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Leveraging Hazard, Exposure, and Social Vulnerability Data to Assess Flood Risk to Indigenous Communities in Canada

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Accepted: 16 November 2021 / Published online: 10 December 2021
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Abstract This study integrates novel data on 100-year flood hazard extents, exposure of residential properties, and place-based social vulnerability to comprehensively assess and compare flood risk between Indigenous communities living on 985 reserve lands and other Canadian communities across 3701 census subdivisions. National-scale exposure of residential properties to fluvial, pluvial, and coastal flooding was estimated at the 100-year return period. A social vulnerability index (SVI) was developed and included 49 variables from the national census that represent demographic, social, economic, cultural, and infrastructure/community indicators of vulnerability. Geographic information system-based bivariate choropleth mapping of the composite SVI scores and of flood exposure of residential properties and population was completed to assess the spatial variation of flood risk. We found that about 81% of the 985 Indigenous land reserves had some flood exposure that impacted either population or residential properties. Our analysis indicates that residential property-level flood exposure is similar between non-Indigenous and Indigenous communities, but socioeconomic vulnerability is higher on reserve lands, which confirms that the overall

risk of Indigenous communities is higher. Findings suggest the need for more local verification of flood risk in Indigenous communities to address uncertainty in national scale analysis.

Keywords Canada · Flood risk assessment · Indigenous communities · Social vulnerability

1 Introduction

Indigenous communities in Canada, including First Nations, Métis, and Inuit peoples living on- and off-reserve, are often identified as among the populations most socially vulnerable to climate change (Ford 2012). A growing body of research has shown disparities in socioeconomic status of Indigenous populations relative to benchmark populations and other Canadian communities (Hajizadeh et al. 2018). Indigenous disadvantage and marginalization persist in part due to Canada's colonial legacy and the intergenerational effects of residential schools (Reading and Wein 2009). But other factors, such as environmental and social injustice (Thompson 2015) and inequalities in education, employment, and income opportunities (Anderson et al. 2016), are also implicated.

Broader scholarship suggests that persistent social and economic inequalities exacerbate the social vulnerability of marginalized and socially deprived communities (Cutter 1995), which results in greater susceptibility of vulnerable groups to the impacts of environmental hazards (Cutter et al. 2003; Andrey and Jones 2008). Vulnerability to hazards and disasters represents “the degree of potential for loss; the propensity or predisposition to be adversely affected; or circumstances that put people at risk” (Mavhura et al. 2017, p. 104). Research has revealed ways to

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locate and quantify socially vulnerable populations, which have been useful to design targeted risk reduction and awareness building strategies to reduce social vulnerability (Wisner et al. 2004; Arias et al. 2016; Drakes et al. 2021; Tate et al. 2021).

Waldram (1988) argued that Indigenous communities around the world are the most vulnerable to the impacts of flooding, because they have been forced to live on marginal land and in remote locations to make room for settlers. Indeed, a few studies have documented that Canadian Indigenous communities bear significant financial, psychological, and social burdens associated with flooding, and they have been disproportionately affected by flood-related displacement (Thompson et al. 2014; Martin et al. 2017). Moreover, these communities are likely to face greater flood exposure in a changing climate (McNeill et al. 2017; Ford et al. 2018; Khalafzai et al. 2019). To date, however, there has been no comprehensive, national-scale assessment of flood risk to Indigenous communities in Canada that combines hazard and exposure data with a measure of social vulnerability (Patrick 2017; Fayazi et al. 2020). This is unfortunate, because measuring social vulnerability to flooding provides valuable information to support Indigenous emergency management planning, especially under accelerating climate change. Moreover, the geospatial assessment of flood risk provides foundational inputs for the evaluation of flood risk management (FRM) strategies (Koks et al. 2015) and informs culturally appropriate climate change adaptations (McNeeley and Lazrus 2014).

This study is the first to assess place-based social vulnerability and flood exposure for Canadian Indigenous populations living on reserves, including lands classified as “Indian reserves,” “Indian settlements,” and “unorganized territories” across 3701 census subdivisions (CSDs).¹ The purpose is to assess the extents of flood risk to Indigenous communities and to compare this risk to non-Indigenous communities at the national scale. Furthermore, the study contributes to knowledge about socioeconomic factors that contribute to flood risk among First Nations, Métis, and Inuit peoples living on-reserve. This knowledge is critical to identifying socially vulnerable neighborhoods where scarce FRM resources are needed most, and to inform a socially equitable approach to FRM policy (Sayers et al. 2018).

This study considered flood risk to be a product of exposure to flood hazards, combined with social vulnerability to their impacts as advocated by Byers et al. (2018). It analyzed social vulnerability at the Indigenous

community level, where communities were defined based on the boundaries of CSDs in the 2016 census administered by Statistics Canada (2019a). Our social vulnerability index (SVI) was measured by quantifying population subgroups within CSDs that have lower socioeconomic status before floods occur, based on an index of 49 variables. Flood exposure analysis captured the percentage of the population and number of residential properties within a CSD exposed to fluvial, pluvial, or coastal flooding at the 100-year recurrence interval. Geographic information system (GIS)-based bivariate choropleth mapping indicated spatial hotspots of flood risk and delineated location-specific flood disadvantage by revealing neighborhoods that face the greatest flood risk; that is, where high social vulnerability coincides with flood exposure.

2 Data and Methods

This study utilized national datasets of flood hazards, residential properties, census of population, and official community boundaries at the CSD level to identify people and property exposed to flooding across Canada. Table 1 presents the datasets used in this study to identify hazards, estimate exposure, construct the SVI measures, and delineate flood risk at the CSD level.

2.1 Indigenous Peoples and Communities

Census subdivision is the term used by Statistics Canada to reference “municipalities (as determined by provincial/territorial legislation) or areas treated as municipal equivalents for statistical purposes (e.g., Indian reserves, Indian settlements, and unorganized territories)” (Statistics Canada 2018, p. 81). Statistics Canada records a total of 5162 CSDs and categorizes them into 53 types, such as city, rural community, and Indigenous reserve, based on official designations adopted by federal, provincial, and territorial authorities. In Canada, “Indigenous peoples” refers collectively to the original inhabitants of North America and their descendants, who are categorized into three groups of Aboriginal peoples, including Indians (or First Nations), Inuit, and Métis (Crown-Indigenous Relations and Northern Affairs Canada 2017). As the purpose of this study was to estimate flood risk to Indigenous communities and to compare this risk to non-Indigenous communities, the CSDs representing Indigenous communities included “on-reserve” populations legally affiliated with First Nations or Indian bands, living in any of six CSD categories, including Indian reserve/Réserve indienne (IRI), Indian settlement (S-É), Indian government district (IGD), *Terres réservées aux Cris* (TC), *Terres réservées aux Naskapis* (TK), and Nisga’a land (NL) (Fig. 1).

¹ “Residence on or off reserve refers to whether the person’s usual place of residence is in a CSD that is defined as ‘on reserve’ or ‘off reserve’” (Statistics Canada 2018, p. 18).

Table 1 Social and flood datasets used to assess flood risk to Indigenous communities in Canada

Dataset	Format	Purpose	Source
Flood hazard area at 30 m horizontal resolution	Raster datafile (GeoTIFF)	Identify flood hazard extents (for example, 1-in-100-year flood recurrence scenario)	JBA Risk Management (2019, 2020)
Address points of residential properties (counts)	Spatial layer in point shapefile (.shp)	Estimate flood exposure of residential properties	DMTI Spatial Inc. (2018)
Census dissemination block (DB)-level population (counts)	Spatial layer in polygon shapefile (.shp)	Estimate flood exposure of populations	Statistics Canada (2019b)
The 2016 census of population microdata	Stata datafile (.dta)	Construction of the social vulnerability index (SVI)	Statistics Canada (2019c)
The 2016 CSD cartographic boundary	Spatial layer in polygon shapefile (.shp)	Create flood risk maps for Canadian communities at the census subdivision (CSD) level	Statistics Canada (2019d)

Fig. 1 Flood-prone areas in Indigenous reserves as determined by JBA Risk Management (2020). *Source* The 2016 census subdivisions cartographic boundary from Statistics Canada; and the 2018 flood hazard data from JBA Risk Management

The study included flood exposure analysis of population and residential properties for all 985 Indigenous reserve lands of the six CSD types from the total 5162 CSDs. Due to Statistics Canada's confidentiality regulations concerning geographic and population thresholds for statistical output vetting, the SVI scores were available for

only 360 of the 985 Indigenous reserves. Considering a national scale socioeconomic vulnerability assessment of on-reserve Indigenous communities, the unavailability of microdata on remaining reserves may underestimate or overestimate SVI scores. Hence, the results of relative

vulnerability scores across Indigenous reserves should be interpreted carefully.

2.2 Flood Hazard Areas

The study analyzed undefended, flood-prone areas for three types of flood hazards: fluvial (riverine and ice-jam overall), pluvial (intense precipitation-caused inundation of lands that are not necessarily proximate to a body of water), and coastal (storm surge), as determined by JBA Risk Management, a global, market-leading flood catastrophe modeling firm. JBA Risk Management (JBA)'s 2018 flood hazard datasets (that is, Canada Flood Maps at 30-meter horizontal resolution) were made available through a research partnership with the University of Waterloo. These Canada Flood Maps, the most widely used in the Canadian (re)insurance market, are national in scope, so they enable flood hazard assessment at any location in Canada (JBA Risk Management 2020).

Indigenous communities are located across the country, which justifies the use of JBA's datasets since JBA possesses the only map resource available at a national scale that is independent of political, jurisdictional, or land-claim considerations. Although a national scale dataset is required to ensure coverage of all Canadian Indigenous communities, it is important to note several limitations. Flood inundation modeling in Canada at a national scale involves tremendous uncertainty given the dynamic range of geography, topography, and available data inputs. Most Canadian flood hazard assessments are conducted at the provincial, local, or watershed scale where more precise measurement is possible (Faulkner et al. 2016). For example, several uncertainties in the flood model used for the study's maps limit the accuracy of local scale determinations of flood risk. These uncertainties include a 30-meter resolution, a lack of data on pluvial flood defences (for example, storm sewer capacity), and insufficient gauge and HYDAT (National Water Data Archive-Canada) data proximate to Indigenous communities. The latter uncertainty is a particularly important limitation since Canada has many lakes that remain ungauged relative to other countries and Indigenous communities are often located near these lakes. For this reason, the use of these data is considered an initial assessment that with further local validation can be used alongside socioeconomic vulnerability to improve flood risk assessment of Indigenous communities.

The geospatial analysis in this study focused on the 100-year return period—a flood that has a 1-in-100 (1%) probability of occurring in any given year—and assumed no defences for fluvial flooding or coastal flooding. The 100-year flood is the generally accepted regulatory standard for most of Canada, which is also commonly used in

flood hazard research and policy documents (Burton and Cutter 2008; Ludy and Kondolf 2012; Burn et al. 2016). Pluvial flooding was modeled using a direct rainfall method whereby Canadian intensity-duration-frequency curves were used to estimate rainfall and then applied to model cells before runoff was calculated using a hydraulic model (Hall 2015).

JBA's flood hazard extent datasets (in raster GIS file format) were first imported into ArcMap 10.7.1 to visualize flood-prone areas (Fig. 1). Statistics Canada's spatial layers of the 2016 CSD-level boundaries (in polygon shapefile) were added to visualize the hazard and exposure, and to generate flood risk maps for Indigenous and other Canadian communities measured at the CSD level. Figure 1 shows spatial delineation of flood-prone areas in Indigenous reserve lands (for example, Nisga's NL, Mistissini TC, and Blood 148 IRI) that are subject to fluvial, pluvial, and coastal flood hazards.

2.3 Calculating Flood Exposure of Population and Residential Properties

Physical exposure refers to the people and assets, including residential properties and critical infrastructure, that are likely to be affected by a hazard (UNDP 2004). Flood exposure is typically measured by identifying and quantifying the people and assets that would be affected by a flood of a particular size, such as the 100-year flood (Holmes and Dinicola 2010). Following the methods of Qiang (2019), our study estimated flood exposure using population and residential properties, which involved three phases. First, we calculated the total number of people and residential properties within each dissemination block (DB), the smallest geographic unit used by Statistics Canada to disseminate population and dwelling counts, which refers to "an area bounded on all sides by roads and/or boundaries of standard geographic areas" (Statistics Canada 2018, p. 90). We then aggregated the DB-level totals to the CSD level, and finally, calculated the percentage of the population and number of residential properties (as described in Eqs. 1 and 2) and spatially combined them with the 100-year flood hazard extents at the CSD level.

$$\begin{aligned} \%Population\ Exposed\ to\ Flood_{CSD} &= \frac{Number\ of\ Population\ Exposed\ to\ Flood_{CSD}}{Total\ Population_{CSD}} \end{aligned} \quad (1)$$

$$\begin{aligned} \%Residential\ Properties\ Exposed\ to\ Flood_{CSD} &= \frac{Number\ of\ Residential\ Properties\ Exposed\ to\ Flood_{CSD}}{Total\ Residential\ Properties_{CSD}} \end{aligned} \quad (2)$$

To calculate the total number of residential properties located within each DB, Statistics Canada's 2016 DB boundary data were spatially joined with the national address points dataset on "residential properties (count)" (spatial layer in point shapefile) from DMTI Spatial Inc., Canada's leader with renowned expertise in location analytics and intelligence solutions (DMTI Spatial Inc. 2018). Using the 2016 census, each DB was also paired with its respective population count. The points dataset contained about 15.9 million addresses in Canada, including industrial, commercial, and residential addresses, but only the approximately 11 million residential address points were included as part of this analysis. A 15-meter buffer was generated for all the residential properties in the absence of building footprint data for residential property point locations. Using the output buffer polygons of residential properties, a binary analysis (that is, yes = 1; no = 0) was used to indicate whether properties intersected with the flood hazard extent.

The roughly 11 million residential address points were spatially joined with their respective DBs, and these were aggregated to the CSD level. An address point represented a single unit (for example, apartment, unit), so there were cases in which multiple addresses were present in the same geographic location (for example, a condominium building). The majority of the CSDs had at least one residential property, but 1730 of the 5162 CSDs did not intersect with any residential addresses. We calculated the total number of residential properties on Indigenous reserve lands (that is, 24,020 properties located among 260 reserve lands) by creating a binary flag to distinguish the CSDs that were recorded by Statistics Canada as reserves (that is, the six Indigenous CSD types noted above) with a "1" and non-reserves (that is, the other 47 CSD types) with a "0."

The analysis determined that 4869 of the 5162 populated CSDs were exposed to the 100-year flood hazard. To estimate the exposed population, we multiplied the exposed land area by the population density (that is, number of people per square kilometer) for each DB and then aggregated that population count at the CSD level. The study determined that about 5.2 million of the total 35.2 million population was exposed to flood hazard across 4702 CSDs, compared to 56,646 of the total 382,587 population exposed across 787 Indigenous reserve lands.

It is important to note some of the uncertainty associated with this exposure analysis due to limitations in the dataset. Exposure is likely to be overestimated in some areas since the hazard is measured at 30 meters and buildings without footprints were assigned 15-meter buffers. As a result, the assessment captures more property within flood risk zones than with maps using a higher resolution (for example, 5 meter). The decision to include these properties was based

on the need to take a conservative and comprehensive assessment of exposure. Recent analysis in Halifax, Canada did confirm that the 30-meter resolution 100-year flood map aligned with local maps, but a more rigorous validation is necessary using multiple communities (Thistlethwaite et al. 2018). Furthermore, some overestimation occurred because the exposure data do not differentiate whether an address is on the ground floor of multi-unit buildings. As a result, all addresses in these buildings were included even if they were on different floors to ensure all potential exposure was captured.

2.4 Measuring Social Vulnerability

The study used microdata from the 2016 census to populate an index of 49 context-specific variables that have been used frequently in previous empirical studies to measure social vulnerability to floods and other hazards (Cutter et al. 2003; Messer et al. 2006; Oulahan, Mortsch et al. 2015; Oulahan, Shrubsole et al. 2015; Fatemi et al. 2017). These variables, which were extracted at the CSD level, represented diverse aspects of socioeconomic, demographic, ethnic, and cultural characteristics (Table 2). Before constructing the index, we removed CSDs that did not comply with Statistics Canada's census data analysis guidelines, statistical output vetting rules (for example, confidential homogeneity rule and dominance rule for dollar value variables such as household income and owner estimated home values), and a geographical requirement (for example, CSDs containing less than 250 population and 40 households).

The study used Principal Components Analysis (PCA) to construct the SVI, following the "hazard-of-place" model to measure neighborhood-level relative social vulnerability (Cutter et al. 2003). We also used PCA diagnostics tests such as the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (Kaiser 1974), Bartlett's Test of Sphericity (Bartlett 1954), and Cronbach's alpha (α) coefficient (Cronbach 1951) to examine multicollinearity problems, validity, and reliability of the dataset. As our data passed all three diagnostics tests, we applied PCA with varimax rotation to all standardized variables for extracting orthogonal components. The number of components were then selected using Cattell's (1966) scree plot (Fig. 2).

A directional adjustment (or cardinality) was applied to the components that had positive loading scores on the indicators of income and wealth (such as median per capita income of component 1 and median home value of component 3 in Table 3). Theoretically, a wealth indicator decreases vulnerability (negative cardinality), so the component scores on that dimension were inverted (Cutter et al. 2003; Cutter et al. 2013). The component scores were then

Table 2 Social vulnerability index (SVI) factors/components and description of variables

Factor (group)	SVI Indicator (subgroups)	Variable	Description
Demographic	Special Needs Population/ Coping Ability	Female	Female
		Age	Median age
		Senior	Age 65 and above
		Children under 5 years of age	Age below 5 years
		Children under 15 years of age	Age under 15 years
		Psychological disability	Population with activity limitations due to emotional, psychological, or mental health conditions
Social	Household/Family Arrangement	Physical disability	Population with difficulty seeing, hearing, walking, using stairs, using hands or fingers, or doing other physical activities
		Unattached one-person household	Living alone with separated, divorced, or widowed status
		Unattached elderly	Age 65 and above and living alone
		Lone parents	Lone parent families
		More than three children in a family	Marries and having 3 or more children
		Household size	Average number of people per household
		Official language knowledge	No knowledge of the official language in either French or English
		English/French	English or French ethnic background
		No certificate/diploma	Age 15 or older with no certificate/diploma/degree
		Post-secondary certificate	College diploma/trade certificate/university certificate at bachelor level or above
Cultural	Race, Ethnicity, and Visible Minority ^a	First-generation status ^b	First-generation status
		Foreign-born Canadian citizens	Canadian citizens not by birth
		Aboriginal Peoples ^c	Aboriginal Peoples ethnic background
		Indian/Inuit/Métis	North American Indian/Inuit/Métis ethnic background
		Year of immigration	Recently immigrated (between 2010 and 2016)
		White	White
		Black	Black
		South Asian	South Asian
		Chinese	Chinese
		Filipino	Filipino
		Latin American	Latin American

Table 2 continued

Factor (group)	SVI Indicator (subgroups)	Variable	Description
Economic	Access to Financial Resources/Wealth	Shelter-cost-to-income ratio	Shelter-cost-to-income ratio of over 30%
		Government transfer	Receipt of government transfers
		Low income	Annual family income less than \$30,000
		Dwelling value ^d	Median per capita home value (owner-estimated) as a proxy for per capita wealth
		Income ^e	Median per capita income of census family for all persons aged 15 or older
		Occupation in Management	Management occupations
		Occupation in Business, finance & administration	Business, finance, and administration occupations
		Occupation in Health	Health occupations
		Occupation in Education, law, social, community & govt service	Education, law, social, community, and government services occupations
		Occupation in Sales and service	Sales and service occupations
		Unemployed	Unemployed, including experienced, inexperienced, and temporary layoff
		Female labor force participation	Working-age females aged 15 or above participating in the labor force
		Not in the labor force	Male not in the labor force
		Crowded home	Not living in suitable accommodations according to the National Occupancy Standard (NOS)
Infrastructure/community	Built Environment/Accessibility	Period of home construction	Living in buildings or dwellings built before 1970
		Dwelling is in apartment with 5+ stories, built before 1980	Living in apartments of a building that has five or more stories constructed before 1980
		Renters	Occupying a rental, private dwelling
		No private vehicle/Public transit	Primary mode of transportation is public transit such as bus, subway, ferry
		Population density (urban/rural)	Living in medium and large urban population centers, with a census population of 100,000 or more—percent urban population
		Mobility	Place of residence in the same CSD but different dwelling a year ago (in 2015)
		Dwelling size	Average number of rooms per dwelling
		House with major repair	Living in private dwellings in need of major repair

^aThe *Employment Equity Act* defines visible minorities as “persons, other than Aboriginal peoples, who are non-Caucasian in race or non-white in colour” (Statistics Canada 2018, p. 151)

^bFirst-generation includes “persons who were born outside Canada” and typically refers to those people “who are now, or once were, immigrants to Canada” (Statistics Canada 2018, p. 143)

^cAboriginal identity includes persons who are “First Nations (North American Indian), Métis or Inuk (Inuit) and/or those who are Registered or Treaty Indians (that is, registered under the *Indian Act* of Canada) and/or those who have membership in a First Nation or Indian band. Aboriginal peoples of Canada are defined in the *Constitution Act*, 1982, section 35(2) as including the Indian, Inuit and Métis peoples of Canada” (Statistics Canada 2018, p. 14)

^dValues for tenant-occupied dwelling, band housing, and farm dwelling were excluded from dwelling value variable and replaced with median (owner-estimated) home value of dwellings of all census tracts

^eNegative reported household income (that is, loss of income) values were omitted and replaced with a median income of Census families of all census tracts to normalize the dollar value variable after removing outliers

Fig. 2 Scree plot of eigenvalues of components. *CI* confidence interval

weighted and added to generate a non-standardized SVI for each CSD j ($NSSI_j$), where weights were calculated as follows:

$$W_i = \frac{\text{Proportion of Variance for Factor}_i}{\text{Total Variance Explained}}; \quad (3)$$

$$i = 1, 2, \dots, 10$$

Since the values of the $NSSI_j$ index can be negative or positive, making it difficult to interpret and compare the scores by CSDs, a standardized SVI was developed. The values of SVI ranged on a scale of 0 to 100, and they were calculated using the following formula for each CSD j (Chakraborty et al. 2020):

$$SVI_j = \frac{NSSI_j - NSSI_{\text{Minimum}}}{(NSSI_{\text{Maximum}} - NSSI_{\text{Minimum}})} \times 100 \quad (4)$$

The SVI scores were reversed for ease of interpretation and comparison between CSD-level communities, such that a CSD with higher SVI score represented a better socioeconomic status and lower social vulnerability to environmental hazards (Chan et al. 2015). The spatial distribution of social vulnerability was visualized through GIS-based choropleth mapping, by joining the SVI scores to the 2016 CSD level cartographic boundary.

2.5 Assessing Flood Risk

The study assessed flood risk at the CSD level for Indigenous and other communities across Canada by identifying the spatial intersection of the 100-year flood hazard extents, exposure of residential properties and population, and social vulnerability. This method is more comprehensive than those typically applied in the hazard and disaster risk management literature (Albano et al. 2017; Armenakis et al. 2017). By following a GIS-based bivariate choropleth mapping technique (Frigerio et al.

2016), we developed a flood risk assessment matrix (Fig. 3).

The matrix depicts a spatial relationship between social vulnerability (that is, proportion of CSD-level inverted SVI scores) and flood exposure of residential properties and population. To represent the spatial distribution of flood risk, the inverted SVI scores, exposure of residential properties (in percentage), and exposure of population (in percentage) were classified into five categories, including Very Low, Low, Moderate, High, and Very High. The SVI scores were divided using the Jenks natural breaks classification method, which is also known as the goodness of variance fit. By minimizing the squared deviations of the class means, the method seeks to reduce the variance within classes and maximize the variance between them (Jenks 1967). The exposure variables were classified using the “quantile (equal count)” scheme. Finally, flood risk maps for all CSDs were generated to identify “hotspots” across Canadian provinces, meaning those CSDs with both a high level of social vulnerability and high exposure of residential properties and population to 100-year flood hazards.

3 Results

A statistical summary of GIS-based flood exposure results was reported in Sect. 3.1, whereas PCA-based statistical summary results of SVI indicators and geographic patterns of social vulnerability were evaluated and compared by communities in Sect. 3.2. Finally, the results of social vulnerability and flood exposure of residential properties and population were spatially combined at the CSD level using GIS-based classification (described in Fig. 3) to comprehensively assess flood risk in Sect. 3.3.

3.1 Flood Exposure

The study found that 80.7% of the 985 Indigenous reserves have some flood exposure in terms of either population or residential properties at the 100-year return period. Indigenous communities in the 985 reserve CSDs have a slightly higher percentage of population exposed to 100-year flood hazards (14.8%) than other Canadian communities (14.7%). In terms of population exposure, we found that almost 98.3% of the 809 populated Indigenous reserve CSDs were exposed to some of the three types of flood hazards. The study also estimated 66.5% of the total 260 Indigenous reserve CSDs have some flood exposure of residential properties.

At the provincial scale, Indigenous peoples in Prince Edward Island (PE) have the highest flood exposure (Fig. 4). Manitoba has the highest percentage of total

Table 3 Principal Components Analysis results: Rotated component matrix

Variable ^a /indicator	Component									
	1	2	3	4	5	6	7	8	9	10
ZPFEMALE					0.40					0.31
ZFEMLFRATE										0.41
ZPAG15UN		− 0.35								
ZPAG5UN		− 0.37								
ZPDISABLE1							0.61			
ZPDISABLE2							0.61			
ZPCHILD3OVER						0.43				
ZPONEPERHH					0.44					
ZPUNATTELDER					0.47					
ZPNOLANG				0.51						
ZPRECIMMI									0.57	
ZPWHITE	− 0.31									
ZPBLACK								0.44		
ZPCHINESE				0.40						
ZPFILIPINO									0.67	
ZPLATINAME ~ A								0.33		
ZPABORIGIN	0.31									
ZPINDINUTM ~ S	0.30									
ZPNOHIGHEDU			− 0.41							
ZPOSTSECOND			0.38							
ZPHOMETYPE								0.43		
ZPTRANSPUB								0.31		
ZPOCCMGT						0.46				
ZPOCCBUSFIN			0.32							
ZPOCCEDUC										0.36
ZPOCCSALES						− 0.37				0.32
ZPUNEMPLOYED		0.32	− 0.37							
ZPMALENOLFS										− 0.33
ZPURBANPOP								0.42		
ZMEDAGE		0.32								
ZPERCAPINC	0.31									
ZPERCAPHOM ~ L			0.40							
ZDWELSIZE						0.33				
Total variance (%)	18.0	9.6	6.8	6.3	6.2	5.7	5.4	5.3	4.9	4.8

Varimax rotation with Kaiser normalization

^aA variable with a positive loading score suggests a negative association to the corresponding component (Cutter et al. 2003).

population (49.8% of the total 1,278,365) exposed to 100-year flood hazards. Manitoba also has the highest proportion of non-Indigenous population (51.8%) exposed to flooding, but this includes all of its largest city, Winnipeg, which is protected by the Red River Floodway, a 47-kilometer diversion channel that was built to accommodate 100-year riverine flooding. British Columbia has the second highest percentage of population exposed to

flooding, in both cases of Indigenous and non-Indigenous communities.

The analysis revealed that residential flood hazard exposure is similar between Indigenous communities (21.5% of 24,020 properties) and other Canadian communities (19.1% of 11,025,746 properties). Comparing provinces, more than 80% of on-reserve residential properties in Alberta are exposed to flooding, which is the highest proportion among all Canadian provinces and territories

Fig. 3 Flood risk matrix comparing social vulnerability and flood exposure extents

		Social Vulnerability (SVI scores)				
		Very Low (A)	Low (B)	Moderate (C)	High (D)	Very High (E)
Flood Exposure (% of residential properties exposed to flood hazard) (% of residential properties exposed to flood hazard)	Very Low (1)					
	Low (2)					
	Moderate (3)					
	High (4)					
	Very High (5)

Fig. 4 Population at-risk of flood hazards by province/territory in Canada. *AB* Alberta, *BC* British Columbia, *MB* Manitoba, *NB* New Brunswick, *NL* Newfoundland and Labrador, *NS* Nova Scotia, *NT*

Northwest Territories, *NU* Nunavut, *ON* Ontario, *PE* Prince Edward Island, *QC* Quebec, *SK* Saskatchewan, *YT* Yukon

(Fig. 5). Manitoba has the highest percentage of total residential properties (62.7% of the total 323,926) exposed to flooding. Although Prince Edward Island has the lowest

percentage (11.7% of the total 30,210) of its residential properties exposed to flooding across Canada, it has the second highest percentage of residential properties (41.9%

Fig. 5 Residential properties at-risk of flood hazards by province/territory in Canada. *AB* Alberta, *BC* British Columbia, *MB* Manitoba, *NB* New Brunswick, *NL* Newfoundland and Labrador, *NS* Nova

Scotia, *NT* Northwest Territories, *NU* Nunavut, *ON* Ontario, *PE* Prince Edward Island, *QC* Quebec, *SK* Saskatchewan, *YT* Yukon

of the total 31) exposed to flooding considering only Indigenous reserve communities.

To visualize spatial variation of flood exposure of residential properties through geospatial mapping, we categorized the total number of residential properties exposed to fluvial, pluvial, and coastal flood hazards into five categories based on an “equal count quantile” classification scheme. These categories included Very Low (less than 3.1% of residential properties exposed at the CSD level), Low (between 3.1 and 8.3%), Moderate (between 8.4 and 14.1%), High (between 14.2 and 22.2%), and Very High (more than 22.2%). The same “equal count quantile” classification scheme was applied for mapping population exposure to flooding, and the total population exposed to 100-year flood hazards was divided into five categories, including: Very Low (less than 4.7%), Low (between 4.7 and 8.4%), Moderate (between 8.5 and 11.8%), High (between 11.9 and 16.5%), and Very High (more than 16.5%).

3.2 Social Vulnerability Index Indicators

Principal Components Analysis with orthogonal varimax rotation and eigenvalues of greater than 1 have identified ten multidimensional components based on our data. These components explain 72.9% of the total variation. Table 3 reports component loading scores on individual variables. Findings suggest that 33 of the 49 sociodemographic indicators represent close membership of social vulnerability.

The first component accounts for 18.1% of the total variation in the data, where the proportion of population with Aboriginal Peoples (ZPABORIGIN), North American

Indian/Inuit/Métis (ZPINDINUTM~S), and median per capita income of census family (ZPERCAPINC) show positive loadings and the proportion of white population (ZPWHITE) show negative loading scores. Hence, the first component represents a combination of cultural and economic factors with racial/ethnic characteristics of the Canadian population, including Indigenous peoples and communities, which is a strong indicator of social vulnerability. Variable loading scores in the second component, with 9.6% variation in the data, represent both demographic and economic factors of social vulnerability, whereas the third component, with 6.8% variation in the data, represents a combination of social and economic factors of vulnerability.

We interpret each component listed in Table 3 based on the SVI indicators and factors of social vulnerability group membership as described in Table 2. For example, component seven can be interpreted as a pure demographic factor, describing the SVI indicators of a special needs population; component eight as a mixed factor of cultural and infrastructural/community membership, listing racial/ethnic and built environment characteristics of populations; and component nine as a pure cultural factor, reporting racial/ethnic indicators of vulnerability and so on. Overall, we find that the components of SVI are multidimensional in Canada.

3.2.1 Patterns of SVI

By joining the SVI scores with the 2016 census subdivisions and provincial/territorial cartographic boundary files, we produced a GIS-based choropleth map to visualize

national-scale socioeconomic disparities and the extents of social vulnerability across CSDs. Using the equal count (quantile) classification method, we divided the SVI scores into five categories, including Very Low, Low, Moderate, High, and Very High. We used graduated classification along with spectral color ramping to display spatial patterns of social vulnerability in an inverted color ramp such that a higher SVI score indicates lower social vulnerability in a CSD (as indicated in the map legend of Fig. 6). For more visual clarity, we mapped social vulnerability and flood exposure, and combined these variables to produce flood risk maps for three adjacent provinces in Canada.

By ranking and comparing mean SVI scores, we determined that Indigenous peoples living on reserve lands are more socially vulnerable than inhabitants of other Canadian communities (Fig. 7; Table 4). This difference is reflected via lower mean SVI scores for Indigenous reserve communities in all Canadian provinces and territories, except for Yukon and Nunavut territories in which SVI scores are unavailable (Fig. 7). The SVI scores for all CSDs were also ranked according to their level of social

vulnerability, and Table 4 displays the 10 most socially vulnerable CSDs. The ranking value of “1” in Table 4 suggests highest vulnerability (that is, lowest SVI score) for a CSD.

3.3 Combining Social Vulnerability and Flood Exposure to Assess Flood Risk

We combined high flood exposure of residential properties and population with the high vulnerability of the human environment, resulting in a critical assessment of the place-based “social risk” of flooding (Roder et al. 2017). The most socially vulnerable areas (that is, red colored geographical areas in Fig. 6) were spatially combined with the areas with Very High flood exposure of residential properties (that is, red colored geographical areas in Fig. 8a) and Very High flood exposure of population (that is, red colored geographical areas in Fig. 8b) to delineate hotspots of flood risk across Indigenous communities and other Canadian communities (for example, dark red and black colored geographical areas in Fig. 8c, d). Due to limited

Fig. 6 Spatial distribution of the Social Vulnerability Index at the census subdivisions level. *Source* The 2016 census of population microdata; Census subdivisions cartographic boundary; Statistics Canada

Fig. 7 Comparison of the mean SVI scores by communities (SES = socioeconomic status). *AB* Alberta, *BC* British Columbia, *MB* Manitoba, *NB* New Brunswick, *NL* Newfoundland and Labrador, *NS* Nova Scotia, *NT* Northwest Territories, *NU* Nunavut, *ON* Ontario, *PE* Prince Edward Island, *QC* Quebec, *SK* Saskatchewan, *YT* Yukon

Table 4 The ten most socially vulnerable communities

Indigenous reserve communities					Other Canadian communities				
Rank	CSDUID	CSD name	Province/territory	SVI score	Rank	CSDUID	CSD name	Province/territory	SVI score
1	4623071	Shamattawa 1	Manitoba	7.6	1	4816051	Improvement District No. 24 Wood Buffalo	Alberta	10.7
2	4811802	Pigeon Lake 138A	Alberta	9.9	2	4718074	La Loche	Saskatchewan	11.0
3	2498806	Natashquan	Quebec	12.2	3	6208081	Gjoa Haven	Nunavut	11.1
4	1217020	Eskasoni 3	Nova Scotia	13.5	4	6205027	Naujaat	Nunavut	11.9
5	1215008	Whycocomagh 2	Nova Scotia	15.6	5	6103031	Behchokò	Northwest Territories	12.3
6	2462802	Manawan	Quebec	15.6	6	6208047	Kugaaruk	Nunavut	13.3
7	2497804	Maliotenam	Quebec	16.2	7	6204001	Sanikiluaq	Nunavut	13.4
8	1208014	Indian Brook 14	Nova Scotia	16.5	8	6208087	Taloyoak	Nunavut	13.5
9	2498808	Mingan	Quebec	16.5	9	4718065	Pinehouse	Saskatchewan	15.0
10	5919822	Cowichan	British Columbia	18.4	10	6205016	Whale Cove	Nunavut	15.5

CSDUID = Census Subdivision Unique Identifiers; SVI = Social Vulnerability Index

space, we created flood risk maps for three adjoining Canadian provinces only (Ontario, Manitoba, and Saskatchewan). This GIS-based bivariate choropleth mapping procedure permitted us to assess flood risk by visualizing the relationship between social vulnerability and flood hazard exposure across 3701 CSDs. The spatial integration

method also allowed for detection of the hotspots of flood risk in Canada (Table 5)—CSDs with elevated 100-year flood hazard exposure and elevated social vulnerability—which highlights the distribution of the highest-risk CSDs and provinces/territories.

Fig. 8 Delineation of flood risk maps for Manitoba, Ontario, and Saskatchewan. *Source* The 2016 census of population microdata; Census subdivisions cartographic boundary; Statistics Canada; The

2018 Canada flood map and pricing data; JBA Risk Management; The 2018 DMTI CanMap Route Logistics; DMTI Spatial Inc

The study found that 41 of 3701 CSDs are located in the range of High to Very High risk of flooding (Table 5). There are only five CSDs in areas with Very High flood risk (with 20.8–29.4% of population and 30.9–66.7% of residential properties exposed to flooding, and a score of 7.6–18.4 on the SVI). Most importantly, all high-risk CSDs are located in Indian reserve/Réserve indienne (IRI) areas except the Carmacks village (VL) in the Yukon. At the national scale, 40 hotspot areas among the 360 Indigenous reserves are geographically stratified across eight provinces, including Alberta, British Columbia, Manitoba, New Brunswick, Nova Scotia, Ontario, Prince Edward Island, and Quebec. Among all provinces, the highest number of hotspots were found in British Columbia (13 IRI) and in Ontario (10 IRI). Although flood risk and its extents appear to be distributed unequally in terms of flood exposure and social vulnerability at the national scale, no hotspots were located in Saskatchewan, Newfoundland and Labrador, the Northwest Territories, and Nunavut. Overall,

flood exposure is similar between non-Indigenous and Indigenous communities, but social vulnerability is higher on reserve lands, which confirms that the overall risk of Indigenous communities is higher.

4 Implications for Flood Risk Management Policy in Canada

The results of this study emphasize that both flood exposure and social vulnerability have considerable spatial variation, which contributes to a heterogeneous pattern of flood risk across Canada. Our findings show that Indigenous peoples living on reserve face a higher flood risk than the general population, due to higher social vulnerability. This suggests that policymakers must consider the spatial pattern of socioeconomic vulnerability in the design of flood risk management (FRM) strategies to optimize the allocation of scarce resources (Koks et al. 2015). Many

Table 5 Hotspots of flood risk in Manitoba, Alberta, Nova Scotia, Quebec, and British Columbia

CSDUID	CSD name	CSD type	Province	Population exposed (%)	Residential properties exposed (%)	SVI score	Population exposure class	Residential properties exposure class	SVI class
4623071	Shamattawa 1	IRI	Manitoba	22.3	64.3	7.6	5	5	E
4811802	Pigeon Lake 138A	IRI	Alberta	25.0	66.7	9.9	5	5	E
1215008	Whycocomagh 2	IRI	Nova Scotia	20.8	31.6	15.6	5	5	E
2498808	Mingan	IRI	Quebec	21.7	31.5	16.5	5	5	E
5919822	Cowichan	IRI	British Columbia	29.4	30.9	18.4	5	5	E

CSDUID = Census Subdivision Unique Identifiers; SVI = Social Vulnerability Index; IRI = Indian reserve/Réserve Indienne

scholars have argued that development of comprehensive risk maps by combining measures of hazard exposure and social vulnerability is an essential step towards efficient and effective resource allocation, which will ensure flood mitigation measures are implemented where they are needed most (Tapsell et al. 2010).

The SVI developed in this study can be used to locate geographical areas with high concentrations of socially vulnerable groups and their relevant socioeconomic, demographic, cultural, and built environment characteristics. This method can further guide flood risk communication to spur household preparedness, risk awareness, and risk reduction (Cutter et al. 2013). Creating a knowledge base of place-based social vulnerability would be a valuable policy and planning tool to increase flood risk awareness and flood preparedness programs, because those who are aware of the risks are more likely to invest in flood mitigation measures (Kuhlicke et al. 2011). By using the SVI, FRM policies could be tailored to enhance community resilience that ultimately increases people's capacity to resist, cope with, and recover from the impacts of flooding (Thieken et al. 2007).

Tailored flood risk reduction policies based on the SVI offer greater fairness in line with principles of environmental justice, and can guide practical and economically efficient investments in integrated FRM (Sayers et al. 2018). Although our findings, along with the risk mapping approach developed in the current study, have identified high-risk communities and the most socially vulnerable places across Canada, it is critically important to adopt a portfolio of policy instruments, such as flood mitigation measures, regulations, economic incentives, and comprehensive geospatial data analysis, in order to reduce flood risk to Indigenous peoples (Hegger et al. 2018).

5 Discussion and Conclusion

The aim of this study was to explore the attributes and spatial patterns of social vulnerability and flood exposure for on-reserve Indigenous communities versus other Canadian communities at the municipal (CSD) scale in order to support community-based flood risk analysis. The study confirmed that using novel data about the flood risk exposure and vulnerability of Indigenous communities can be measured at a national scale in Canada. This finding justifies a focus on Indigenous communities in Canada's approach to FRM and provides a method for assessing how resources should be prioritized according to risk.

Our findings indicate that the factors influencing social vulnerability in Canadian communities include attributes of race and ethnicity, income, built environment, elderly populations, education, occupation, family structure, and access to resources. Our findings are congruent with the conclusion of previous studies, government reports, and briefings, and affirm community-based case studies on flood risk and exposure, which show Indigenous people living in vulnerable communities experience greater environmental risk (Thompson 2015; McNeill et al. 2017). This study also finds an unequal spatial pattern of social vulnerability and flood exposure across communities, which contributes to systemic flood disadvantages, the heterogeneous nature of flood risk, and the differential impact of flooding on Canadian society as a whole. The spatial analysis method developed here and the results that it produced are useful for systemic spatial planning, identify suitable flood mitigation measures, and facilitate community-level risk financing (Linnerooth-Bayer and Hochrainer-Stigler 2015).

The flood risk analysis presented in this article has a few limitations that should be acknowledged. First, the study used a flood hazards dataset from JBA Risk Management

because it is the only national-scale flood hazards dataset available for Canada. There is bound to be tremendous uncertainty in flood exposure analysis, particularly when scaling to local levels. A potential disagreement between the flood risk exposure identified through the JBA model and flood exposures measured through other means or based on a local dataset could justify more future research. The exposure analysis did not include estimates of physical vulnerabilities consistent with actual flood damage and depth analysis. As a result, some sites of cultural significance without physical structures in Indigenous communities are excluded.

Second, the study was unable to “ground-truth” exposure and vulnerability due to a lack of pre-event and post-event data. Absence of field work limited access to local information related to exposure and vulnerability that might be collected only through site visits and qualitative survey methods (Oulahen, Shrubsole et al. 2015). It is particularly important to address data gaps for ungauged waterbodies. This gap contributes to uncertainty in the JBA dataset assumptions given the lack of a developed methodology for measuring how ungauged lakes contribute to 100-year flood plain predictions. For this reason, an important recommendation for future work involves improving assessment of flood risk associated with ungauged lakes near Indigenous communities, and how proximity to these lakes influences exposure. We have also explored the feasibility of mapping and measuring Indigenous proximity to lakes. Due to time and the additional analysis required, this area warrants a future paper focusing on uncertainty associated with Canada’s national-scale flood models.

Finally, JBA’s Canada Flood Map hydrology datasets are based on historical data that do not incorporate future climate change projections. Further research should assess future flood risk by integrating climate change scenarios in flood exposure analysis and climate change vulnerability index development (Debortoli et al. 2019). Moreover, developing community-based flood mitigation strategies that incorporate socioeconomic and cultural considerations should be the key agenda for future research, and become a means to promote fairness and social equity in flood risk management.

Acknowledgements Social vulnerability analysis as presented in this article was conducted at the South-Western Ontario Research Data Centre (SWORDC) – a part of the Canadian Research Data Centre Network (CRDCN). The services and activities of SWORDC are made possible by the financial or in-kind support of the Social Sciences and Humanities Research Council of Canada, the Canadian Institutes of Health Research, the Canadian Foundation for Innovation, Statistics Canada, and the University of Waterloo. The views expressed in this article do not necessarily represent those of the CRDCN or its partners. Flood hazard data © JBA Risk Management 2018. Residential housing stock data © DMTI Spatial Inc. 2018.

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