with evacuation docks, shelter locations, and routes.

area with markers for the evacuation docks, shelter locations and vessel evacuation routes. Fig. 5 marks the default shelter locations on the map in blue. In addition, other temporary shelter locations should be considered. Even though the lack of access to further infrastructure and supplies may only make these suitable as a temporary staging location before evacuees get transported further, the resulting reduction in evacuation time may significantly contribute to the safety of the evacuees. When running the S-ICEP model for different staging considerations, the sensitivity of the model results to these changes can provide decision guidance on temporary shelter locations. For this case study, the temporary shelter locations are Keats Island and Pasley Island, and are marked in green in Fig. 5.

3.2. Scenario design

The scenarios were generated in collaboration with the Bowen Island Fire Rescue Fire Chief on the basis of local expertise with regards to high-risk or vulnerable areas and experience with previous wildfire incidents on Bowen Island. Thus, the four scenarios presented in this study focus on particularly challenging fire scenarios that are both likely and that would be difficult to contain by first responders. Table 2 describes the scenarios in detail. The maps in Fig. 6 visualize the affected areas for every scenario in red.

As Table 2 shows, the scenarios considered for the case study vary in their size and how likely they are to occur in comparison to each other. It is important to note that the variety of these real-world scenarios ensures that also extreme scenarios, both on the upper and lower probability end are included in the analysis.

3.3. Evacuation fleet

In addition to considering different shelter locations and testing for the sensitivity of the model results based on these, it is important to consider from how far away an evacuation fleet should be sourced. For a coordinated evacuation effort, both vessels that are regularly located in the Howe Sound area and vessels that are located further away can be useful for evacuation. Using the S-ICEP model framework with two different fleets allows to test the marginal effect of considering only local resources or also considering resources that are located further away. Table 3 presents the resources considered for the evacuation study. These resources were considered after evacuation workshops and evacuation simulations that were completed together with first responders and local vessel operators. These discussions included exchanges on the compatibility and availability of the vessels.

4. Modeling results

To generate optimal results for the case study, an instance of the S-ICEP was implemented using Python as a general purpose language and was executed on a Mac with a 2.6-GHz Dual-Core Intel Core i5 CPU. The model was implemented using the deterministic equivalent of the conservative objective function 1 presented in Section 3. The model was run considering each scenarios listed in Section 4.2, for both the primary and the entire fleet from Section 4.3 and for different configurations on shelter locations listed in Section 4.1. An overview of the results condensed in one figure is illustrated in Fig. 7. Figs. 8–11 illustrate the evacuation progress over time for each affected location.

For the Mt. Collins Scenario, the result shows that the evacuation time with the primary fleet takes around 165 min. Extending the fleet can reduce the total evacuation time to 150 min. The reason for the low improvement is that the secondary vessels are located farther away and thus, require more time to reach the affected area. Due to the geographical location of the Mt. Collins scenario, using Keats and/or Pasley Island as shelter locations does not provide any benefits. Fig. 8 further confirms this, as the evacuation time savings generated by using the entire fleet, irrespective of the staging choice only reduce the expected evacuation time for both affected locations marginally. Furthermore, it can be seen that the objective function of the model that minimizes total evacuation time shows to be very efficient, as the achieved evacuation times for both locations are very close to each other. This shows how efficient the

Table 2
Wildfire scenario descriptions.

Scenario	Description	Affected population	Approx. private evacuations	Useable docks
1: Mount Collins Relative probability: 40%	On a hot summer weekend with southwesterly winds, a wildfire starts on the southern flank of Mt. Collins and cuts off traffic at the Legion branch on Scarborough Road and cuts off the northern part of the island. An evacuation notice for Snug Cove, Millers Landing and all communities north of the Legion is issued.	3308	204	Hood Point Cates Bay Snug Cove Mannion Wharf
2: Mid Island Relative probability: 10%	A wildfire starts south of Grafton Lake and makes Grafton Rd impassable, which cuts off the western part of the island. It's a hot summer weekend and strong wind causes a western expansion of the fire; an evacuation notice is issued for all communities west of Grafton Lake.	4289	344	Tunstall Bay Bowen Bay
3: Killarney Lake Relative probability: 15%	A campfire south of Killarney Lake gets out of control mid-week and Mt Gardner Road becomes impassable. An expansion of the fire to the north due to southeasterly winds forces the municipality to issue an evacuation for Mount Gardner.	300	29	Mt. Gardner
4: Eagle Cliff Relative probability: 35%	A wildfire emerges at Eagle Cliff and cuts off the northern part of the island. Easterly winds drive the fire northwest along the shore and forces the EOC to evacuate all communities north of the fire location. Evacuation needs to be executed, as the fire threatens residences.	708	148	Hood Point Cates Bay

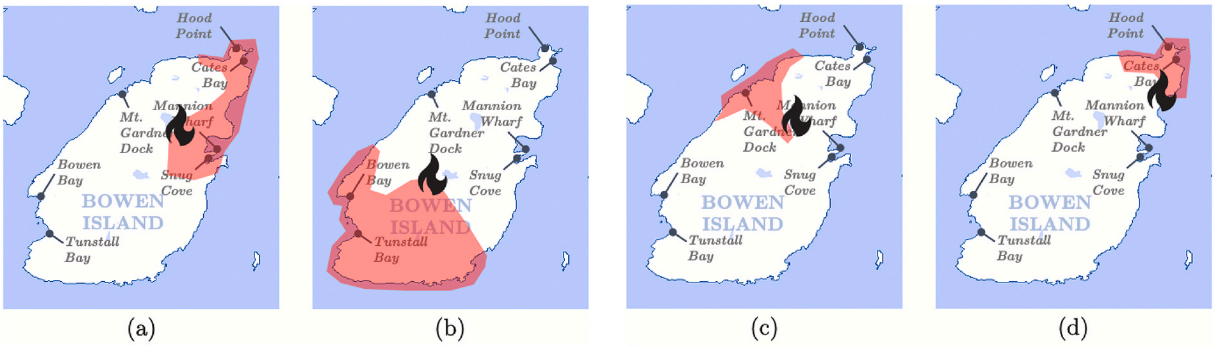


Fig. 6. Visual illustration of affected areas for wildfire scenario 1 (a), 2 (b), 3 (c), and 4 (d). Map sourced from Google [60].

Table 3
Candidates for the evacuation fleet.

Vessel Provider	Vessel Type	Number of Vessels	Location (Port)	Fleet Category
BC Ferries [54]	Vehicle and passenger ferry	1	Horseshoe Bay	Local
Cormorant Marine [47]	Water taxi	4	Snug Cove	Primary
Mercury Water Taxi [48]	Water taxi	3	Horseshoe Bay	Primary
Sunshine Coast Water Taxi [49]	Water taxi	1	Gibsons	Primary
Harbor Ferry Bertram [50]	Water taxi	1	Gibsons	Primary
Kona Wind Charters [51]	Water taxi	2	Gibsons	Primary
Royal Canadian Marine Search and Rescue (SAR) [53]	SAR boat (up to 12 passengers)	3	Horseshoe Bay/Gibsons	Primary
Royal Canadian Marine Search and Rescue (SAR) [53]	SAR boat (up to 12 passengers)	1	North Vancouver	Regional
Royal Canadian Coast Guard [52]	SAR vessel (above 12 passengers)	3	Kitsilano	Regional
Royal Canadian Coast Guard [52]	SAR hovercraft	2	Richmond	Regional

model is at allocating vessels strategically to the right locations. Hence this also confirms that there is no room to shortening the evacuation time through shifting resources in between locations. For the Snug Cove evacuation plan we can further see how large the contribution of the ferry is, indicated by the large drops in evacuation numbers every time the ferry made an evacuation, significantly reducing the slope of the evacuation curve.

For the Mid Island Scenario, the model returned large differences in evacuation times in between different model configurations. Using only the primary fleet and not considering shelter locations on Keats and/or Pasley Island, a marine evacuation would take more than 450 min, if vessels are routed optimally. This is caused by the limited number of access points on the western shore of Bowen Island, which only allow the usage of relatively small vessels. However, the evacuation time can be significantly reduced by considering shelters on Keats Island (308 min) or both Keats and Pasley Island (240 min) as temporary staging locations. Despite the small size of compatible vessels, the reduction in distance the vessels have to cover to evacuate the population strongly improves the evacuation time. This positive effect can be even increased by also using the secondary fleet, which leads to evacuation times of approx. 295 mins (nominal), 215 min (shelters on Keats Island), and 175 min (shelters on Keats and Pasley Island). Hence, the benefit of temporary shelter considerations is large. The evacuation progress illustrated for both affected locations in Fig. 9 shows that the effect of different configurations in staging choice and fleet size has similar effects on both affected locations, with similar outcomes for evacuation time for both locations.

For the Killarney Lake scenario, the proximity of the Mt. Gardner Wharf to Keats Island, a temporary shelter on the island enables a reduction of evacuation time from approximately 70 min–57 min. However, due to the larger distance, considering additional shelters on Pasley Island does not provide any benefits. Further, the small size of the scenario allows a relatively quick evacuation of the area with the vessels from the primary evacuation fleet. Due to the time it takes for the secondary fleet to reach the area, activating these vessels does not offer any benefit. Since the Killarney Lake scenario only affects a single region, Fig. 10 shows the effect of strategic staging. What is remarkable about this result is how large the time share is to get the resources to the affected area. This is due to the relatively remote location of the Mt Gardner wharf in relation to the regular locations of the response vessels. Stationing vessels closer to the region could improve the evacuation time.

Similarly, for the Eagle Cliff scenario, the evacuation time is approx. 74 min under all configurations. The geographical location of the affected area results in no benefit by shelter locations on the islands west of Bowen Island. Due to the small size of the scenario, using the secondary evacuation fleet is not beneficial to reducing evacuation time. Fig. 11 confirms that the evacuation time could only be further reduced if the size of the primary fleet would be increased.

5. Discussion

5.1. Implications of modeling results

The collaborative analysis has shown that the fleet of local (primary) vessels alone is able to manage scenarios of smaller size

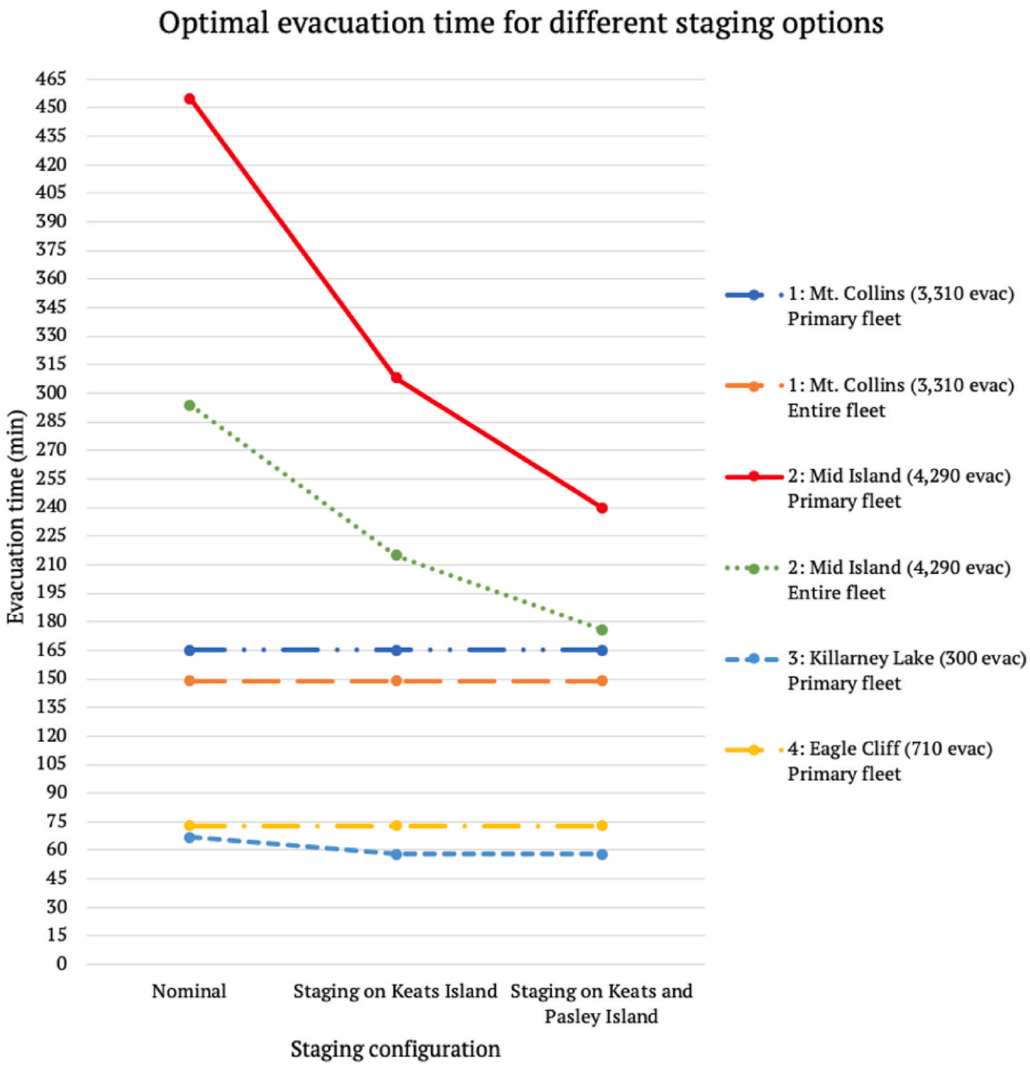


Fig. 7. Results from marine evacuation modeling for Bowen island.

(approx. up to 1000 evacuees). A further reduction in evacuation time could be achieved through permanently increasing the number of emergency response vessels in the immediate surroundings of Bowen Island (e.g. SAR landing vessels). However, during a smaller evacuation scenario, requesting additional vessels from more distant locations (e.g. Kitsilano, Richmond, Sechelt, Nanaimo, Squamish), does not enable a reduction of the evacuation time because it takes too much time to reach Bowen Island. For larger scenarios (approx. above 1000 evacuees) however, requesting additional vessels from distant harbors will significantly reduce the time to evacuate the affected area. Even though it appears to be a natural conclusion that more resources will reduce the evacuation time that does not require extensive analysis, the study results present significant findings. Before the analysis presented above, no information was available as to what extent the ferry and the primary vessel fleet that is permanently in the area will be sufficient to evacuate the area and under what scenarios this could lead to serious problems. The only knowledge that existed previous to this study was that it would take the ferry approximately 11 h to evacuate 4000 people and approximately 27 h to evacuate 10,000 people [18][p. 48]. These previous estimates did not include considerations on the use of multiple access points, additional vessels, or scenarios that affect parts of the island that are not accessible by the ferry. Using the model by Krutein and Goodchild [39] provided a lot more insights.

The need for an extended vessel fleet is particularly high for areas that cannot evacuate through the Snug Cove Ferry Terminal, since the primary fleet is too small to move a large number of evacuees quickly. Hence, activating CCG, additional SAR vessels, and other options will decrease the time evacuees will be exposed to the hazard. For very large scenarios, it is further recommended to recruit any additional available vessel in the area. This could be harbor cruises, fishing boats and recreational vessels. While adding these vessels to the fleet will make coordination more difficult, the potential to further reduce evacuation time is high. For the Western parts of Bowen Island, the limited number of public and private docks makes it challenging to evacuate a large number of evacuees. Particularly in this area, the CCG hovercrafts and landing vessels are useful due to their ability to land directly at beaches. Furthermore, because the distance to the closest mainland harbor in Gibsons is relatively high, the model strongly recommends considering

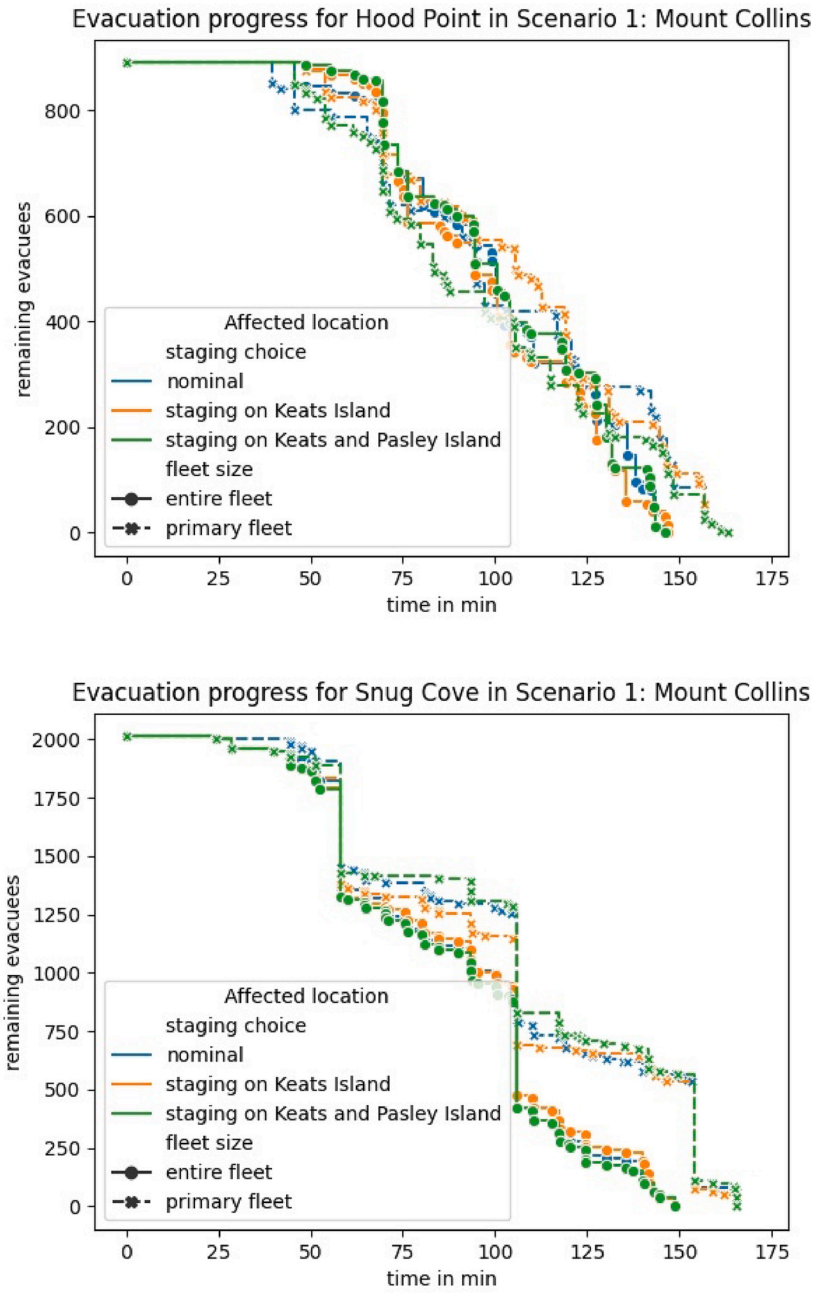
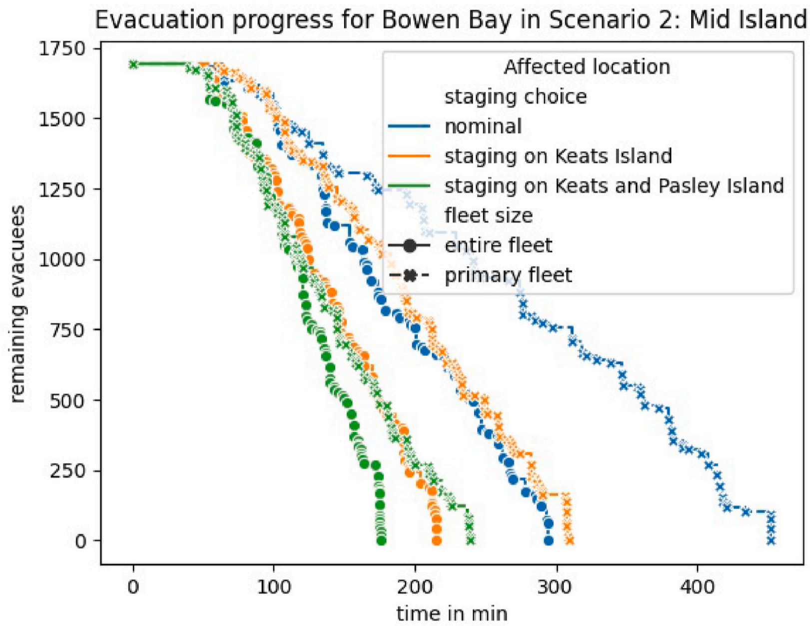


Fig. 8. Scenario 1: Mount Collins - Evolution of Remaining Evacuees over time for different configurations.

temporary shelters on Keats Island and Pasley Island to shorten the distance the evacuation fleet has to cover and thus allow the transportation of more evacuees in a shorter amount of time. An additional, though more unreliable approach, could be to create a temporary dock at a beach upon evacuation that allows serving the area with larger vessels. Examples could be to beach a barge or a floating dock to provide a useable path for evacuees to deeper water, where larger vessels can be used. We furthermore identified that across scenarios, the evacuation times for each affected locations obtained by the model are similar and evacuation vessels are allocated accordingly to obtain this. This is caused by the objective function that aims to minimize the total time of the entire evacuation plan. In case a prioritization between different locations is necessary (e.g. if in Scenario 2, the evacuation of Bowen Bay is more urgent than the evacuation of Tunstall Bay), a staged objective function or individual time limits for each evacuation time would need to be introduced.

With regards to general applicability of the results, the results show that up to a certain population size of island communities, the evacuation by vessels regularly stationed in the area may be sufficient to achieve reasonably short evacuation times. This is particularly



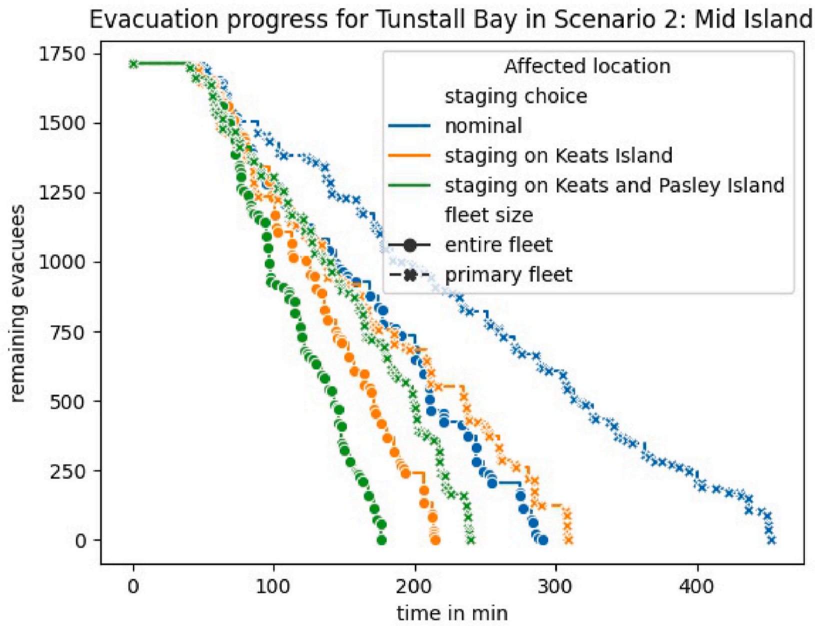


Fig. 9. Scenario 2: Mid Island - Evolution of Remaining Evacuees over time for different configurations.

the case when a large port with passenger ferry access is available. The results however also show that if such a port is not available, evacuations times grow significantly. In fact, the case study shows that a fast moving hazard may necessitate staging in neighboring locations that are less than ideal for long term evacuee support: while support (food, clothing, shelter) for evacuees on these smaller islands is unavailable or limited, the evacuation times could be significantly reduced when staging evacuees temporarily at these areas. Further preparation regarding establishing use of nearby staging areas in an emergency is warranted for evacuations of similarly challenged locations to facilitate staging in the affected areas. Alternatively, these results can also inform local land use planning and other community amenity discussion; ensuring that an island community has a well distributed network of access points, such as public boat docks can significantly accelerate evacuation procedures in case of an emergency. The obtained insights do not only support the evacuation plan itself, but are further instrumental for reducing the risk for a disaster through preventative investments into infrastructure and recovery access points. These results could only be identified through using the integrated end-to-end collaborative approach that was taken combined with optimization-based modeling to revise the data collection and modeling process based on its

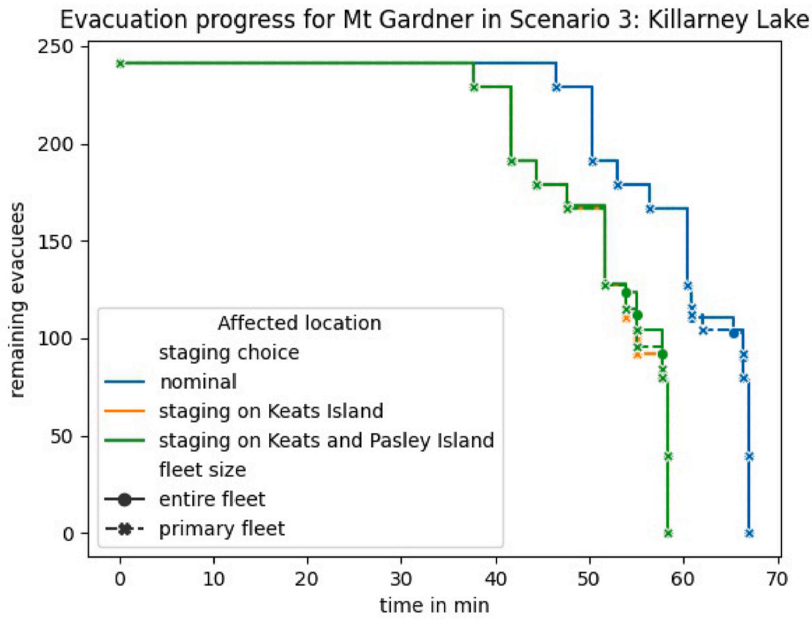


Fig. 10. Scenario 3: Killarney Lake - Evolution of Remaining Evacuees over time for different configurations.

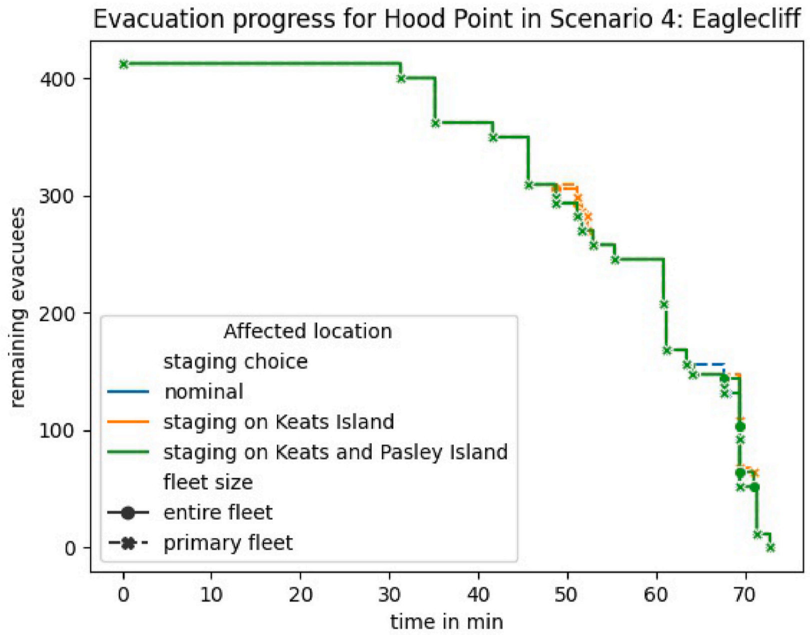


Fig. 11. Scenario 4: Eaglecliff - Evolution of Remaining Evacuees over time for different configurations.

interactions.

As already mentioned in section 2.3, despite the insights and their respective values described above, making decisions solely based on mathematical modeling is not perfect. The main difficulty lies in the problem of evacuation behavior. Thompson et al. [61] have reviewed over eighty-three eligible studies concerning evacuation behavior and the perception of risks associated with natural hazards in a vulnerable population, which is why we refrain from restating all these studies at this point and instead refer the reader to this review. The main conclusion from these studies is that it is very challenging to predict the behavior of humans while exposed to a hazard, as humans do not always act rational when in fear and the reaction is highly dependent on previous evacuation experience, cultural backgrounds, demographics, warnings, government orders, and local circumstances [62]. This can cause a serious disruption to an optimization model-based evacuation plan, if, for example, parts of the population refuse to leave their residences, self-evacuate, attempt to pick-up other family or household members from other locations, or move to a different evacuation point than expected [44]. On the other hand, the commander of an evacuation vessel may decide at their own discretion to take on a higher number of evacuees than the official maximum number of passengers the vessel is rated for. Furthermore, no matter how many scenarios a modeler uses, there are infinitely many ways on how a disaster can unfold, and thus a certain uncertainty level remains. This leads to the problem that it is almost impossible to know what exactly will happen if a hazard becomes a disaster and how long an evacuation will actually take. However, Thompson et al. [61] also mention that the existence of an evacuation plan itself influences evacuation behavior [63]. Hence, a marine evacuation plan generated with the proposed methodology gives valuable insights as mentioned above, as it gives clear indications on how to organize the marine evacuation, where the bottlenecks lie, and what properties of a potential disaster scenario influence what actions actually reduce the evacuation time and increase population safety. Therefore, instead of expecting that the outputs of the model can be interpreted literally at their exact values as recommendations that guarantee reduced risk, substantial safety margins should be applied. During disaster response, the gained insights can then be used to make decisions quickly and take advantage of the preventative measures taken based on the real-world hazard.

5.2. Conclusions and future outlook

The research presented in this paper conducted a case study on finding an optimal evacuation plan for Bowen Island in Canada through the use of marine resources. This study was based on a collaborative approach between the research community and emergency managers with a high participation and involvement of a broad range of stakeholders, from local residents and volunteer groups to agencies from all levels of government and the private sector. The key findings of this study are that the total time of the marine transportation portion of the evacuation of Bowen Island can be kept below 3 h if either the ferry can be used, or if the number of evacuees remains below 1000 people. This drastically changes when the Western part of the island is impacted, where a large number of residents live, but where no larger port is available. This allows emergency planners to take action immediately to activate a larger set of resources if the western part of the island is effected, which is a consideration that was not made before. The study further identified that for similar islands, the use of temporary staging areas, even in locations with little to no infrastructure, can offer a quick relief and reduce evacuation time significantly. Alternatively, a permanent improvement of infrastructure can eliminate the problem of high evacuation times and thus reduce the risk for a disaster in the first place. This idea has not been entertained at the community level before and is another key finding of the study. In addition, the model results provide example route plans for each scenario that can be used as a baseline by emergency managers, if a comparable disaster occurs, but the time line is insufficient to allow for another modeling run. In particular, comparing the results of this study to the previously existing information about pure ferry evacuation [18], the additional capability of providing scenarios that cannot be evacuated through using the ferry alone and allowing for multiple access points and vessels show the value of using the presented approach. This further confirms that the model proposed by Krutein and Goodchild [39] is an appropriate tool to conduct real-world evacuation studies that provide meaningful answers to emergency planning and management. This is particularly the case when it is paired with an integrated approach that includes a substantial data collection effort that involves different stakeholders. The success of this approach is further confirmed by the inclusion of the results of this model in the official evacuation plan of Bowen Island [18]. The high involvement of subject matter expertise makes the findings of this study highly applicable to similarly structured communities with comparable environmental challenges, for which this study can be used as a template. The fact that the study has identified key bottlenecks for evacuation, validates it as a useful approach to reduce disaster risks and ultimately to help preventing a disaster through the preventative improvement of key infrastructure and staging areas. Both researchers and practitioners should however keep in mind the limited predictability of natural hazards and human evacuation behavior when using this approach and how much the model output depends on carefully selected data that is gained through interdisciplinary work with the targeted community and thus apply appropriate safety margins over the model results.

Regarding the lessons learned from applying the aforementioned ICEP model to a real world case study, the study process has shown that despite a sophisticated modeling technique, already moderate changes in the input data can lead to significantly different results. The involvement of a knowledgeable group of stakeholders and accurate input data is therefore crucial, and the lack thereof is a shortcoming of many other academic studies on evacuation. In hindsight, a larger set of scenarios would have enabled the study to cover a larger array of possibilities and produce more robust results. However, larger scenario sets are more difficult to obtain in detail from first responders and further significantly increase the size of the problem and thus increase the time it takes to run the model, which is why the ICEP method would greatly benefit from either using high computational power, or through a solution method that provides results close to the optimum much quicker than a commercial solver does, but more reliably than the constructive heuristics that were provided do [39].

Additional future research could focus on integrating the model with the on-land transportation portion of the evacuation of islands, such as how to transport the population from their residences to the evacuation pick-up points, how to deal with traffic bottlenecks, how to accommodate for mobility impaired populations, and how to account for evacuation behavior. For larger communities where multiple ferries are used, the modeling approach should consider the capacity at the ferry terminal, to avoid being overly optimistic in the solutions, through serving more vessels than possible at the same time at a certain port. In addition, as already mentioned in the discussion section, it could be necessary to plan for evacuations with different priorities for different locations. For that case, model extensions are necessary that either limit the maximum route time for a specific resource, or transform the objective function into a staged, prioritization function. Research should further look into developing a response model to use during actual emergencies, when knowledge about the number of evacuees is uncertain and/or dynamically changing to get recommendations on resource routing that can be implemented quickly, and thus increases the chances that an emergency team can re-run the model during the disaster with the data relevant to the disaster on hand.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Klaas Fiete Krutein reports financial support was provided by the Marine Observation, Prediction and Response (MEOPAR) Network of Centres of Excellence, and the Province of British Columbia. Jennifer McGowan reports financial support was provided by the Province of British Columbia through the Community Emergency Preparedness Fund, administered by the Union of BC Municipalities. Anne Goodchild reports financial support was provided by the Marine Observation, Prediction and Response (MEOPAR) Network of Centres of Excellence, and the Province of British Columbia. Jennifer McGowan reports a relationship with Bowen Island Municipality that includes: employment.

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