Sensitivity Analysis of a Road Clearing and Relief Supplies Distribution Model for Vancouver Island in the Event of a Cascadia Megathrust Earthquake

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ABSTRACT

Southwestern British Columbia is the most seismically active region in Canada because of its proximity to the Cascadia Subduction zone. To improve emergency preparedness for Vancouver Island, models have previously been developed to estimate the potential damage to infrastructure from a major earthquake, to consider community resilience while awaiting relief supplies, and to optimize procedures for repairing damaged roads and routing trucks from marine terminals to needy communities during the 72-hour emergency response phase. However there are large uncertainties in the disaster impacts, and numerous assumptions in the models' parameters, so this study serves to conduct sensitivity analysis on several of the factors to produce more robust recommendations from the model outcomes including: best depot location for road-clearing teams; most critical roads for supply distribution; most critical ports for supply distribution; and the effect of incorporating a community resilience measure. Effective display of results is an important consideration.

Keywords

Relief supplies distribution, road-clearing model, earthquake, sensitivity analyses.

INTRODUCTION

The Cascadia Subduction zone is the tectonic boundary between the Continental North American and the Oceanic Juan De Fuca plates in the Pacific Ocean. Southern British Columbia, Canada, lies on top of the Cascadia Subduction zone, making it the most seismically active region in all of Canada, with a 2-month sample shown in Figure 1 according to the (logarithmic) Moment Magnitude Scale (Rogers, 1998).

The closest densely populated regions to the subduction region, the communities on Vancouver Island (VI) and the smaller nearby Gulf Islands, are the most vulnerable places to large magnitude earthquakes. A Cascadia earthquake of magnitude M9, which recurs at intervals from 100 to 1000 years (Clague, 2002), can cause major infrastructure damage on these islands, impeding relief supply distribution during the immediate response phase following the shock, compounded by potential disruption in transportation modes which could have a significant impact on the flow of essential goods between and within the islands.

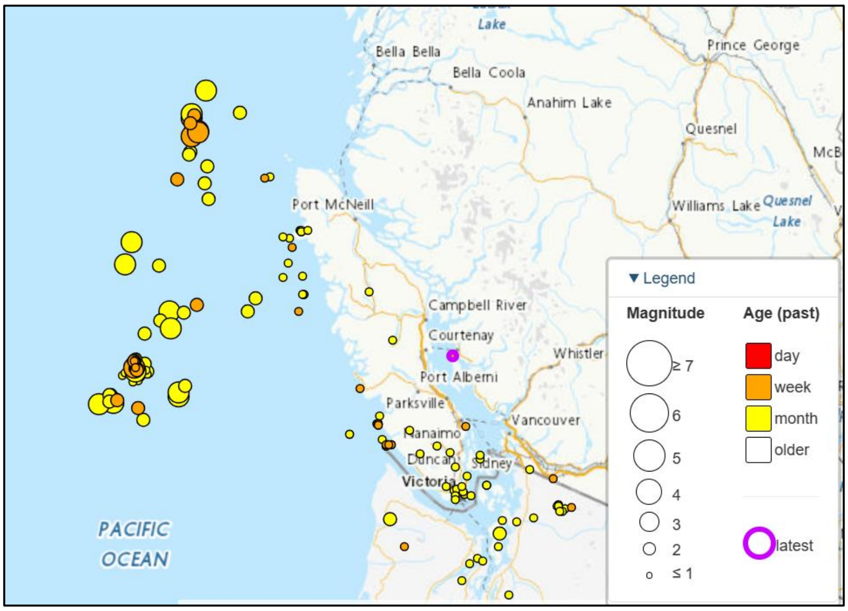


Figure 1. All earthquakes for May and June 2023 (source: Natural Resources Canada, 2010)

A significant contribution to emergency preparedness is to model the main components of the distribution network for relief supplies, how elements may be damaged by a natural disaster, and what mitigating strategies may be considered to minimize the disruption. Studies have been conducted to predict the damage a Cascadia Earthquake may induce on and around Vancouver Island (VI), as well as road network reconstruction and relief supplies distribution plans to deal with the aftermath (Chang et al., 2020). Other models for reconstruction of roads and routing of relief supplies were developed and executed on data available from past disasters (Souza Almeida et al., 2022a). However, little research is available on sensitivity analyses of such models, whether on existing case studies or simulated disaster data. This study deals with analyzing the results of one such model for a simulated Cascadia earthquake scenario on VI.

The relief supplies delivery problem involves boxes of essential goods, with one box per person in the affected region lasting one week. The mechanism is to have the boxes delivered to the islands via ship from the City of Vancouver on the mainland, while having road clearing teams repair roads on VI in the most effective way to reconnect communities whose links to the road network were severed by the earthquake. Delivery trucks pick up the boxes from marine delivery points, and use any undamaged roads or repaired roads to access the communities. However, the earthquake can also shut down ports on the islands temporarily due to damage, and/or halt some shipping routes due to interrupted navigation services. Barges can be used as surge capacity to get boxes to Vancouver Island as they can access many more suitable landing spots. Within the 72-hour emergency phase planning horizon, any unmet demand can be fulfilled by helicopter from mainland airports to an island community.

The post-earthquake optimal resupply plan relies on several foundational models. The Critical Infrastructure (CI) Analysis of Regional Disruption & Ferry Route Interruption model (Bell & Bristow, 2020) characterizes the damages to infrastructure, marine and road transport, and shipping routes given a Cascadia earthquake. Community demand for relief supply boxes is principally proportional to their respective populations, but this can also be weighted by a resilience index (Chang and Tanner, 2022) which captures the relative impact of the earthquake on each community based on multiple factors associated with their preparedness and vulnerability. The resulting community impact factor (CIF) is an integer measure of a community's resilience to the Cascadia earthquake with 1 being the most resilient value and 5 being the least resilient community to an earthquake.

Outputs from those two models concerning CI and CIF respectively produce inputs for relief supply distribution optimization, which comprises two models: a road clearing model on VI to reconnect isolated communities, and a multi-modal distribution model of relief supplies which takes advantage of these reconnected roads to reach affected communities. These two models are synchronised and referred to as the Road Clearing and Relief Supplies Distribution (RCRSD) model. The RCRSD is solved using a Greedy Randomised Adaptive Search Procedure (GRASP) heuristic to optimally satisfy the demand for relief supply boxes as shown in Figure 2. The RCRSD model generates a solution for damaged roads' reconstruction, while simultaneously finding the optimal way to distribute supplies via sea, land, and air to the affected communities.

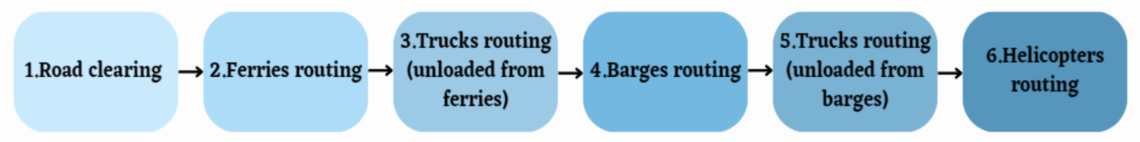


Figure 2. Working order of the RCRSD model

The combination of all of these models provides scenario results to help develop response plans by the relevant authorities, as well as industry and community stakeholders to improve the emergency preparedness for VI. However, there are large uncertainties and multiple assumptions in all stages of each of these models, so the outputs from a single run do not well represent the potential range of outcomes following an actual earthquake. But conversely, it is infeasible to run the models for all possible combinations of conditions, therefore a systematic sensitivity analysis process is needed to reflect the span of post-disaster circumstances and associated risk mitigation strategies to best prepare for the emergency response phase. Such a sensitivity analysis based on the RCRSD model, but also with some variations in outputs from the CI and CIF models, is the subject of this study.

The aim of this paper is to conduct sensitivity analyses on multiple input parameters to the RCRSD model to answer the following questions. The sensitivity analyses are primarily conducted given a situation where the earthquake damage to roads and ports is moderate (Case A: *Partial disconnection*), with an extension considering limited variations for the situation where damage is much greater (Case B: *Extensive disconnection*).

- Where are the best and worst locations to establish the depot on Vancouver Island where the road clearing teams are pre-positioned?
- Which damaged road segments are consistently cleared over multiple runs of the RCRSD model (as the solution method is heuristics based), and how does that affect communities supplied?
- For a given level of roads consistently cleared within the 72-hour window (i.e. in 25%, 50% and 70% of the runs respectively), if those road segments are then considered undamaged, what is the next priority set of roads to be cleared?
- Which ferry port and which barge port respectively supply the most relief boxes, and what is the impact of having one or the other unavailable?
- What is the impact of having the number of available ferries or barges from the mainland reduced?
- What is the effect on the relief box supply distribution if the communities' relative neediness (CIF – community impact factor) is omitted?
- How should the results of the above analyses be presented to be intelligible and useful?

METHODOLOGY

The methodology for conducting the sensitivity analysis is essentially these four major steps, each of which is expanded upon below:

a) Determine which variables will be considered to be altered for the sensitivity analysis;

b) Determine how to represent the results effectively, given the large number of outputs;

c) Determine a framework for altering combinations of the input variables for the sensitivity analysis;

d) From the plethora of results, synthesize recommendations for Emergency Management planners.

Input Variables

Over 50 input variables are used in the RCRSD model. Many of them are considered fixed, such as the road network on Vancouver Island, and the communities' populations. The sensitivity analyses focus on factors within the planners' control, such as where to pre-position road clearing teams, and anticipation of various state variables affected by the earthquake such as which ports will be opened or closed and the number of ferries or barges available.

Output Parameters

For each run of the RCRSD model, 17 output files are generated as shown in Table 1.

Table 1. List of all output files generated from a single run of the RCRSD model

	Output name	**Output ID**	**Content details**
1	Initial demand	ID	List of demands of every community on VI in terms of number of boxes of supplies
2	Road clearing edges	RCE	Objective value of road clearing sub-model and list of unblocked edges with the time taken and ID of the team that clears it
3	Road clearing routes	RCR	Route taken by each road clearing team
4	Ferries island delivery	FID	Demands delivered on ferries to each of the smaller islands in terms of number of trucks
5	Ferries demands	FD	Objective value of the ferries routing optimization model and the demands delivered to each port via ferries in terms of number of trucks
6	Ferries routes	FR	Routes details for every ferry
7	Ferries truck delivery	FTD	Demands delivered by trucks that arrived on VI via ferries to each community in terms of number of boxes
8	Ferries trucks routes	FTR	Routes details of trucks that arrived on VI via ferries
9	Barges island delivery	BID	Demands delivered on barges to each of the smaller islands in terms of number of trucks
10	Barges demands	BD	Objective value of the barges routing optimization model and the demands delivered to each port via barges in terms of number of trucks
11	Barges routes	BR	Routes details for every barge
12	Barges truck delivery	BTD	Demands delivered by trucks that arrived on VI via barges to each community in terms of number of boxes
13	Barges trucks routes	BTR	Routes details of trucks that arrived on VI via barges
14	Helicopter community demands	HD	Demands delivered by helicopters to communities on VI
15	Helicopter routes	HR	Routes details of helicopters
16	Communities with unsatisfied demands	UC	List of communities whose demands are not 100% met
17	Communities completely supplied	SC	List of communities whose demands are completely met

Regional Division of Vancouver Island

Given the large number of output variables (Table 1), coupled with the 109 communities on VI included in the model (Figure 3), it is ineffectual to provide the results solely in terms of distinct community supply satisfied, segments of roads fixed within the time horizon (out of 3707 possible), ports and barges and ships operating, etc. While all of these details are calculated and stored, they must be aggregated in effective ways to provide useful insights regarding the outputs.

Various techniques were used to aggregate the results and render them digestible. For some, percentages were applied such as the percent of damaged roads repaired within the specified time horizon, or the percent of total community demand for boxes met via water and land avenues (versus helicopter). To represent changes in supplied amounts under different run conditions, the levels of supplies are often aggregated by four different regions of VI namely North Island, Central Island, Pacific Rim, and South Island as shown in Figure 3. Sunshine Coast and Gulf Islands, although used in the RCRSD model, were excluded from the sensitivity analyses done in this study.

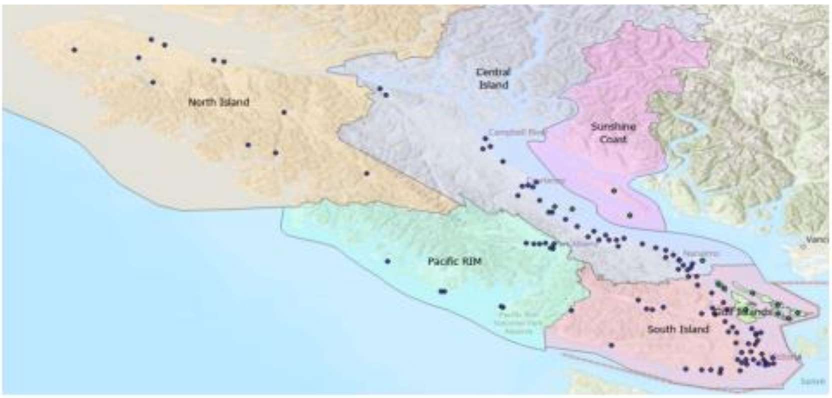


Figure 3. Communities and regional division of Vancouver Island used in the RCRSD model (Chang et al., 2020))

Framework for Altering Combinations of the Input Variables

Figure 4 illustrates the framework used to vary the models for the sensitivity analyses. Since there is an infinite number of possible infrastructure damage combinations arising from a Cascadia earthquake, the (CI) model (Bell & Bristow, 2020) was used to generate two scenarios: Case A of *Partial disconnection*, and Case B with *Extensive disconnection*. The sensitivity analyses were conducted primarily on Case A in this study, with a few runs run as an extension to examine how the more severe Case B might alter some key outcomes.

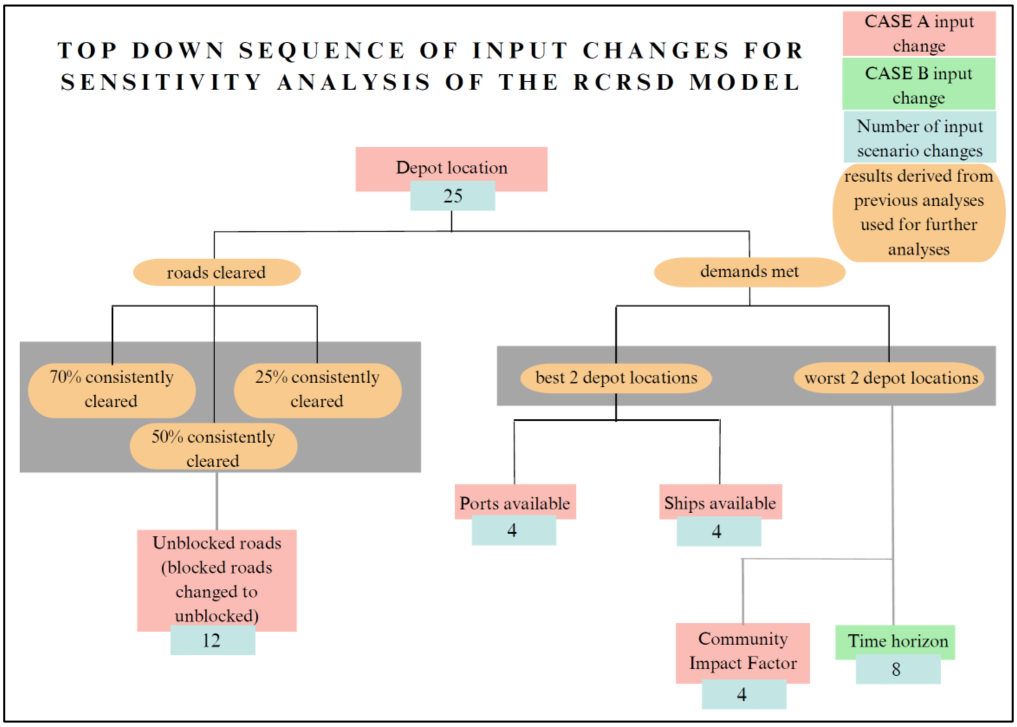


Figure 4. Sequence and number of input changes done for the sensitivity analyses

The depot location where the road clearing teams are co-located can have a significant effect on the efficiency of getting damaged roads reopened thus connecting more communities within the modelled time horizon, hence this variable is extensively studied in the sensitivity analysis, comparing 25 different base locations as noted in Figure 4. A previous study has shown that four road-clearing teams at one station is a reasonable limit, as there are greatly diminishing returns in having more (Souza Almeida et al., 2022b). One modelling outcome of particular interest is which road segments are most critical in quickly reestablishing connectivity between communities. Since the optimized set of cleared roads varies from run-to-run, one way to measure these priority roads is to observe which segments are consistently repaired across all of the computer runs. Since the concept of "consistently repaired" is subjective, three levels of consistency are defined, namely roads that are consistently cleared in at least 70% of the model runs, or 50% of the runs, or 25% of the runs respectively. Then, given each of these prescribed levels of road repair, the models were then rerun assuming that those consistently repaired roads were not damaged to see what would be the next priority segments for repair (Figure 4).

Concurrently, the RCRSD runs were used to identify the two best depot locations, as well as the worst two depot locations (Figure 4, middle right). Even though only one depot is considered in practice in this model, comparing the best two depot locations allows the decision makers to consider choosing either of them based on other practical reasons, especially if their effectiveness is similar. Considering the worst two depot locations provides insights on how important depot location is on VI for effective goods supply (i.e. comparing the best vs the worst depot location), while also highlighting the deleterious impact of making a poor decision about this risk mitigation strategy.

For each of the best two depot locations, sensitivity was conducted on the base Case A conditions of which ports on the island are open or closed throughout the planning horizon, and which ships routes are operational or not during that period due to navigational constraints (Figure 4, bottom right). Finally, for the best and worst two depot locations respectively, the outcomes for the scenario with *Extensive disconnection* (Case B) are contrasted with those for *Partial Disconnection* (Case A). For case B, extensions in the 3-day time horizon are also examined, since very few roads are repaired within the 72-hour response window given the severe Case B conditions.

INPUT DATA

Inputs Related to Roads

The RCRSD model has a total of 2543 nodes and each node corresponds to a geographic location on or around Vancouver Island as shown in Table 2 (Souza Almeida et al., 2023).

Table 2. Types and locations of nodes used in the RCRSD model

Node range	Node type	Location
0 – 108	Community	VI
109 – 2414	Road intersection	VI
2415 – 2421	Ferry port	VI
2422 – 2428	Ferry/barge port	VI
2429 – 2457	Barge dock	VI
2458 – 2470	Community	Small islands
2471 – 2477	Ferry port	Mainland Vancouver
2478 – 2480	Ferry/barge port	Mainland Vancouver
2481 – 2515	Barge port	Mainland Vancouver
2516 – 2536	Airport/Heliport	Mainland Vancouver
2537 – 2542	Port community	VI

Port communities are the communities on VI that have a port nearby from which they can receive supplies directly via ship or barge (i.e. no road clearing required). Out of the 3707 road segments used in the RCRSD model, 1123 are assumed to be blocked in this study, with the available roads and the blocked roads for Case A shown in Figure 5. Assuming that the unblocking rate is constant for all the road-clearing teams, the unblocking time is calculated for each damaged road segment based on its length.

Inputs Related to Shipping

For the Case A Cascadia earthquake scenarios, the RCRSD model considers that there are 57 available ships, with 35 ferries and 22 barges. Each ship has its own capacity of truck containers with emergency supplies that it can carry from mainland Vancouver to Vancouver Island. Based on the structural damage model, each port is associated with an opening time, from 0 hours which indicates that it was not closed due to the earthquake, to 72 hours, which means that it is not open at all during the emergency response phase (i.e. the 3-day time horizon). For Case A, the ferry ports that are available are shown in Figure 6, while Figure 7 represents the barge docks. The barge docking locations are always available because it is assumed that barges do not require any particular infrastructure to unload supplies.

Figure 5. Open and blocked roads for Case A (source: Souza Almeida et al., 2023)

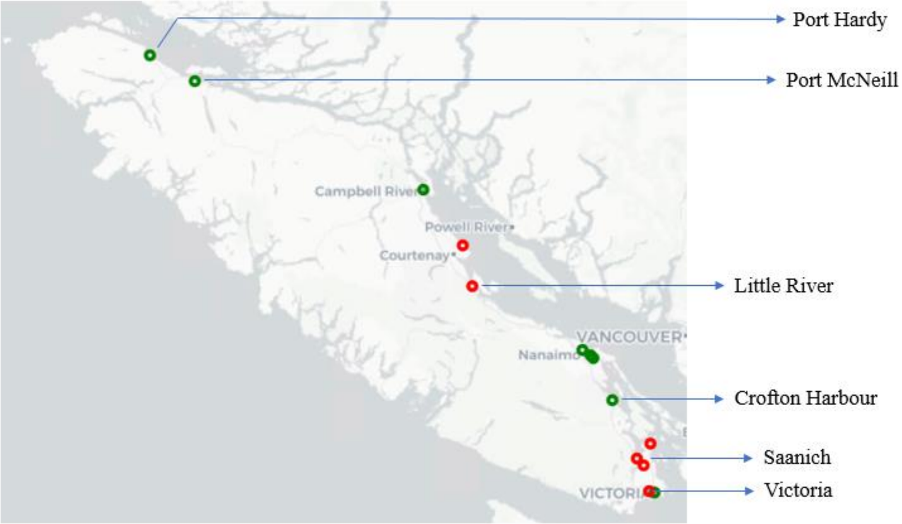


Figure 6. All ferry ports for Case A (red ones damaged)

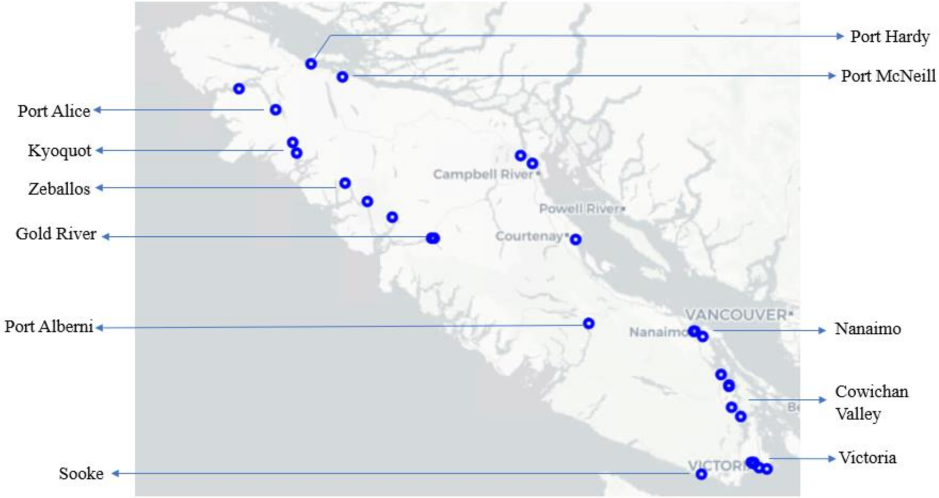


Figure 7. All barge docks for Case A

Inputs Related to Community Resilience

The resilience of communities is captured by assigning their respective nodes a value between 1 and 5. For the analysis that is done without accounting for the CIF (Community Impact Factor), all these values are changed to 5, thus giving the same priority for all communities. The CIF is used as a weight for each community in the optimization model, where the objective function is a combination of community population and CIF.

Case B Inputs

The structure of inputs for Case B is same as that of Case A, but given this more severe CI damage scenario, the roads that are considered blocked in Case B are shown in Figure 8 (Souza Almeida et al., 2023).

Figure 8. Open and blocked roads for Case B

RESULTS

Depot Changes Results

The first step in the sensitivity analysis for Case A was to change the location of the road clearing teams' depot. The different depot locations for which the RCRSD model was run are shown in Figure 9. For each scenario of input variation, the model was run three times to account for the changes in model results arising from the use of the GRASP heuristics method. The results of community demands supplied under every scenario (averaged between the three runs of same scenario) were tabulated as shown in Table 3. The total demand for each run is to deliver 777,646 boxes, equal to the total population on VI and the Gulf Islands.

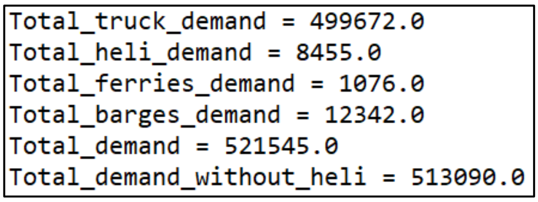
Figure 9. Alternative road clearing teams' depot locations for Case A

Table 3. Road clearing and demands supplied observations when depot location is changed (for Case A)

Scenario ID	Depot node ID	Depot location region	% Total demand supplied	% Supplied Communities
D1	42	Central Island	57.1	54.69
D2	46	North Island	63.8	60.68
D3	57	Central Island	49.9	51.04
D4	80	North Island	43.1	33.85
D5	219	Pacific Rim	42.9	33.85
D6	220	South Island	65.7	60.16
D7	742	South Island	62.6	58.85
D8	778	Central Island	61.1	57.55
D9	802	Central Island	47.8	48.70
D10	1075	Central Island	47.8	49.74
D11	1195	Central Island	65.6	61.98
D12	1544	South Island	41.6	35.16
D13	1579	Pacific Rim	63.6	58.07
D14	1926	Pacific Rim	43.5	35.42
D15	2002	North Island	41.4	35.71
D16	2012	North Island	42.3	34.90
D17	2069	North Island	43.5	36.46
D18	2165	North Island	43.0	34.64
D19	2227	North Island	43.0	35.16
D20	2313	Pacific Rim	43.3	35.94
D21	2324	Pacific Rim	44.5	38.28
D22	2343	South Island	31.6	24.74
D23	2375	South Island	63.8	60.16
D24	2395	South Island	59.3	53.65
D25	2431	Pacific Rim	53.4	51.82

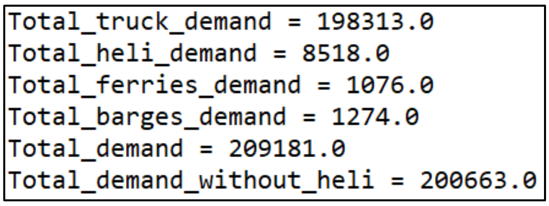
From the results shown in Table 3, the best depot locations (Scenario IDs: D6, D11) and worst depot locations (Scenario IDs: D22, D15) were mapped (see Figure 10). The ranking is done based on the demands supplied and not the number of roads cleared because for certain depot locations, although there is a high degree of road clearing activity, the demands supplied and the reach to communities is very low. The demands met by the different modes of transport for the best depot location (Scenario ID: D6) and the worst depot location (Scenario ID: D22) are also shown in Figure 11 and Figure 12 respectively.

Figure 10. Best and worst depot locations



```
Total_truck_demand = 499672.0
Total_heli_demand = 8455.0
Total_ferries_demand = 1076.0
Total_barges_demand = 12342.0
Total_demand = 521545.0
Total_demand_without_heli = 513090.0
```

Figure 11. Demands met for D6 by different modes



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Total_truck_demand = 198313.0
Total_heli_demand = 8518.0
Total_ferries_demand = 1076.0
Total_barges_demand = 1274.0
Total_demand = 209181.0
Total_demand_without_heli = 200663.0
```

Figure 12. Demands met for D22 by different modes

The results by regional division of VI are shown in Table 4, where it is seen that having the road clearing teams' depot located at either Central Island or South Island yields better results compared to having it located at Pacific Rim or North Island.

Table 4. Region-wise depot location details in terms of total demand met

Depot location region	Scenario IDs used for aggregation	Mean % demand met by region
Central Island	D1 D3 D8 D9 D10 D11	54.88
North Island	D2 D4 D15 D16 D17 D18 D19	45.74
South Island	D6 D7 D12 D22 D23 D24	54.08
Pacific Rim	D5 D13 D14 D20 D21 D25	48.53

At a higher level of aggregation, the demand results averaged for each region of VI (and the Island overall) are shown in a bar chart in Figure 13.

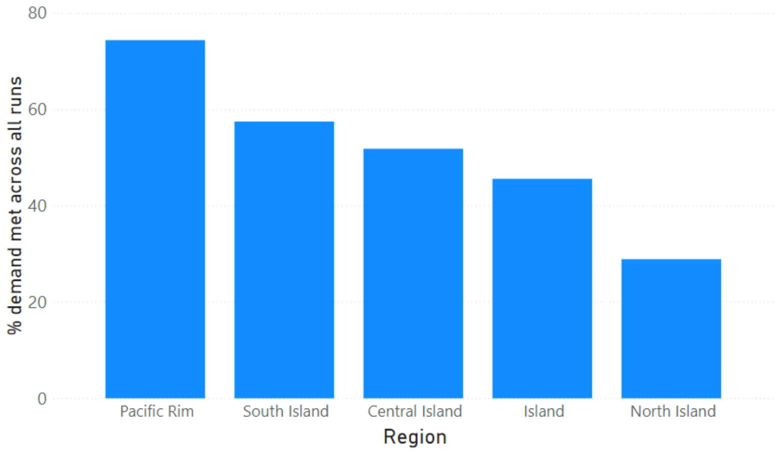
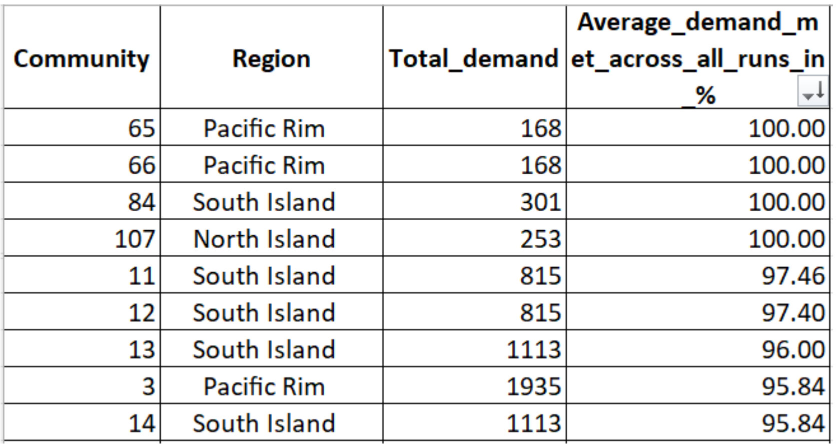


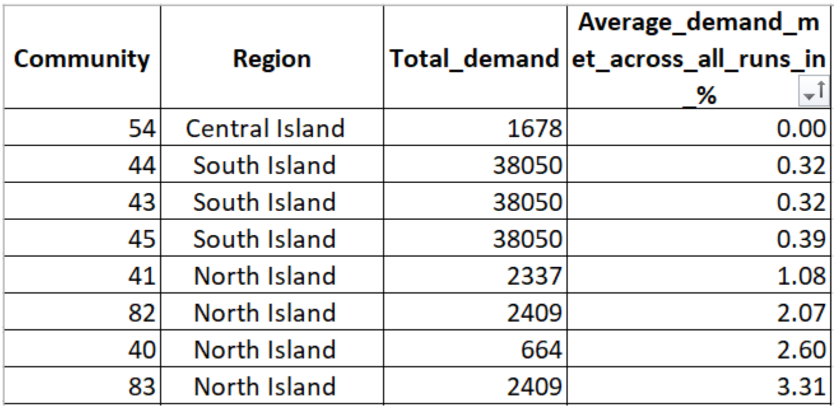
Figure 13. Regional demands satisfied across runs D1 to D25

Across the 25 input scenario variations, the communities on VI that received over 95% of their demands satisfied are shown in Figure 14. The communities that received under 5% of their demands met are shown in Figure 15. The communities in the Pacific Rim region of VI had most of their demands satisfied. The communities in the North Island region were the least likely to receive supplies.



Community	Region	Total_demand	Average_demand_met_across_all_runs_in_%
65	Pacific Rim	168	100.00
66	Pacific Rim	168	100.00
84	South Island	301	100.00
107	North Island	253	100.00
11	South Island	815	97.46
12	South Island	815	97.40
13	South Island	1113	96.00
3	Pacific Rim	1935	95.84
14	South Island	1113	95.84

Figure 14. Communities that received over 95% of their demands



Community	Region	Total_demand	Average_demand_met_across_all_runs_in_%
54	Central Island	1678	0.00
44	South Island	38050	0.32
43	South Island	38050	0.32
45	South Island	38050	0.39
41	North Island	2337	1.08
82	North Island	2409	2.07
40	North Island	664	2.60
83	North Island	2409	3.31

Figure 15. Communities that received under 5% of their demands

Roads Cleared and Subsequent Analyses

For the runs done by changing the depot locations of the road clearing teams as shown in Table 3, it was found that out of the 25 input scenarios there were no roads cleared for 5 scenarios (Scenario IDs: D4, D5, D12, D14, and D16). The reason why no roads were cleared was because the depot locations were too distant from any port or community to be reconnected within 72 hours. For example, the depot location for scenario D5 is shown in Figure 16, where the depot location is surrounded by only damaged roads, from which there is no completion of any connecting road clearing activity within the time window.

Figure 16. Map showing depot location of scenario D5 amidst blocked roads

The road segments that were cleared for each run were separately counted and for the runs with at least some road clearing activity, an average of 49 blocked road segments were cleared. The highest cleared was 81 road segments (out of 1123 damaged), associated with depot location at node 220. From all the runs, the outputs are then analyzed to find the road segments or edges that are frequently unblocked.

When all the runs are compared, it is seen that some of the blocked roads are cleared more frequently across the input scenario variations shown in Table 3 than other road segments. Figure 17 shows the road segments that were cleared for at least 70% of the original runs. This set of roads is referred to as RC1 in this study. The road segments that were most consistently cleared all lie in the South Island region. Similar results were generated for the situation with roads that were cleared for at least 50% of all the runs (referred to as RC2, see Figure 18), and for those cleared for at least 25% of all the runs (referred to as RC3, see Figure 19). For the last case, the map shows that there are significant road clearing activities happening in South Island and a few roads being fixed consistently in Central Island.

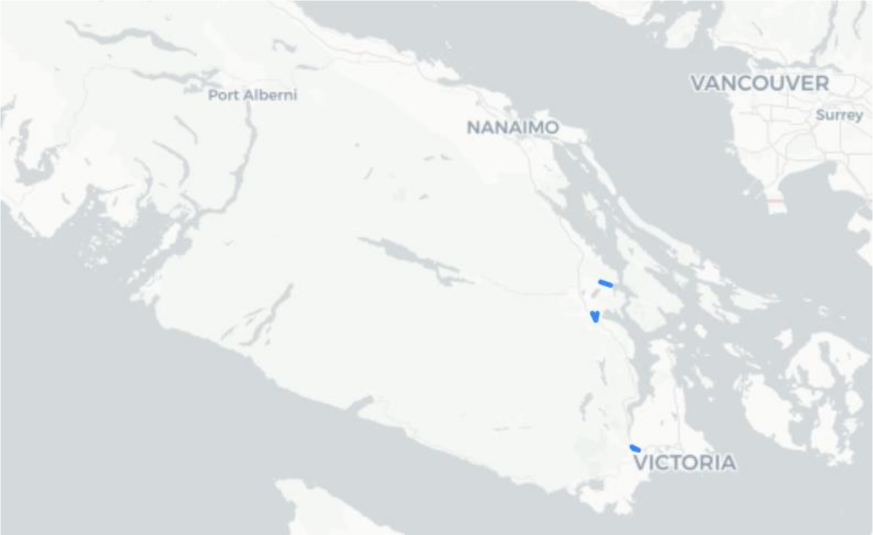


Figure 17. Roads cleared for at least 70% of the runs (RC1)

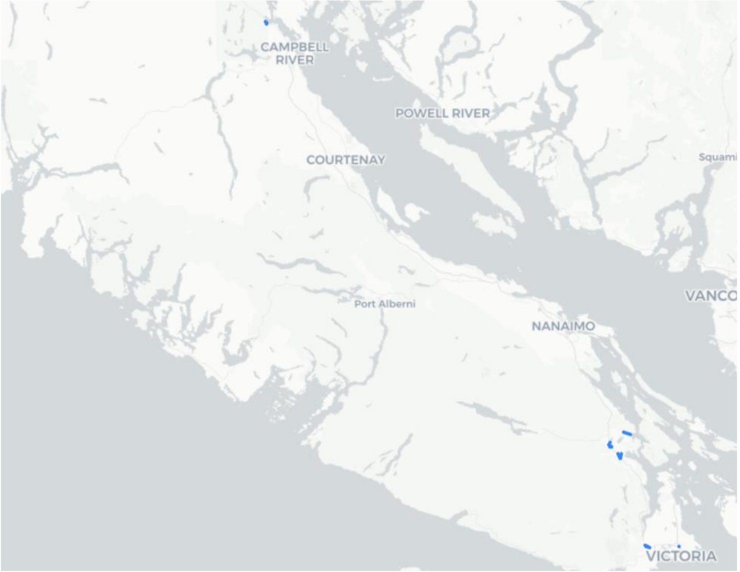


Figure 18. Roads cleared for at least 50% of the runs (RC2)

Figure 19. Roads cleared for at least 25% of the runs (RC3)

The consistently cleared roads shown in these three figures were then used as input changes for further analyses of the RCRSD model. For the 2 best depots (D6 and D11) and the two worst depots (D15 and D22), the blocked roads from the original dataset that are consistently cleared were considered to be unblocked as shown in Table 5 (at RC1, RC2 and RC3 levels respectively).

Table 5. Input variable scenario changes for consistently unblocked roads

	Input Variable chosen for analysis	
Run ID	**Depot location**	**Consistently unblocked roads**
D6RC1	220	RC1
D11RC1	1195	RC1
D15RC1	2002	RC1
D22RC1	2343	RC1
D6RC2	220	RC2
D11RC2	1195	RC2
D15RC2	2002	RC2
D22RC2	2343	RC2
D6RC3	220	RC3
D11RC3	1195	RC3
D15RC3	2002	RC3
D22RC3	2343	RC3

Table 6 shows the number of boxes that are supplied for each scenario, as well as the percentage of the total demand that is met, as the average of 3 runs done for each scenario. The total demand for all communities for each run is 777,646 boxes of supplies (i.e. the population of Vancouver Island and the Gulf Islands). The results can be contrasted with the original results reproduced in the final two columns. For the depots in the best locations (D6 and D11), there are no significant changes in the demands satisfied when the roads represented by RC1, RC2, and RC3 are considered undamaged. However, for the depot's worst locations, D15 and D22, that earlier showed demands satisfied as less than or around 40%, when the consistently cleared ones are considered unblocked, there are significant improvements in the demands satisfied as well as the number of communities that receive supplies.

Table 6. Results observed for changes in unblocked roads

				Original results	
Scenario ID	**Demand met in number of boxes**	**% Total demand met**	**% Communities supplied**	**Scenario ID**	**% Total demand met**
D6RC1	491645	63.22	61.33	D6	65.7
D11RC1	485185	62.39	58.98	D11	65.6
D15RC1	486428	62.55	57.42	D15	41.4
D22RC1	438715	56.42	52.01	D22	31.6
D6RC2	453078	58.26	55.08	D6	65.7
D11RC2	504896	64.93	60.94	D11	65.6
D15RC2	477331	61.38	56.64	D15	41.4
D22RC2	484570	62.31	58.98	D22	31.6
D6RC3	526870	67.75	60.55	D6	65.7
D11RC3	522386	67.18	62.89	D11	65.6
D15RC3	507548	65.27	60.94	D15	41.4
D22RC3	525983	67.64	62.89	D22	31.6

Critical Ports and Subsequent Analysis

The location of the most critical barge dock based on box supplies' origin is shown in Figure 20. For the communities serviced by trucks, 55% of the supplies went from this location. In comparison, the busiest ferry port, shown in Figure 21, contributed to only about 6% of the total supplies dispatched from the ports.

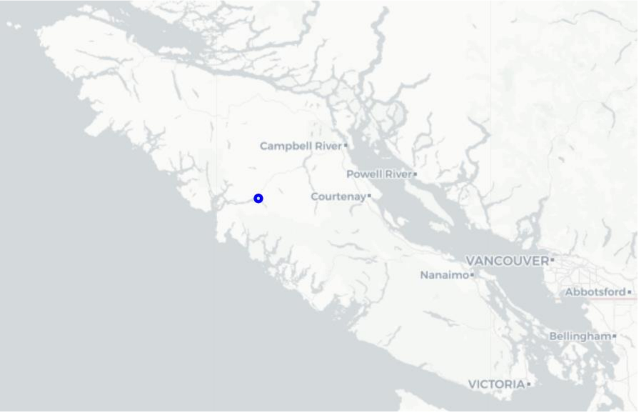


Figure 20. Location of critical barge dock

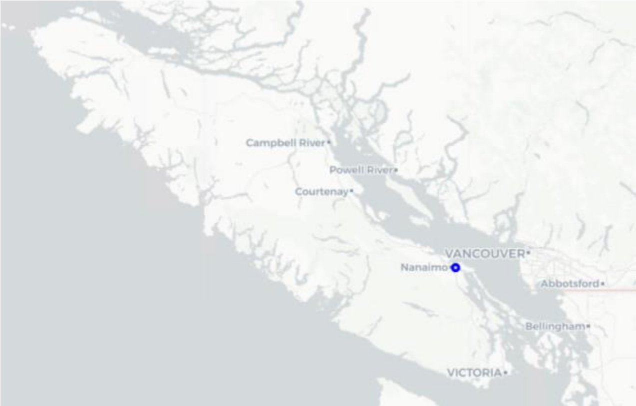


Figure 21. Location of critical ferry port

The next set of analyses were done by considering having either of the critical ports closed. The various input scenarios for which this analysis was done is shown in Table 7. For the two depots with the best locations (scenarios D6 and D11), combined with either the barge port closed (P1) or the ferry port closed (P2), the impact on deliveries are shown in Table 7, with the original results shown in the last two columns. For the scenarios where the barge port is considered closed (D6P1 and D11P1), the total demands satisfied are significantly less when compared to the scenarios where they are considered open (scenarios D6 and D11). The last two rows show that the impact of having the ferry port closed is much less, as it delivers a small proportion of the supply in the first place.

Table 7. Results observed for changes in ports availabilities

				Original results	
Scenario ID	**Demand met in number of boxes**	**% Total demand met**	**% Communities supplied**	**Scenario ID**	**% Total demand met**
D6P1	97075	12.48	21.61	D6	65.7
D11P1	26435	3.40	13.80	D11	65.6
D6P2	453662	58.34	53.91	D6	65.7
D11P2	464374	59.72	55.73	D11	65.6

Availability of Ships

Since the barge deliveries are greater than ferry deliveries, the RCRSD model is run by considering only 50% of the barges to be available, considering the two best depot locations. The case where all ferries are available and only 50% of barges are available is labelled as S1 in Table 8, while the case with all ferries unavailable and all barges operational is S2. When the barges are reduced by 50%, the total demand satisfied is reduced by a significant amount (comparing for example the original D6 result on the right, with the new D6S1), where the demand satisfied drops from 65.7% to only 12.1%. In contrast, for scenarios D6S2 and D11S2 where all ferries are assumed non-operational, the demands met are reduced by only about 10% from the runs D6 and D11 where all ferries are in use.

Table 8. Results observed for changes in ships' availabilities

				Original results	
Scenario ID	**Demand met in number of boxes**	**% Total demand met**	**% Communities supplied**	**Scenario ID**	**% Total demand met**
D6S1	94104	12.10	14.50	D6	65.7
D11S1	147291	18.90	21.58	D11	65.6
D6S2	435185	55.96	51.56	D6	65.7
D11S2	437010	56.20	51.82	D11	65.6

Community Impact Factor (CIF) Change

For the two best (D6 and D11) and two worst (D15 and D22) depot locations, new scenarios are run where the CIFs are neglected by making them all the same value, represented by C1 in Table 9. Comparing the results with the original outputs given in the two rightmost columns, there are no significant changes in the total demands met (greatest variation is 3%), except scenario D11C1 where total demand served dropped from about 65% to 47.68%. However, there is a decrease in the percentage of communities that receive supplies when the CIF is neglected in all scenarios.

Table 9. Results observed for changes in CIF

					Original results	
Scenario ID	**Demand met in number of boxes**	**% Total demand met**	**% Communities supplied**	**Scenario ID**	**Scenario ID**	**% Communities supplied**
D6C1	483812	62.22	53.51	D6	65.7	60.16
D11C1	370800	47.68	42.44	D11	65.6	61.98
D15C1	327414	42.10	34.47	D15	41.4	35.71
D22C1	261209	33.59	24.08	D22	31.6	24.74

Case B Findings

For the extensive disruption scenario (Case B, see Figure 4), the RCRSD model is run for only the two best and two worst depot locations from Case A analysis. All of the B scenario runs resulted in the same number of boxes being delivered. Changing the depot location does not make a difference in the results because there is no clearing activity completed in any in the B scenarios, so no communities are being reconnected to ports or barge docks within 72 hours. Out of the supplies that were dispatched, 5% was done by helicopters, 10% by barges directly, less than 1% by ferries directly, and about 84% by trucks of which 79% originated from the port in Victoria. When the time horizon was increased to 360 hours (15 days), although some road clearing happens, there is only about a 10% increase in the demands supplied when compared to the time horizon of 72 hours. Further details are provided in Vattoni (2023).

DISCUSSION

These sensitivity analyses on the distribution of relief supplies on Vancouver Island have explored the impacts of changes in some of the key factors affecting the outcome. While detailed outputs for each of the model runs are conserved, namely which roads are repaired and which communities receive supplies, better insights are provided through the use of regional aggregation of results, maps, and tables showing percentages of achievement. In response to the questions posed in the introduction section, select observations from these runs are presented in the following paragraph, while more extensive sensitivity analyses can be conducted eventually on a broader range of scenarios with varying degrees of earthquake damage.

The partial disconnection scenario (Case A) showed that the best location to have the depot would be the Central or the South Island regions of VI, but the latter is more likely to suffer damage from the earthquake. It was also shown that if the roads on South Island were reinforced so that they stayed unblocked, supplies are able to reach a larger percentage of the population. On changing the inputs related to shipping such as the ports that are open or the number of ships available, it was seen that over 50% of the supplies to communities went from a single barge dock halfway up the west coast. Additionally, when the critical roads were considered undamaged, it was found that the supplies to communities increased because the roads to this barge dock were cleared. These findings would help decision makers ensure to the degree possible the availability and strengthening of this infrastructure. Eliminating the Community Impact Factor (CIF) from the calculations does not affect the total supply significantly, but the number of communities that receive supplies are fewer. Preparedness experts can use these findings to help advocate for improved resilience (strengthening community infrastructure, maintaining more emergency supplies), particularly for certain towns which consistently receive less than 2% of their demand across all model runs (with those results housed in the detailed output files). The main findings from the more extreme Case B analysis is that 3 days is insufficient for conducting any appreciable road clearing, thus longer waits for deliveries are to be expected, or additional air response would be required.

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