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Prioritizing Flood-Prone Areas Using Spatial Data in the Province of New Brunswick, Canada

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Abstract: Over the years, floods have caused economic damage that has impacted development in many regions. As a result, a comprehensive overview of flood-prone areas at the provincial scale is important in order to identify zones that require detailed assessment with hydrodynamic models. This study presents two approaches that were used to prioritize flood-prone areas at the provincial scale in New Brunswick, Canada. The first approach is based on a spatial multi-criteria evaluation (SMCE) technique, while the second approach pertains to flood exposure analysis. The results show the variation in the identified flood-prone areas and, depending on the methodology and scenario used, prioritization changes. Therefore, a standard methodology might not be feasible and should be developed based on the objective of the study. The results obtained can be useful for flood risk practitioners when making decisions about where to commence detailed flood hazard and risk assessment.

Keywords: multi-criteria analysis; meso-scale; flood risk prioritization; exposure analysis

1. Introduction

In New Brunswick, floods are the most destructive type of hazard, with costs estimated at $245 million Canadian dollars for the period 1913–2014, although damage estimates have not been completed for many flood events [1]. These events have led to the destruction of properties, infrastructure and ecosystems. Infrastructural assets (roads, railways, ports, airports, electricity grids, Information and Communications Technology (ICT)) are important to our society, as they provide the means through which economic activity, connectivity and transportation are facilitated [2]. The disruption of movement along roads is recurrent in the province, and causes the displacement of people, goods and services. For instance, the flood event between 13 December and 14 December 2010, resulted in the closure of about 120 roads in the southern and western section of the province [1]. Flooding also caused the closure of the Trans-Canada Highway between Fredericton and Moncton for many days, especially during the May 2018 flood [3].

Prioritizing flood-prone areas is therefore important in identifying regions that require detailed mapping using hydrodynamic models. In fact, flood hazard identification and priority setting is one of the steps in the Federal Flood Mapping Guidelines Series document that is being developed by Natural Resources Canada (NRCan) and Public Safety Canada [4], as shown in Figure 1. A methodology is therefore needed to determine where to commence flood mapping based on the prioritization of flood-prone areas. However, this component of the guideline has not been completed. As a result, flood risk practitioners in Canada will have to develop their own methodology based on the availability of data and the scale of the analysis.

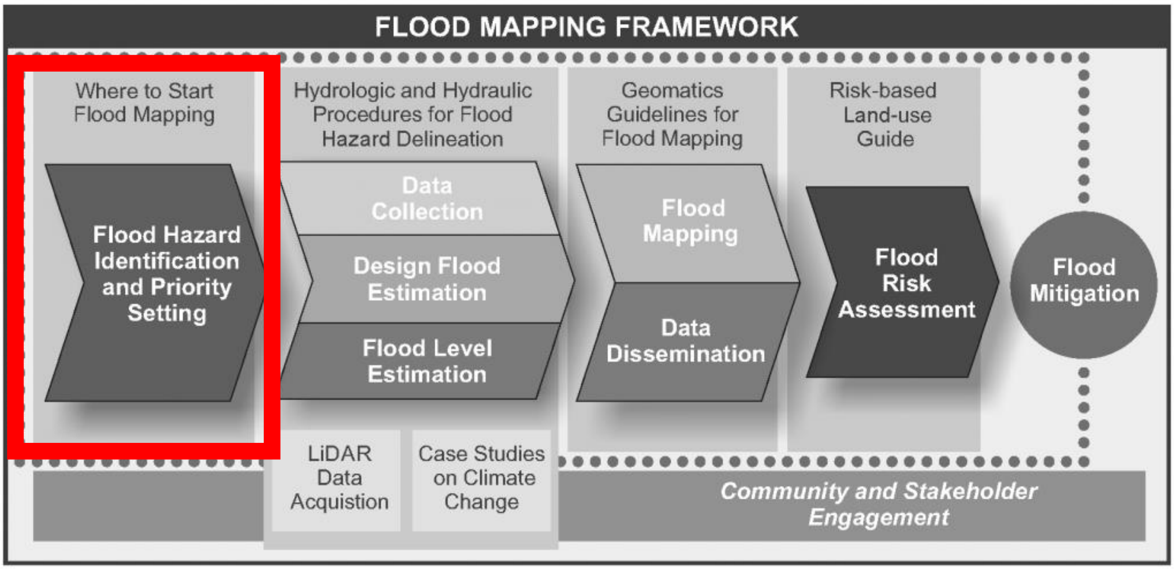

Figure 1. Federal flood mapping framework. Source: NRCan [4].

Various studies on the prioritization of flood-prone areas have been conducted in Canada. In Halifax, the capital of Nova Scotia, a flood risk assessment was conducted after the prioritization of flood-prone areas [5]. The high-risk areas were obtained through literature reviews, workshops and stakeholder consultations, along with the use of the Risk Assessment Information Template (RAIT), which was developed by Public Safety Canada, where weights were applied to each criterion in the form of a matrix. Afterwards, the sites ranked (numerically) with the highest priority were selected for a detailed assessment.

In the Regional District of Central Kootenay in British Columbia, a multi-hazard assessment was carried out to identify and prioritize floods and steep creek hazards that might threaten physical assets [6]. This resulted in a geohazard and consequence rating generated based on an exposure and geohazard assessment with the use of weights to produce high-risk areas.

Similarly, in Edmonton, Alberta, a multi-criteria analysis by sub-basins was conducted in order to rank mitigation options for flood risk management based on three levels of impact: moderate, major, and extreme [7]. The methodology incorporated the use of stakeholder participation, where public opinions were collected via surveys, community meetings, and in a focus group setting. The preferences were ranked according to the most and least important.

As this relates to the prioritization of flood risk in other jurisdictions, a wide variety of approaches have been used. For example, a qualitative flood risk prioritization study was conducted in a rural area in Columbia at the watershed level [8]. The study utilized a geomorphic approach to delineate the floodplain, which was combined with vulnerability indicators to produce an index that indicate watersheds that were ranked from low to high priority.

Prioritizing flood-prone areas was also conducted in the United Kingdom based on exposure analysis [2]. The methodology shows how to locate and make comparisons between transportation networks within flood-prone areas in order to prioritize mitigation options and increase the ability to cope with floods. Specifically, the authors assessed the impact of these assets on customer interruption. Additionally, a spatial prioritization of flood-prone areas at the catchment level in Newcastle was conducted based on the following priority criteria: contribution to total flood extent, maximum flood depths, flooded green spaces and roads and the likelihood of flood exposure [9]. For this, the physical impact of floods, land use and exposure to settlements and road infrastructure were considered.

In Bangkok, Thailand, the quick scan methodology was used to assess the vulnerability and mitigation of critical infrastructure from floods in urban areas in order to identify and rank critical infrastructural assets and building clusters in flood-prone areas in three communities [10]. This was achieved through the use of stakeholder engagement in workshops and interviews to gain input and feedback. The results demonstrated that secondary roads, markets, shopping centers, residential water supply and sanitation were ranked the highest.

As indicated, different approaches were used in the prioritization of flood risk. While some used stakeholder engagement and quantitative analysis, others applied weights to variables that represented flood hazard, vulnerability or exposure. Currently, there is no specific standard that is available; hence, the methodology used in flood priority studies depends on many factors. Furthermore, most of the studies presented, except [8] and [6], were within urban areas, and might not be applicable at the provincial scale and in rural areas.

Flood assessment can be conducted at various scales [11]: the supra-national (global), macro(national), meso (province, watershed or large city) and micro levels (town or river). Macro-level analysis can include the use of a single model or the aggregation of analysis conducted at the meso-scale; however, this can lead to inconsistency. At the meso-scale, the use of a standard return period can be misleading for large-scale analysis, resulting in the overestimation of flood risk. To overcome this, continuous rainfall runoff and hydrodynamic modelling can be used, but long computational times and the unavailability of data act as hindrances to hydrodynamic modelling at the meso-scale. Therefore, simple methods are normally used to circumvent the aforementioned issues [11]. Hence, the methodology used in flood research depends on the scale of analysis and the availability of data.

In this study, we present two approaches to prioritize flood-prone areas at the meso-scale in New Brunswick, a rural province in Canada. The first method involves a spatial multi-criteria evaluation technique (SMCE) [12]. The second approach involves the use of a geomorphic procedure to delineate floodplains based on a 20-year return period and the assessment of exposed assets [13]. Specifically, the prioritization based on the exposure analysis was conducted by intersecting the flood-prone areas with roads that were ranked similar to the method proposed in France for analyzing potential flood damage to transportation networks at the meso-scale [14]. The United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER) also suggests a similar approach for the damage assessment of assets after flood events [15].

As indicated by the World Bank [16], multi-criteria assessment is one of the methods that can be used for prioritization, especially in data-scarce environments. However, this approach might be challenging due to the difference in temporal and spatial scales of the datasets, which are available [17] and can have some amount of bias when weights are applied. Nonetheless, there has been an increase in the utilization of this technique for prioritization [18]. Furthermore, multi-criteria analysis is useful for analyzing flood hazard above the micro-scale in order to identify priority areas so that detailed analysis using hydrodynamic models can be conducted [19].

Even though the impact of infrastructural assets during floods can be severe, there a is paucity of studies that assess their impacts [2]. Moreover, most of the studies that have been undertaken might not be applicable in certain environments due to the complexity of the methods, which sometimes lead to unreliable results, particularly in data-sparse regions [20] such as New Brunswick. As a result, the use of a simple technique is sometimes necessary for the identification and ranking of infrastructural assets [10].

2. Materials and Methods

2.1. Study Area

This study was conducted at the provincial scale in New Brunswick, Canada (Figure 2). The province is located in the Atlantic Maritime Ecozone and has an area of approximately 71,388 km^2.

Based on the Ecological Regions of North America, New Brunswick is classified as the Northern Forests region, which is associated with "long, cold winters and short, warm summers" [21].

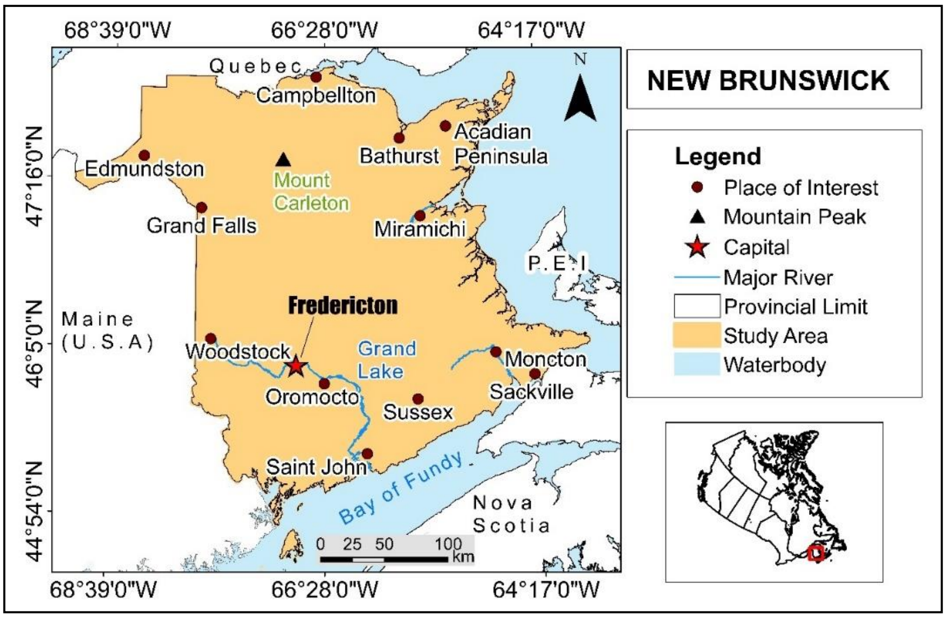

Figure 2. Location of study area.

The province has a continental climate, though variability occurs. In fact, the mean annual rainfall was estimated at 856 mm, while the mean snow fall is about 303 cm [22]. Mount Carleton, located in the north-central region, is the highest point.

New Brunswick is subdivided into seven ecoregions: the Highland, Northern Upland, Central Upland, Fundy Coastal, Valley Lowland, Eastern Lowland and Grand Lake ecoregions. These regions were classified based on landform, soil, vegetation, water, fauna and climatic factors [23].

The province is vulnerable to flood events; however, as shown in Figure 2, there are limited streamflow gauges. Furthermore, some of the gauges have been discontinued, which makes flood mapping challenging in some areas.

2.2. Methodology

The prioritization of flood-prone areas was completed using two approaches. The first method incorporated a modification of the multi-criteria technique used in Toronto, Canada [24], to conduct flood risk mapping at the provincial level in New Brunswick [12]. The second method included an exposure analysis based on the Geomorphic Flood Area (GFA) tool [13] in QGIS, which is the same technique used to assess the risk of flood damage to the transportation network in France [14]. ArcGIS was used to prepare the dataset used in this study for the multi-criteria and exposure analyses.

2.2.1. Multi-Criteria Analysis

As it relates to the SMCE, each dataset used was assigned the same resolution (20 m) as the Canadian digital elevation model (DEM) that was obtained from the Government of Canada Open Data portal [25]. Afterwards, hydrological and terrain parameters were used to create a flood hazard map, while a socio-economic map was generated from census and land use data in order to create the flood risk map [12,22] for prioritization (Figure 3).

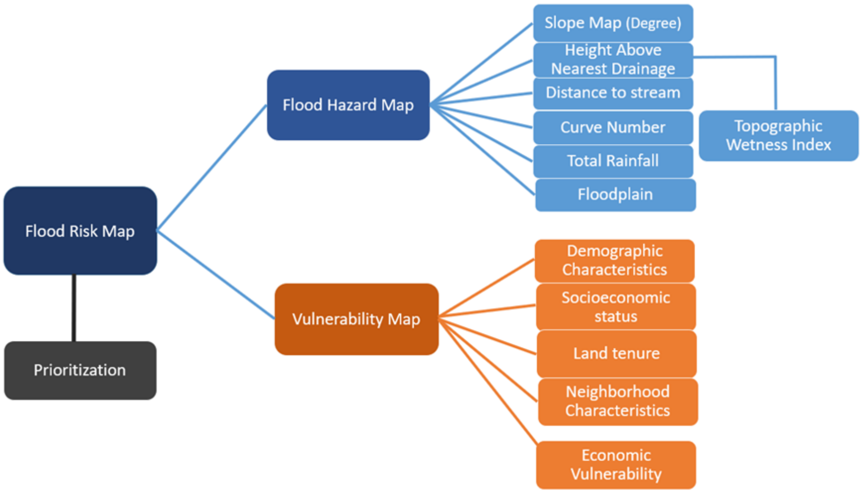

Figure 3. Flood risk prioritization schematization based on SMCE.

First, a flood hazard map was generated using three scenarios [12]. Scenario 1 included a slope map, the height above nearest drainage (HAND), the distance to stream, the curve number (index which is a function of soil group, land cover and antecedent soil moisture condition to estimate direct runoff from rainfall excess) and total rainfall, while scenario 2 substituted HAND with the topographic wetness index (TWI). Scenario 3 incorporated floodplain, distance to stream, HAND, slope map and curve number. Second, a social vulnerability map was created with the use of data gathered from the 2016 Canadian Census (social) obtained from [26]. The third step involved the creation of an economic vulnerability map using the land-use data (30 m) provided by Agriculture and Agri-Food Canada [27]. Each of the input data was converted to raster format and reclassified (Tables 1–3) to values ranging from 1 to 5, where 1 represents low flood risk and 5 refers to high flood risk 3. The indicators were reclassified to reflect the potential risk to flood hazard (the steeper the slopes, the lower the hazard; the closer the distance to river, the higher the hazard; the lower the curve number, the lower the runoff potential; the higher the rainfall value, the higher the risk of flooding; the lower the HAND value, the higher the risk of flooding; the lower the TWI, the lower the risk of flooding). Appendix A shows the different criteria maps used.

Afterwards, a spatial multi-criteria evaluation was conducted using the Integrated Land and Water Information Systems (ILWIS) software [28], where weights were applied to both variables (Tables 1 and 2). Final weights of 33% and 67% were applied to social and economic vulnerability, respectively, to produce one vulnerability map. The flood hazard and vulnerability maps were then combined to produce a flood risk map with equal weights (50%) applied to both. This resulted in a map with values ranging from 0 to 1, where 0 refers to low flood risk and 1 to very high flood risk. Afterwards, the results were exported to ArcGIS, where they were re-scaled between 0 and 100 and also reclassified using natural breaks. The classification ranged from very high flood risk (Class 5 in dark red) to very low flood risk (Class 1 in dark green). The flood risk map was validated with reported flood events in the province that were obtained from the New Brunswick Flood History Database [12]. The next step involved the prioritization of the flood-prone areas per the dissemination area in ArcGIS using the Zonal Statistics and Frequency Tools based on the flood risk map. The Zonal Statistics tool was used to quantify the mean flood risk per dissemination area, while the Frequency Tool counts the occurrence of each pixel in the very high-risk zone in each of the dissemination areas in order to prioritize potential flood-prone areas. The results were then exported to Excel and ranked. Figure 3 shows the methodology utilized for the multi-criteria analysis. Appendix B shows the risk maps for Scenarios 1, 2 and 3.

Table 1. Flood hazard indicators and weight.

Hazard Indicator	Category	Hazard Reclassification	Scenario 1 Weight [%]	Scenario 2 Weight [%]	Scenario 3 Weight [%]
Slope (degrees)	0–10	5	14	14	12
	11–20	4			
	21–30	3			
	31–50	2			
	>51	1			
Distance to Stream (m)	0–100	5	25	25	22
	101–300	4			
	301–500	3			
	501–1000	2			
	>1000	1			
Curve Number	30–39	1	9	9	8
	40–61	2			
	62–77	3			
	78–85	4			
	86–100	5			
Total Rainfall (mm)	76–94	1	36	36	
	95–110	2			
	111–129	3			
	130–152	4			
	>152	5			
HAND	0–5	5	16		13
	6–10	4			
	11–15	3			
	16–20	2			
	>21	1			
TWI	1–7	1		16	
	8–9	2			
	10–11	3			
	12–16	4			
	17–28	5			
Floodplain					45

Source: adapted from the flood risk assessment study in New Brunswick and Toronto [12,24].

Table 2. Criteria used for social vulnerability.

Demography	Indicators	Specific Indicators	Weight [%]
Demographic characteristics	Age	People 85 years and older	18
		Children four years and younger	17
	Family structure	Lone parents	16
	Language proficiency	Non-English or French-speaking people	15
Socio-economic status	Income	Total Median Income Per Household	11
	Education	High school education or less	9
Land tenure	Renters	Rented apartments	8
Neighborhood characteristics	Population density	Population density per km2	6

Source: Adapted from the Risk Assessment Study in New Brunswick and Toronto [12,24].

Numerous approaches exist for assigning weights when conducting SMCE [29]. Weighting can be selected based on a subjective approach, where decision makers use skills and knowledge to determine the importance of each criterion [30]. Likewise, an objective method can be incorporated, where decision makers are not required to highlight the importance of one criterion over another.

In this study, expert knowledge was used to select the criteria and weights that were applicable to New Brunswick. Following literature review, it was revealed that the criteria and weights used in the Toronto case study [24] might be applicable to the prioritization of flood risk in the province. In fact, a study that was conducted by Environment Canada [31] identified rainfall as the leading cause of flooding in New Brunswick. Therefore, even though the other factors cause floods, rainfall being assigned the highest weight is justifiable within this regard.

Additionally, people over 85 years old were identified as the most vulnerable groups during flood events in New Brunswick [32]. Consequently, the direct weigh method, which allows users to specify relative importance of each factor in ILWIS was used. These weights were then normalized automatically by the software. Given that uncertainty might permeate the analysis through the application of weights, the incorporation of the three different scenarios becomes important.

Table 3. Classes for Economic Vulnerability.

Class	Level	Land Use
5	Very high	Water Bodies and Wetlands
4	High	Developed
3	Moderate	Agriculture
2	Low	Grassland
1	Very low	Forest

Source: adapted from the risk assessment study in New Brunswick [12].

2.2.2. Exposure Analysis–DEM-Based Identification

The prioritization of flood-prone areas based on the exposure analysis was based on the technique used to assess the risk of flood damage to transportation network in France [14]. This approach was tested because it was conducted at the meso-scale, which is the same level of our analysis. The floodplain was delineated based on the 20-year return period using the GFA tool in QGIS [13]. The parameters extracted from the Canadian DEM (raw DEM, filled DEM, flow direction, flow accumulation) and flood extent from GeoNB [28] for calibration were inputs for the Geomorphic Flood Area (GFA) tool. Figure 4 illustrates the floodplain that was generated.

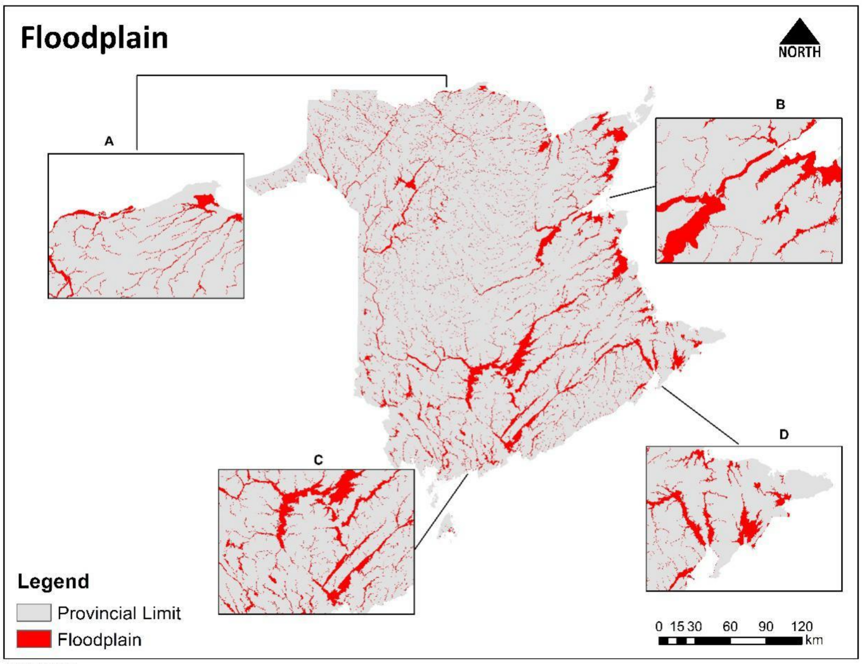

Figure 4. Floodplain generated with GFA.

The railway and road network derived from GeoNB [33] were merged, reclassified and ranked (the higher the number, the greater the potential damage) similar to the methodology used in France [14] as shown in Table 4. Subsequently, the Intersect tool in ArcGIS was used to combine the floodplain and transportation network maps to produce one map. The final step involved the prioritization of the exposed transportation network using natural breaks.

Table 4. Example of the ranking of the roads.

Original Classification	Classification Used	Rank
Highway	Freeway and highway, service lane, weigh station	7
Highway ramp	Highway ramp	6
Two lanes road	Collector, arterial	5
Railway	Railway	5
One lane road	Local, NBDOT Local Named, local named numbered, NBDOT Road Public Access	4
Small lane	Alleyway	3
Stone-paved, gravel road	DOT local named gravel, NBDNR Resource Roads	2
Cycle track	Local strata, local street, unknown, non-vehicular addressed segment	1

Source: Adapted from the Study in France [14].

Only the transportation network was ranked. The floodplain was used as a hazard layer with no value range. Therefore, the hazard layer was just intersected with the road and railway layer that was ranked to produce the final result, using natural breaks. When combined, the roads that are ranked higher, will have a greater risk of being damaged. This was essential to highlight the current situation in the province, as major thoroughfares are impacted the most.

3. Results

3.1. Flood Risk Prioritization Based on Multi-Criteria Analysis

The results obtained from the prioritization study using the SMCE analysis are presented below in the form of maps (Figures 5–7) and Tables (Tables 5 and 6) per dissemination area (CSDNAME) obtained from Statistic Canada [25]. Scenario 1 included a slope map, height above nearest drainage (HAND), distance to stream, curve number and total rainfall while scenario 2 substituted HAND with topographic wetness index (TWI). Scenario 3 on the other hand incorporated floodplain, distance to stream, HAND, slope map and curve number.

As indicated, the level of risk varies across the province. In Scenario 1 (Figure 5), high to very high flood-prone areas are concentrated in the dissemination areas that are within the south-central region (Inset C). Even though the areas with moderate flood risk varies, the majority are located in the east central zone. Likewise, flood-prone areas vary from moderate to low in the Acadian Peninsula (Figure 2) while the north central zone is characterized with low to very low risk.

In Scenario 2 (Figure 6), there is an increase in flood risk for the dissemination areas in the north (Inset A), as some sections changed from low to moderate. More moderate flood risk is also visible for the Acadian Peninsula. However, a reduction in flood risk is evident in the south eastern part of the province.

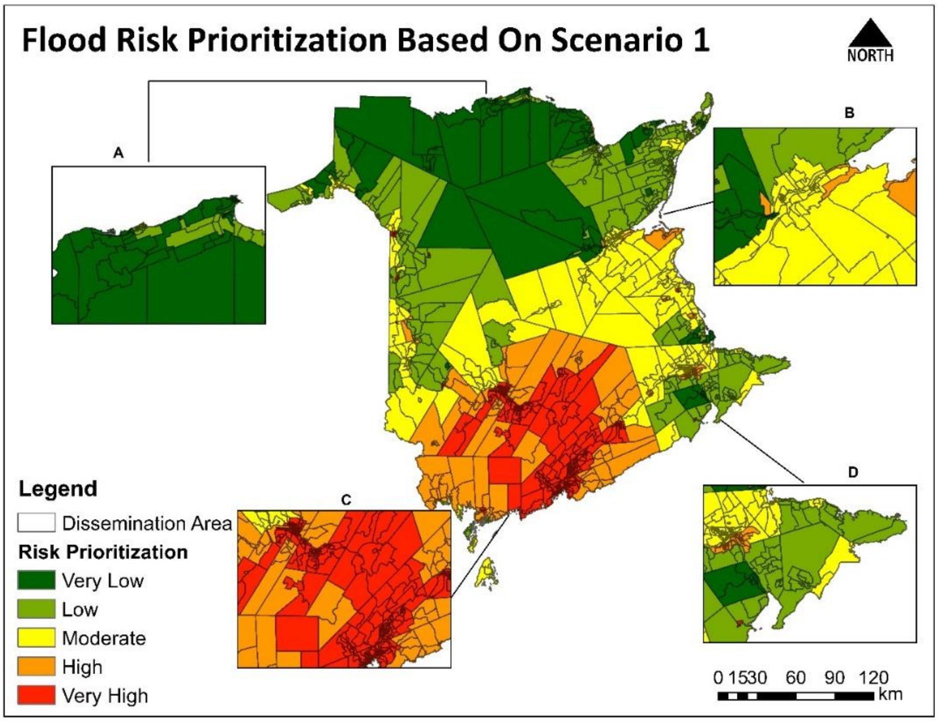

Figure 5. Flood risk prioritization based on Scenario 1 using zonal statistics.

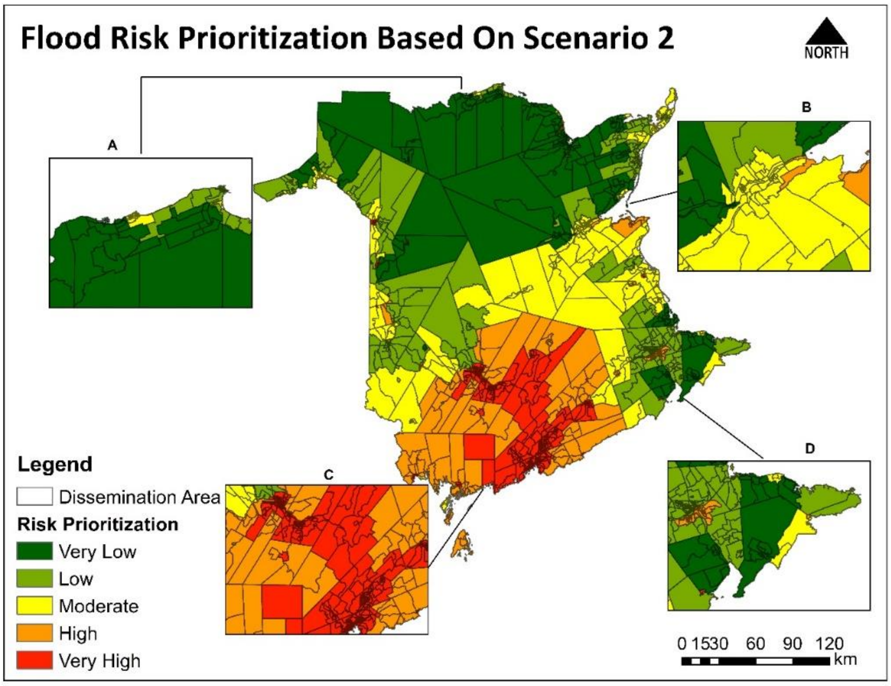

Figure 6. Flood risk prioritization based on scenario 2 using zonal statistics.

For Scenario 3 (Figure 7), the classification with moderate to high flood-prone areas increases and are confined to some of the major towns and cities with higher populations compared to the rest of the province. Additionally, more dissemination areas are classified as moderate flood-prone regions in the north (Inset A). The majority of the dissemination areas in Inset B have a high flood risk, while the risk is reduced for Inset C.

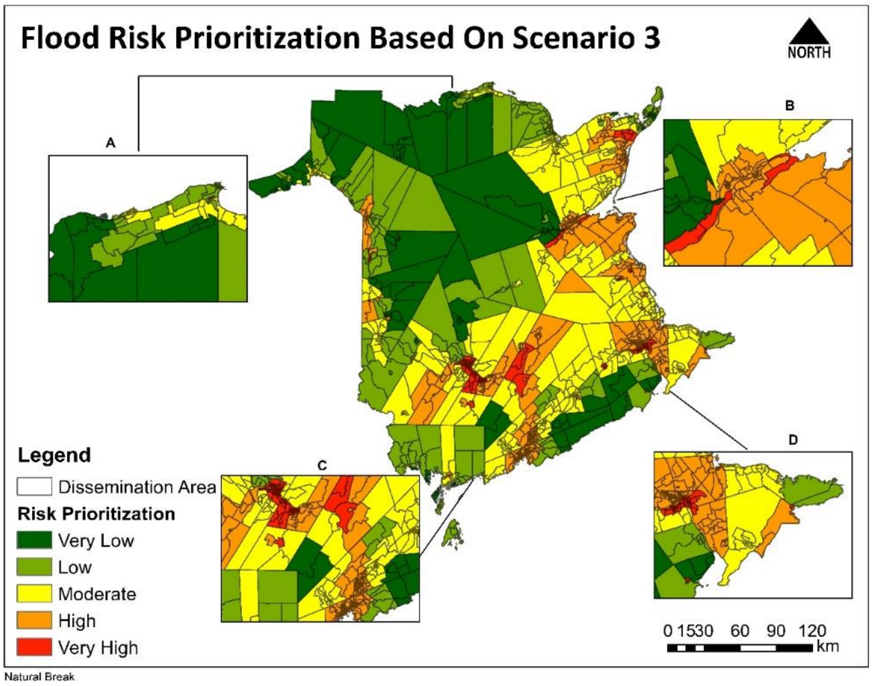

Figure 7. Flood risk prioritization based on scenario 3 using zonal statistics.

In order to generate the prioritization list from the multi-criteria analysis, the Zonal Statistics as Table tool in ArcGIS was used. The results from the analysis indicate the average flood risk per dissemination area (Table 5). Only the dissemination areas that are ranked as very high flood-prone areas are included, along with the mean value of the flood risk map (ranking was done on actual value even though rounded value is shown). As indicated, Oromocto 26 is ranked the highest in all the scenarios, as it relates to the dissemination areas that are located within the very high flood risk zone. Scenario 1 has the majority of the dissemination areas ranked very high (41), while Scenario 3 has the least (19). As illustrated, Scenarios 1 and 2 have the same dissemination areas ranked in the top three. The results also show the change in the ranking of flood-prone areas in each of the scenarios.

Table 5. Prioritization list based on zonal Statistics with a very high ranking.

	Scenario 1		Scenario 2		Scenario 3	
Rank	**CSDNAME**	**Mean**	**CSDNAME**	**Mean**	**CSDNAME**	**Mean**
1	Oromocto 26	4.7	Oromocto 26	4.4	Oromocto 26	4.8
2	Canning	4.0	Canning	4.0	Rexton	4.3
3	Oromocto	3.9	Oromocto	4.0	Canning	3.6
4	Cambridge	3.9	St. Martins	4.0	Riverside-Albert	3.6
5	Fredericton	3.9	Rothesay	3.9	Oromocto	3.5
6	Rothesay	3.8	Fredericton	3.9	Bath	3.5
7	Fredericton Junction	3.7	Quispamsis	3.8	Indian Ranch	3.5
8	Plaster Rock	3.7	Cambridge	3.8	Plaster Rock	3.3
9	Quispamsis	3.7	Plaster Rock	3.8	Riverview	3.3
10	Riverside-Albert	3.6	Saint John	3.8	Derby	3.3
11	Kingston	3.6	Fredericton Junction	3.7	Dieppe	3.2
12	Saint John	3.5	Kingston	3.6	Richibucto 15	3.2
13	Burton	3.5	St. Stephen	3.6	Inkerman	3.2
14	Cambridge-Narrows	3.5	Riverside-Albert	3.5	Saint-Louis de Kent	3.2
15	Rexton	3.5	Sussex Corner	3.5	Fredericton Junction	3.0
16	Saint-Louis de Kent	3.5	St. George	3.5	Aroostook	2.9
17	Lincoln	3.5	Minto	3.5	Chatham	2.9
18	Bath	3.5	Cambridge-Narrows	3.5	Fredericton	2.9

Table 5. *Cont.*

	Scenario 1		Scenario 2		Scenario 3	
Rank	**CSDNAME**	**Mean**	**CSDNAME**	**Mean**	**CSDNAME**	**Mean**
19	Kars	3.5	Lincoln	3.5	Perth-Andover	2.9
20	Sussex Corner	3.4	Grand Bay-Westfield	3.5		
21	Wickham	3.4	Burton	3.5		
22	Minto	3.4	Kars	3.5		
23	Gagetown	3.4	Greenwich	3.4		
24	Sheffield	3.4	Wickham	3.4		
25	Grand Bay-Westfield	3.4	Hampton	3.4		
26	Norton	3.3	Musquash	3.4		
27	Greenwich	3.3	Rexton	3.4		
28	Perth-Andover	3.3	Sheffield	3.4		
29	Centreville	3.3	Bath	3.4		
30	Westfield	3.3	Westfield	3.4		
31	Hampton	3.3	Centreville	3.4		
32	Waterborough	3.3	Saint-Louis de Kent	3.3		
33	Hampstead	3.3	Perth-Andover	3.3		
34	St. George	3.2	Norton	3.3		
35	Sussex	3.2	Waterborough	3.3		
36	Musquash	3.2	Gagetown	3.3		
37	Hanwell	3.2	Hampstead	3.3		
38	Clarendon	3.2	Hanwell	3.3		
39	Blissville	3.2	Clarendon	3.3		
40	Springfield	3.2	Lepreau	3.3		
41	Grand Falls/Grand-Sault	3.2				

Another set of prioritizations from the multi-criteria analysis was conducted using the Frequency tool in ArcGIS, where the results were produced in tabular form. For this, the flood risk map was converted to polygon and the very high flood risk areas were extracted for ranking in Excel. Table 6 shows the top 35 prioritization list based on the number of occurrences of the pixels classified with a very high flood risk per dissemination area. Northesk is ranked the highest in Scenarios 2 and 3, while Brunswick is the highest ranked flood-prone area in Scenario 1. Similar to Table 5, the ranking of flood-prone areas varies in each scenario.

Table 6. Prioritization list based on frequency analysis with a very high flood risk.

	Scenario 1		Scenario 2		Scenario 3	
Rank	**CSDNAME**	**Frequency**	**CSDNAME**	**Frequency**	**CSDNAME**	**Frequency**
1	Brunswick	6229	Northesk	15,866	Northesk	4003
2	Maugerville	5952	Southesk	14,414	Southesk	2987
3	Southesk	5772	Harcourt	11,312	Lorne	2515
4	Saint Martins	5365	Blissfield	9715	Tracadie	2306
5	Harcourt	5209	Brunswick	9289	Bathurst	2102
6	Upper Miramichi	5196	Bathurst	9073	Eldon	1703
7	Blissfield	5188	Upper Miramichi	8737	Saint-Quentin	1575
8	Douglas	4688	Maugerville	8667	Glenelg	1452
9	Waterborough	4302	Saint John	8582	Chipman	1431
10	Petersville	4194	Douglas	8334	Blackville	1420
11	Clarendon	4018	Lorne	7280	Salisbury	1412
12	Saint Marys	3842	Saint Martins	7022	Harcourt	1404
13	Saint James	3817	Glenelg	7001	Upper Miramichi	1392
14	Studholm	3814	Waterborough	6374	Gordon	1387
15	Chipman	3718	Blackville	6311	Inkerman	1310
16	Saint George	3670	Studholm	6189	Douglas	1292
17	Burton	3630	Caraquet	6171	Stanley	1176
18	Northesk	3621	Chipman	6124	Blissfield	1160

Table 6. *Cont.*

	Scenario 1		Scenario 2		Scenario 3	
Rank	**CSDNAME**	**Frequency**	**CSDNAME**	**Frequency**	**CSDNAME**	**Frequency**
19	Pennfield	3598	Saint Marys	6063	Canning	1103
20	Gagetown	3465	Petersville	5657	Weldford	1091
21	Blackville	3203	Shippagan	5347	Saint George	1069
22	Lorne	3108	Saint George	5331	Balmoral	1060
23	Johnston	3065	Saint James	5274	Brunswick	1047
24	Stanley	3029	Stanley	5223	Alnwick	1015
25	Gordon	2849	Burton	5134	Waterborough	965
26	Salisbury	2707	Pennfield	5107	Studholm	964
27	Manners Sutton	2618	Salisbury	5071	Sackville	948
28	Lepreau	2556	Fredericton	4973	Maugerville	936
29	Northfield	2392	Huskisson	4803	Richibucto	932
30	Glenelg	2381	Carleton	4784	Denmark	920
31	Saint John	2360	Johnston	4673	Drummond	919
32	Sussex	2282	Gordon	4670	Addington	842
33	Sheffield	2232	Clarendon	4607	Manners Sutton	829
34	Norton	2225	Sussex	4536	Hardwicke	783
35	Kingston	2215	Gagetown	4378	Saint James	774

3.2. Flood Risk Prioritization Based on Exposure Analysis

The results from the flood exposure analysis are presented in Figure 8. As demonstrated, the number of exposed roads and railways within the floodplain based on the 20-year return period varies. However, the majority of the transportation network that is at high to very high risk of flooding is located along the coast in the north, northwest and south-center of the province. High to very high risk is also depicted in the Acadian Peninsula and southeast region. It is also noticeable that the risk of damage is lower in the north central region.

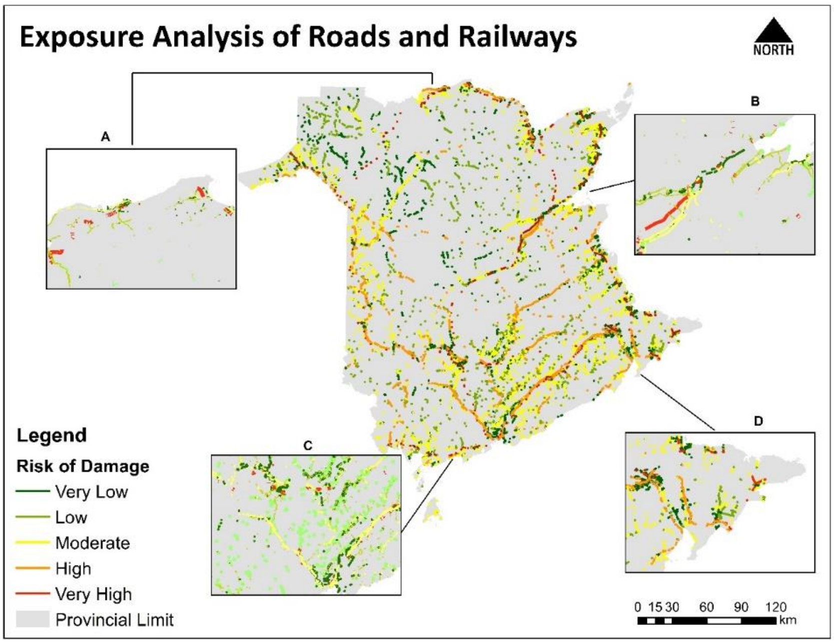

Figure 8. Transportation network that is at risk of being damaged.

The prioritization list (Top 35) generated from the exposure analysis, as it relates to the risk of damage to roads and railways, is presented based on the zonal statistics (Table 7) and frequency analysis per dissemination area (Table 8). Some of the flood exposure results were validated based on expert knowledge and the literature. In Table 7, Hanwell is ranked the highest.

Table 7. Risk of damage from road and railway prioritization based on zonal statistics.

Rank	CSDNAME	Mean
1	Hanwell	5.7
2	Botsford	5.5
3	Dalhousie	5.5
4	Derby	5.1
5	Fort Folly 1	5.0
5	Shippagan	5.0
7	Andover	4.9
8	Saint-Léonard	4.9
9	Sainte-Anne-de-Madawaska	4.8
10	Saint Stephen	4.8
11	Queensbury	4.6
12	Saint David	4.6
13	Nelson	4.6
14	Wicklow	4.6
15	St. Stephen	4.6
16	Saint Croix	4.6
17	Dumfries	4.5
18	Southampton	4.5
19	Northampton	4.5
20	Dorchester	4.5
21	Peel	4.5
22	Pennfield	4.4
23	Musquash	4.4
24	Tracy	4.4
25	Florenceville-Bristol	4.4
26	Cardwell	4.4
27	Brunswick	4.4
28	Saint-Hilaire	4.4
29	Durham	4.4
30	Meductic	4.3
31	Hopewell	4.3
32	Norton	4.3
33	Harvey	4.3
34	St. Hilaire	4.3
35	Blissville	4.2

Based on the frequency analysis, Tracadie (located along the Acadian Peninsula) is ranked as having the highest risk of damage (Table 8). While some of the roads are ranked as having a high risk of potential damage, this does not mean that they will be flooded. For instance, the results are based on the quality of the data used and might not reflect road improvements that will likely reduce the flood risk. Furthermore, some sections of roads might be elevated or have structural protection from inundation, such as dykes, which might not be impacted during regular flood events. However, flooding from extreme events, ice jam, dyke break and the damming of the river could cause them to be at risk.

Table 8. Risk to damage from road and railway prioritization based on frequency analysis.

Frequency	CSDNAME	Final Rank
69	Tracadie	1
68	Moncton	2
49	Sussex	3
37	Blackville	4
35	Alnwick	5
33	Edmundston	6
29	Musquash	7
28	Cardwell	8
28	Miramichi	8
28	Saint John	8
26	Eldon	11
26	Shediac	11
25	Salisbury	13
24	Bathurst	14
23	Inkerman	15
23	Saint-Léonard	15
22	Lincoln	17
22	Neguac	17
22	Richibucto	17
21	Sackville	20
20	Fredericton	21
17	Doaktown	22
17	Rivière-Verte	22
16	Bertrand	24
16	Derby	24
16	Upper Miramichi	24
15	Pennfield	27
15	St. George	27
15	Wellington	27
14	Norton	30
14	Sainte-Anne	30
14	Westmorland	30
13	Burton	33
13	Johnston	33
13	Lepreau	33

4. Discussion

The results obtained from the multi-criteria analysis indicate the complexity involved when prioritizing flood-prone areas at the provincial scale. It is evident that both scenarios 1 and 2 have similarities in terms of the predominance of high flood-prone areas in the south-central part of the province, which is where the capital (Fredericton) and a major city (Saint John) are located. However, the ranking of flood-prone areas changed with each scenario. One possible reason could be due to the fact that scenarios 1 and 2 incorporated rainfall as the main variable that influence floods. In contrast, the floodplain was assigned the higher weight in scenario 3 and rainfall was not included. These very high flood risk areas, observed in dark red, were assigned the highest rainfall values, which implies that the flood hazard map with rainfall had a stronger influence on the results that were generated. Furthermore, HAND is based on height of the drainage network, while TWI demonstrates areas that are likely to become saturated. On the other hand, the floodplain is limited to the flat areas close to river channels that can be flooded.

The areas in the south-central region of the maps (Figure 9) with high risk are in line with flood risk zones that have been mapped in New Brunswick [33]. As demonstrated, many areas are unmapped, even though floods have been reported elsewhere. This provides justification for the use of SMCE in order to identify flood-prone areas that are needed for mapping purposes.

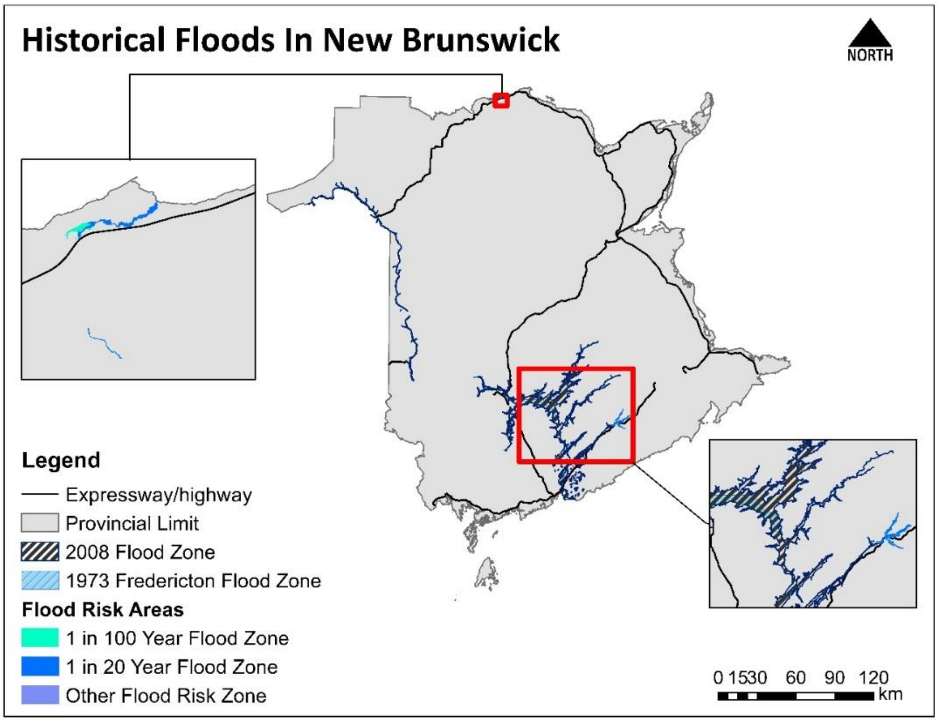

Figure 9. Historical floods in New Brunswick. Adapted from GeoNB [33].

In the exposure analysis, the smaller roads were ranked lower, but the impact of the damage can be enormous, especially in rural areas when repairs are required for a small amount of people. To gain an overview of the impact of roads during floods in the province, the event between 14 April and 20 April 2014, is highlighted. This event caused damage to about 715 homes and commercial entities and the transportation network, which resulted in the closure of numerous roads [1]. The total damage from this event was estimated at $16 million Canadian dollars [1]. Moncton, for example, recorded about six road closures on 11 April 2014, while three roads were closed on 16 April 2014. In Sussex and Sussex Corner, about 1450 people had to be evacuated and numerous roads were damaged. Road closure was also reported in Miramichi, Fredericton, Saint John, Sackville and areas connected with the Trans-Canada Highway [1].

Another catastrophic flood includes the 2018 event that led to the closure of about 81 roads, including the Trans-Canada Highway, mostly along the Saint John River from Fredericton to Saint John [34]. Additionally, the flood between 15 April and 16 April 1994, which affected the Cains River Road in Upper Blackville, caused disruption to movement [1]. The number of roads affected shows the vulnerability of transportation networks during flood events in the province, which can affect the movement of goods, services and evacuation exercise during an emergency.

As demonstrated, it is difficult to use one standard approach to prioritize flood-prone areas, as the ranking can change depending on the criteria that are used. Similar to our study, the flood risk prioritization analysis that was conducted in Columbia [8] revealed changes in the level of vulnerability when a sensitivity analysis was conducted. Specifically, the results obtained were sensitive to the criteria used, as the vulnerability changed from low to medium and medium to high in some instances.

The challenge is, therefore, how to aggregate the risk, as the same dissemination areas in our study are not always ranked first in all the scenarios. This shows the difficulty involved in conducting flood risk prioritization at the meso-scale and the importance of using expert knowledge and stakeholder engagement. While expert knowledge was utilized, the use of stakeholders was a major limitation in our study due to COVID-19. The question is, therefore, on which basis should we evaluate and prioritize areas that are prone to flooding? Certainly, the level of risk will change depending on the methodology, criteria and scale of analysis as demonstrated. Hence, a standard methodology might not be feasible and should be developed based on the objective of the study.

It must be noted that the results obtained in this study are based on a methodology that was feasible, given the data availability and the objective. Numerous approaches exist, but the scale of our analysis presented challenges for replicability. For instance, the following author [35] illustrates the scales at which hazard assessments are normally conducted (Table 9). As indicated, the provincial level normally covers 1000–10,000 km^2. However, New Brunswick has an area of about 71,388 km^2, which is more in line with studies that are generally conducted at the national level (area between 30–600 thousand km^2), as shown in Table 9.

Table 9. Scales for hazard assessment.

Scale	Level	Cartographic Scale (million)	Spatial Resolution	Area Covered (km^2)
Global	Global	<1:5	1–5 km	148 million
Very small	Continental/large countries	1–5	1	5–20 million
Small	National	0.1–1	0.1–1 km	30–600 thousand
Regional	Provincial	0.05–0.1	100 m	1000–10,000
Medium	Municipal	0.025–0.05	10m	100
Large	Community	>0.025	1–5m	10

In some research, one-dimensional models are used to approximate peak flow at the provincial scale [35]. Even though New Brunswick has many rivers, most of the streams are ungauged, which makes the use of such models challenging for use at the meso-scale. Moreover, the incorporation of building information such as height, type and use can be incorporated in flood assessment at the provincial scale with results generated from the models [35]. However, in New Brunswick detailed building information is not yet available for every location. This illustrates the challenges, as it relates to conducting flood hazard and risk assessment at the provincial scale, as the methodologies used in most studies are not always applicable in other locations. Therefore, we tested two approaches that were feasible based on the data availability, computational time and scale of the analysis.

Our approach falls within the context of a qualitative technique, which is normally useful for the identification of hazards and risks as a screening tool, especially at the provincial scale in data-sparse areas [35]. Since the approach used in this study was for screening purposes, other studies should be conducted based on a quantitative approach at other scales in order to obtain the direct and indirect losses for elements at risk (assets).

5. Conclusions

This study prioritized flood-prone areas at the provincial scale based on a qualitative approach in order to identify areas that will require detailed flood mapping using hydrodynamic models. The results from the multi-criteria and exposure analyses revealed some important aspects, as they relate to data, methodology, scale and decision-making, where risk and the prioritization of flood-prone areas are concerned.

Despite the complexity involved in flood assessment at the provincial scale, some patterns are evident. From the multi-criteria analysis, dissemination areas with high to very high flood-prone areas are located mostly in the south-central region of the province, while the lowest-ranked flood-prone areas are concentrated in the north central section in Scenarios 1 and 2 of the SMCE.

Similarly, transportation networks that have a high to very high risk of being damaged are located within the south-central section of the province, although some can be found along the coast and the north-west.

The results also indicate how prioritization changes based on the criteria used, which suggest that a standard methodology might not be applicable when ranking flood-prone areas. Nonetheless, this study can be applied to other locations where data paucity is a challenge.

Author Contributions: Conceptualization, S.H. and A.-M.L.; methodology, S.H.; software, S.H.; validation, S.H., A.-M.L. and A.H.; formal analysis, S.H.; investigation, S.H.; resources, S.H. and A.-M.L.; data curation, S.H., A.-M.L. and A.H.; writing—original draft preparation, S.H.; writing—review and editing, A.-M.L., J.B. and A.H.; visualization, S.H.; supervision, A.-M.L. and J.B.; project administration, A.-M.L.; funding acquisition, A.-M.L. and J.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

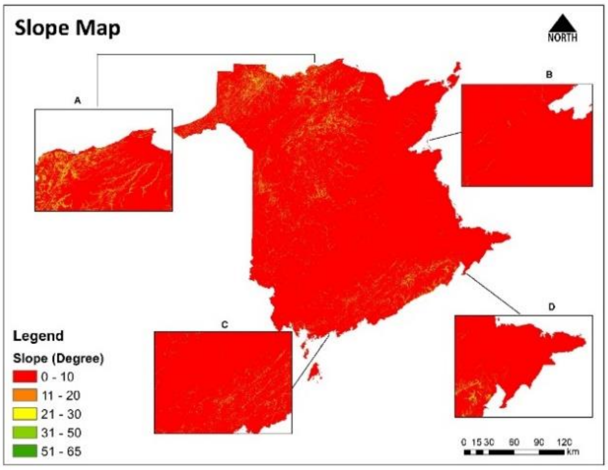

Figure A1. Slope Map.

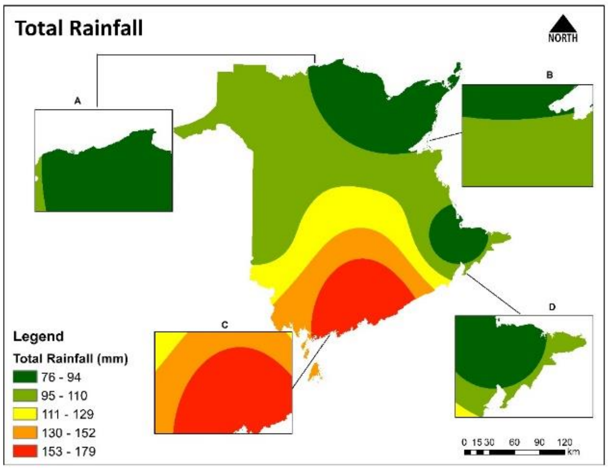

Figure A2. Total Rainfall.

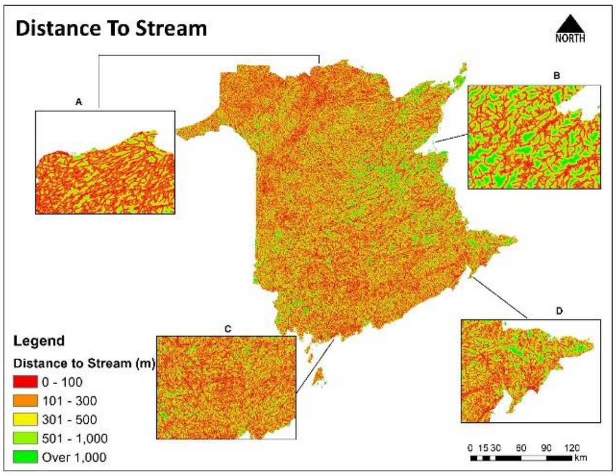

Figure A3. Distance to Stream.

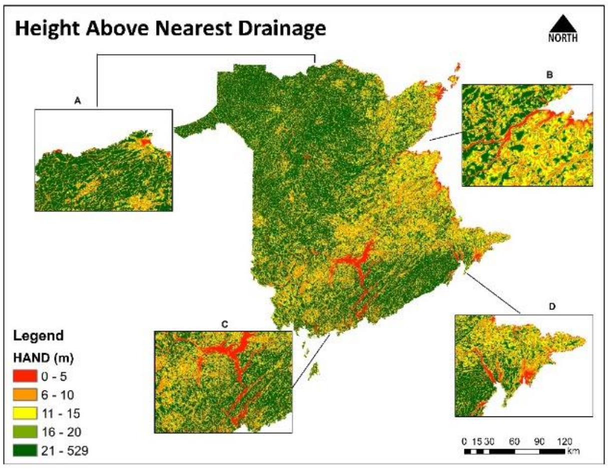

Figure A4. Height Above Nearest Drainage.

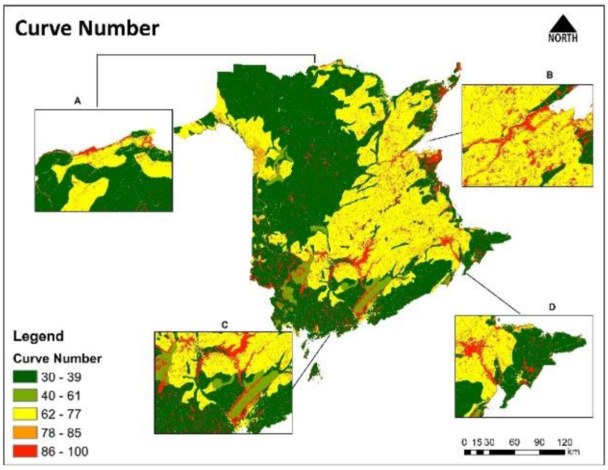

Figure A5. Curve Number.

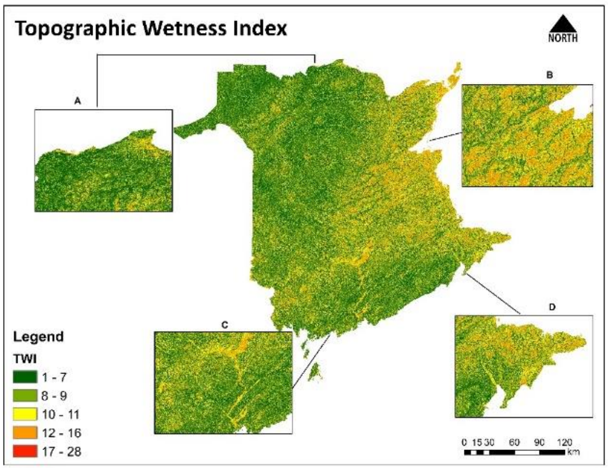

Figure A6. Topographic Wetness Index.

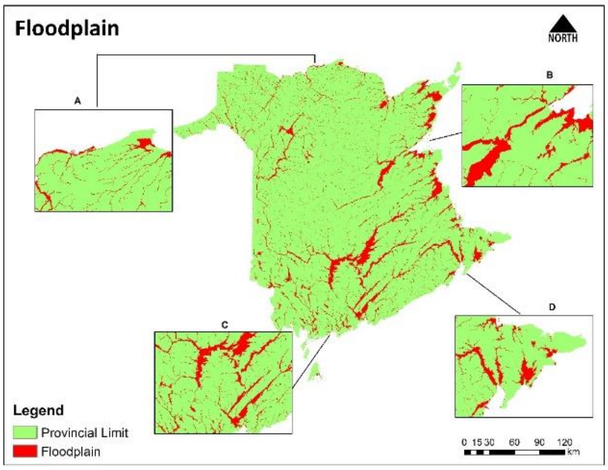

Figure A7. Floodplain.

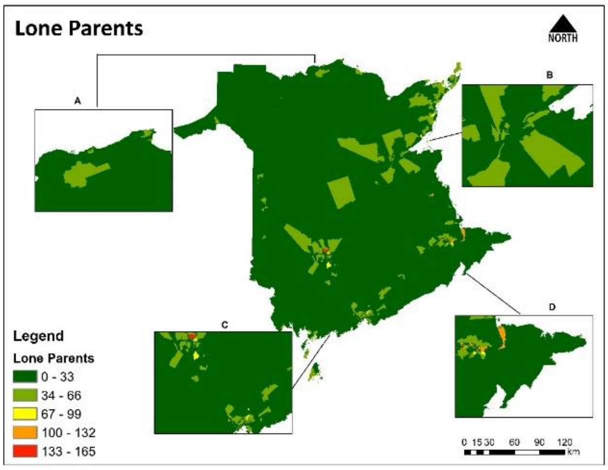

Figure A8. Lone Parents.

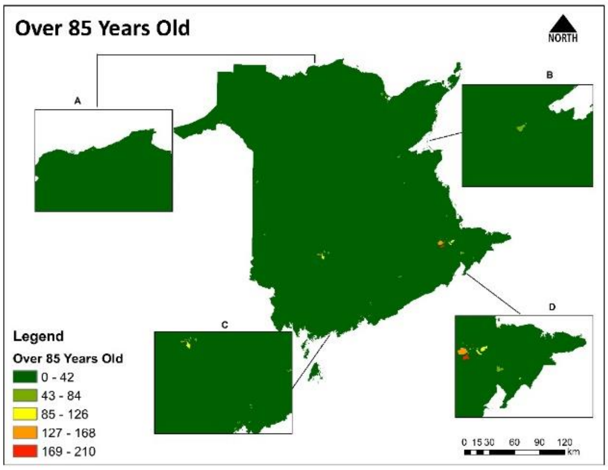

Figure A9. Population Over 85 Years Old.

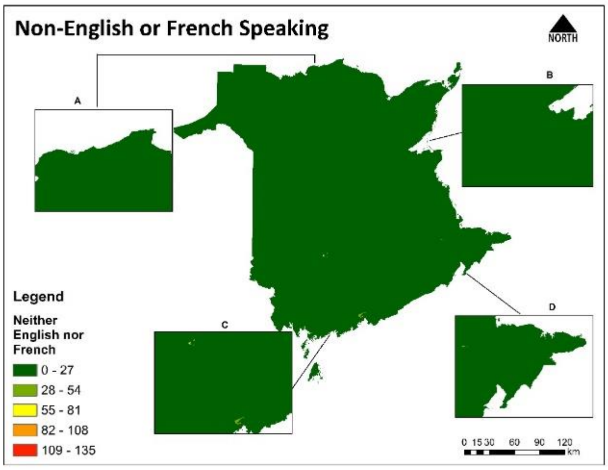

Figure A10. Population Speaking Neither English Nor French.

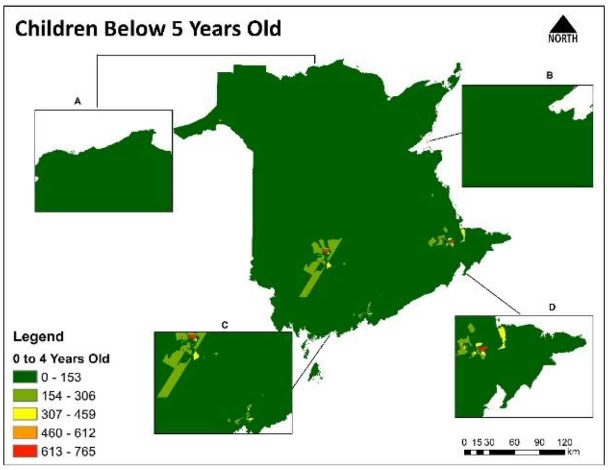

Figure A11. Children Below 5 Years Old.

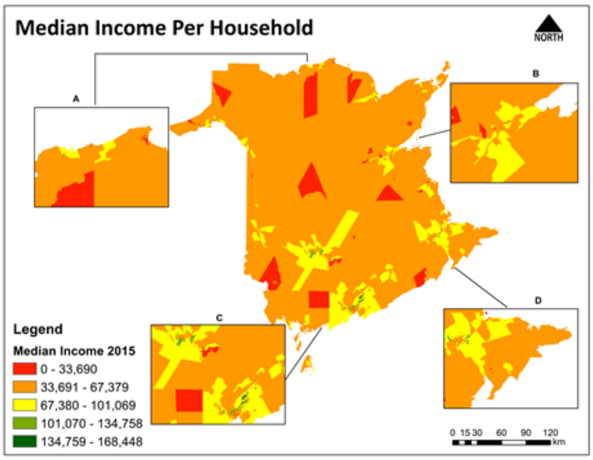

Figure A12. Total Median Income Per Household.

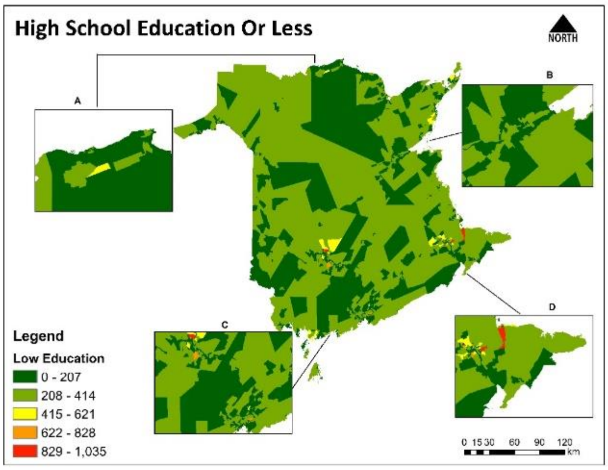

Figure A13. Population with High School Education Or Less.

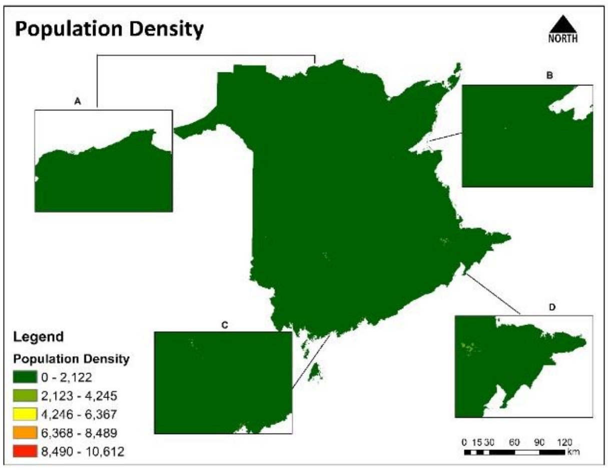

Figure A14. Population Density (km^2).

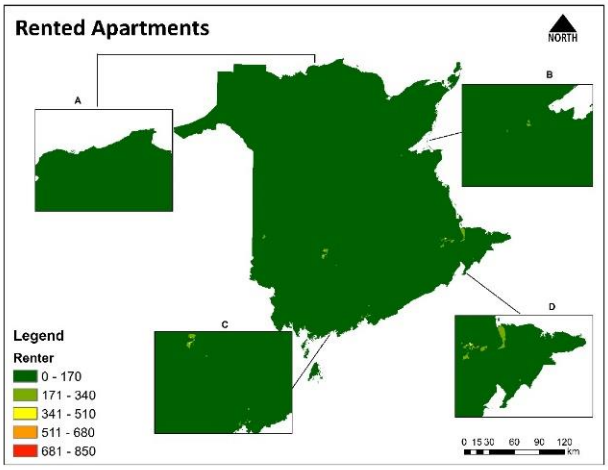

Figure A15. Population living In Rented Apartments.

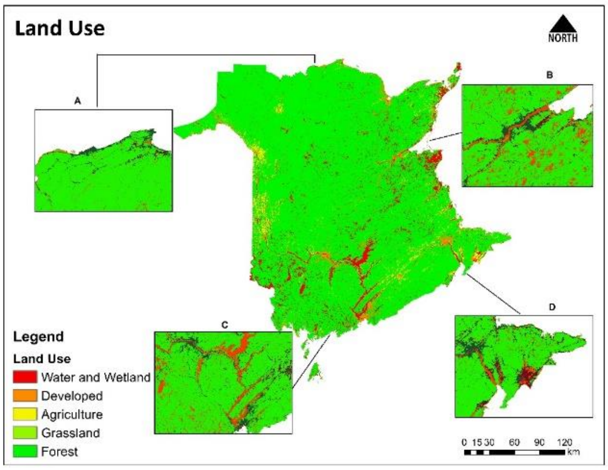

Figure A16. Land Use.

Appendix B

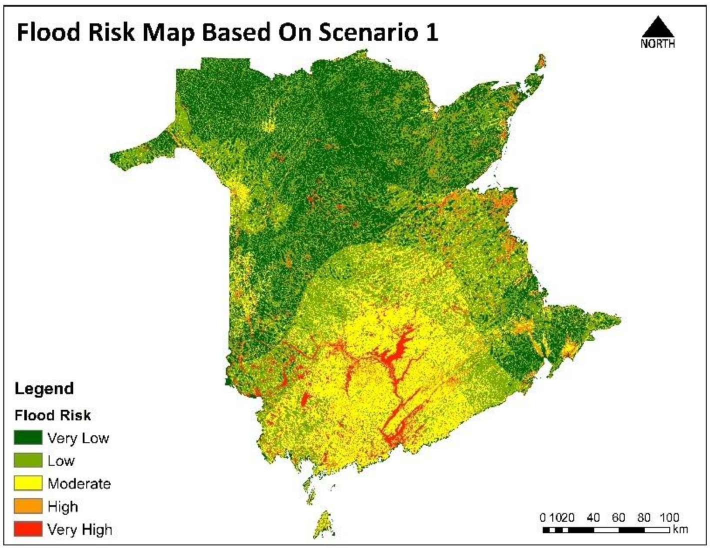

Figure A17. Flood Risk Map Based on Scenario 1.

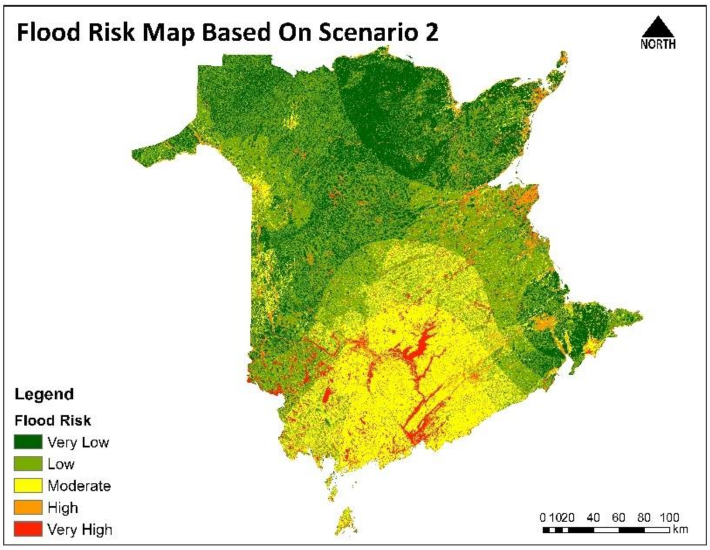

Figure A18. Flood Risk Map Based on Scenario 2.

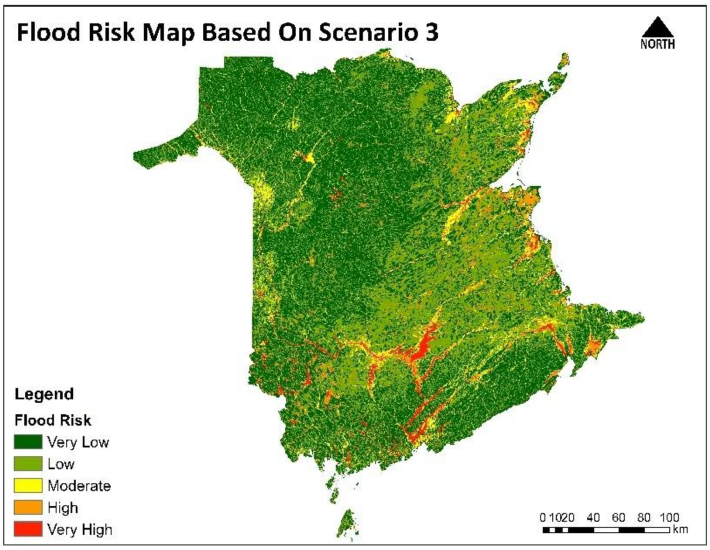

Figure A19. Flood Risk Map Based on Scenario 3.

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