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FLOOD RISK ASSESSMENT IN CANADA: ISSUES OF PURPOSE, SCALE, AND TOPOGRAPHY

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Abstract: Flood risk assessment in Canada is a top priority in both science and policy agendas. Fluvial and pluvial flood assessment, which is the focus of this paper, requires reliable flood mapping in Canada, which in turn raises issues regarding purpose, scale, and topography. Large scale planning of developments, landuse change and zoning, or specific engineering design are examples of different purposes that require different scales for flood mapping. The different topographies across Canada also dictates different approaches for flood modeling and mapping. A national flood risk assessment in Canada, using fine resolution global and national datasets, is presented. A national flood hazard map is prepared using a 20m resolution DEM to identify, for each pixel, the distance from and the height above the nearest river. An exposure map is prepared by using landuse and the satellite-based nightlight data to determine the value of each pixel. A national economic flood risk map is then produced, and subsequently overlaid with population density information to produce a socioeconomic flood risk map for Canada. At local scale, where more detailed flood hazard information is needed, hydraulic models are developed to better map the flood extent that corresponds to specific flood quantiles. A probabilistic flood hazard map (PFHM) for the Qu'Appelle River reach is produced by perturbing input and model parameters within expected ranges of uncertainties using a combined 1D/2D HEC-RAS as a hydrodynamic model.

1 INTRODUCTION

Floods in urban centres and major cities attract attention because of the tangible damage (to life and property) that they cause to large number of people. In Canada, floods claimed the lives of nine people and caused around $9.0 billion in damages since 2000 (Jacob and Church, 2011). Nonetheless, there are several aspects of flood damages that afflict infrastructures, such as highways, vulnerable residents in remote areas, critical powerlines, and environmental services and ecosystems that do not receive equally fair attention. The traditional approach of producing local flood maps in each municipality is insufficient because it lacks consistency in the way flood risks are assessed in different areas in Canada, and it does not allow policy makers to make proper investment decisions with regard to flood damage mitigation. There is enough evidence that societies' flood exposure and vulnerability are increasing both globally (Ceola, 2014) and in Canada (Elshorbagy et al., 2017). For example, Elshorbagy et al. (2017) show that the city of Fort McMurray, Alberta, has expanded significantly between 1992-2013 on the highest flood hazard areas.

The lack of large extent, Canada wide, flood hazard and risk maps can lead to planning, development, and investment decisions that are not flood-smart. FloodNet, a Canada wide strategic research network, started in 2014, and is funded by NSERC to establish flood forecast and flood risk assessment approaches across

Canada (www.nsercfloodnet.ca). The work presented in this paper is part of Theme 4 of FloodNet, which is centered around physical and socioeconomic flood risk assessment in Canada. The objective of this paper is to provide a brief but comprehensive framework of flood mapping and flood risk assessment needs in Canada.

The terms of flood hazard exposure, vulnerability, and risk have some different definitions by different researchers and practitioners, however, we follow the most common definitions provided by UNISDR (2009), IPCC (2012), and Colleantuer et al. (2015). Hazard refers to the disaster itself or its potential occurrence, and usually quantified by engineers as the probability of occurrence of a flood event (de Moel et al. 2009). Intuitively, a low-lying area that is close to a river has a higher level of flood hazard than an area of a higher elevation that is far removed from the river. Elshorbagy et al. (2017) used the distance from and elevation above the river as two indicators of the flood hazard level, which can be better described as flood prone level, of any land pixel. Exposure is given by the economic and intrinsic values that are present at the location involved (IPCC, 2012). Population density, capital investment, and land or property value are indicators of flood exposure. Vulnerability is the capacity of the society to deal with the flood event, which is the state of susceptibility to harm from exposure to floods (Adger, 2006). Risk is the product of hazard, exposure, and vulnerability.

2 LARGE EXTENT FLOOD RISK ASSESSMENT

Parameters representing the concepts of hazard and exposure were identified and, subsequently, a flood risk index was developed. Flood hazard was estimated using elevation above the nearest drainage (EAND), which is similar to height above nearest drainage (Renno et al., 2008) and distance from the nearest from the nearest drainage (DFND). Both parameters were derived from a Canadian digital elevation model (DEM) obtained from natural Resources Canada (http://geogratis.gc.ca/site/eng/extraction). The 20 m DEM resolution was used in this study. Hazard values, calculated as the product of EAND and DFND, were reclassified into five different hazard classes as shown in Table 1. Eventually, a topography-based classified flood hazard map (CFHM) was created for Canada using ArcGIS, and more details of the methodology can be found in Elshorbagy et al. (2017).

Table 1: Classes of EAND, DFND, and the resultant classified flood hazard for Canada

EAND (m)	Class	DFND (m)	Class	Hazard	Class	Hazard level
≤ 2.0	5	≤ 1000	5	21 – 25	5	Severe
2.1 – 4.0	4	1001-2500	4	16 – 20	4	High
4.1 – 6.0	3	2501-5000	3	11 – 15	3	Medium
6.1 – 8.0	2	5001-10000	2	6 – 10	2	Low
> 8.0	1	> 10000	1	1 – 5	1	Very low

The CFHM was validated quantitatively and qualitatively against a flood inundation map developed using hydraulic modeling by the city of Calgary (Government of Alberta, 2013). Validation is meant to assess that the product provides useful information for locating the areas at higher flood hazard (Biondi et al., 2012).

Landuse map for Canada (Latifovic et al., 2012), available at a spatial resolution of 250 m (www.cec.org/tools-and-resources/map-files/land-cover-2005), was used a flood exposure index that reflects the land value. The second exposure parameter considered in this study is nightlights. The nightlight values, based on satellite imagery and defined by a digital number (DN) ranging from 0 to 63 to reflect the degree of luminosity, were classified for Canada into five different nightlight classes. More details on the nightlight classes for Canada can be found in Elshorbagy et al. (2017). An integrated flood exposure index was calculated as the product of landuse value and DN. Finally, flood risk across Canada was calculated as the product of hazard and exposure, as local vulnerability information was not available. Similar to hazard classes, flood risk values were reclassified into five classes, ranging from Severe to Very low.

3 LOCAL SCALE FLOODPLAIN MAPPING

The Qu’Appelle River basin (QRB) in Saskatchewan serves as a significant tributary of the Assiniboine River and flows for a total of 460 km. The case study considered here is located within the QRB and consists of reaches from two rivers: Moose Jaw and Qu’Appelle as shown in Figure 1. The reach under study is 113 km in length and begins at a streamflow gauging station, called Moose Jaw above Thunder Creek (05JE001), and ends just below the city of Lumsden. The Moose Jaw River up to the confluence flows within a defined valley with a limited floodplain and hence, can be modeled with a 1D hydraulic model. The Qu’Appelle River reach from the confluence up to Lumsden has an average channel width of 30 m, whereas the floodplain extends beyond 1 km, and has wetland-dominated terrain, which is suitable for 2D hydraulic modeling. The gauging station 05JE001 was considered as the upstream boundary condition for the Moose Jaw River.

HEC-RAS 5.0.3 was used in this study to perform both 1D and 2D hydraulic modeling. Data requirements for HECR-RAS include cross sections that provide topographic information, friction parameters in the form of manning’s roughness coefficient n, and flow data.

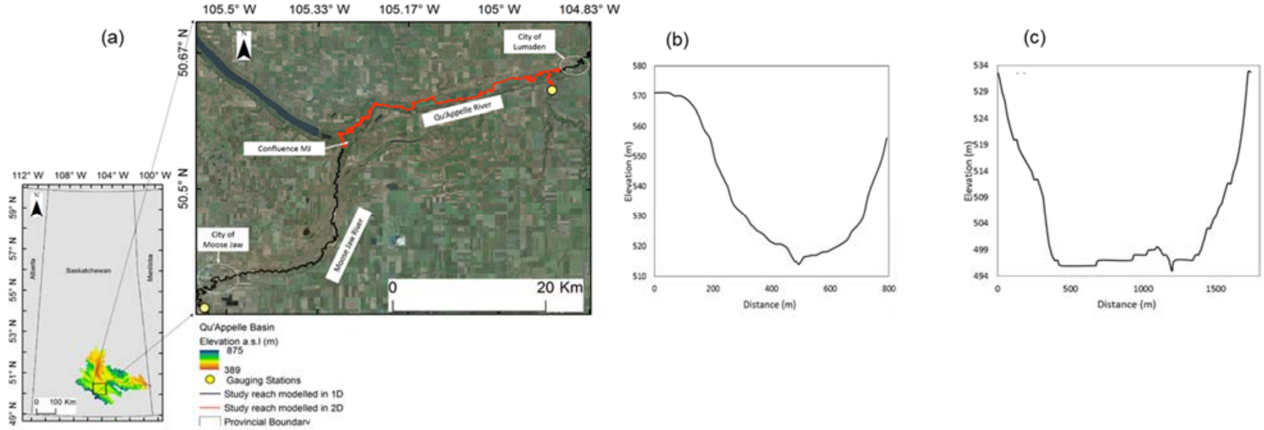

Figure 1: (a) Location of the Moose Jaw and the Qu’Appelle Rivers, (b) typical channel cross section along the Moose Jaw River, and (c) cross section of the Qu’Appelle River.

The hydraulic model was calibrated for the 2011 flood in the Qu’Appelle valley. Daily streamflow measurements were used for a period of 35 days that contained the flood event (April 1 – May 4, 2011). The observed peak flows at Moose Jaw River, Wascana Creek, and at Lumsden are 197 m3/s, 95 m3/s, and 300 m3/s, respectively. Roughness values were lumped into two values, one for the channel and one for the floodplain. The calibrated roughness values were found to be 0.032 and 0.041 for the channel and the floodplain, respectively. Both the roughness parameters (channel and floodplain) and the flood hydrograph were considered to be uncertain, and were varied within reasonable ranges to assess their effect on the flooding extent and depth. Roughness values were sampled in the range of 0.01 to 0.05. Similarly, the flow hydrographs were perturbed to account for 40% uncertainty level (Di Baldassarre and Montanari, 2009). We used the method proposed by Savage et al. (2016) for perturbing the flood hydrograph. A total of 5000 samples for the roughness parameters and the hydrographs were generated to produce probabilistic flood maps in the study area. Eventually, the probability of inundation (PoI), depth of inundation (DoI), and the coefficient of variation with regard to DoI were obtained for each pixel in the study area.

4 RESULTS AND ANALYSIS

4.1 Large Extent Topography- and Nightlight-based Flood Risk Assessment

The topography-based classified flood hazard map (CFHM) of Canada, developed based on the method explained in section 2, is shown in Figure 2. Large areas of the country are classified under severe and high levels of flood hazard due to their elevation and proximity to rivers. However, most of these areas have negligible human presence. The CFHM can be useful for large-scale planning and development, where avoiding encroachment into flood hazardous area is recommended. It can also help identifying critical structures (e.g. highways) and small remote communities that are at stake because of being located within, or surrounded by, high and severe flood hazard areas. A comparison between the CFHM developed in this study and the hydraulic-modeling-based 100-year inundation map is shown in Figure 3. There is good agreement between the 100-year flood inundation and the hazard level classified in this study as severe. A Canada wide flood risk map was produced for Canada according to the methods explained in section 2. To identify flood impact on people (social impact) and separate it from economic impact, we overlaid the flood risk map with the population density layer. Figure 4 shows an example of such flood risk map with and without population for the city of Calgary. The central part of the city with high-rise buildings and high population density remains within the highest level of flood risk. The northern and southern parts, which are mainly commercial areas with lower population density, and thus lower social risk, assume reduced levels of overall flood risk (Fig. 4b) in spite of having severe economic flood risk (Fig. 4a).

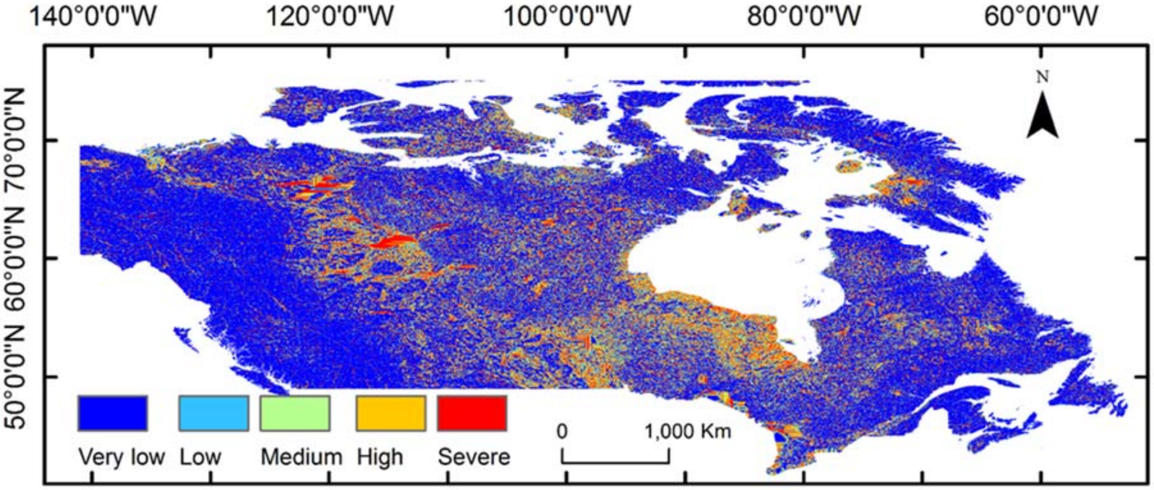

Figure 2: Flood hazard map for Canada obtained using the 20 m DEM.

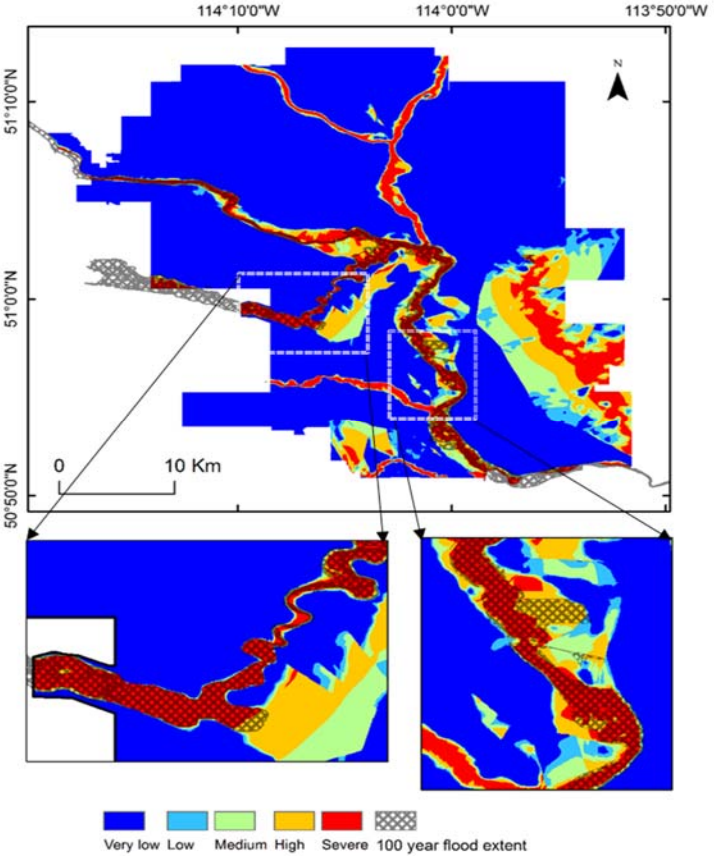

Figure 3: Comparison of the CFHM obtained from the present study and a 100-year flooding map provided by the city of Calgary.

It is important to note that local information is important for estimation of flood hazard and vulnerability. Information on existing flood protection is necessary to provide useful guidelines to decision makers. This information can be used along with the maps provided here to help water resources managers at local scale.

4.2 Probabilistic Flood Mapping

Figure 5 shows the probabilistic flood hazard map (PFHM) with the PoI of each flooded pixel in the floodplain. The PoI values are high at most locations along the reach, and high values of POI (> 0.9) indicate that these locations can be expected to be inundated even when the peak flow is 40% lower than that of the 2011 flood. These high values of PoI can be attributed to the topography of the floodplain along the study reach. The Moose Jaw River is characterized by narrow valley along the river until the confluence with the Qu'Appelle River (Fig 1b). In the Qu'Appele River reach, the floodplain extends over a kilometer and is very flat and thus, water leaving the channel and flowing onto the floodplain is most likely to inundate the entire valley (Fig. 1c). However, even in locations with high PoI, the depth of inundation varies and the variations are shown in Figure 6. In the stretches shown in the figure, the low PoI is associated with those locations where the average DoI is small and vice versa. High DoI is restricted to the channel in the Moose Jaw River, whereas there are multiple locations in the floodplain that have high DoI values in the Qu'Appelle reach. This is due to the presence of potholes in the floodplains that retain water during high flows.

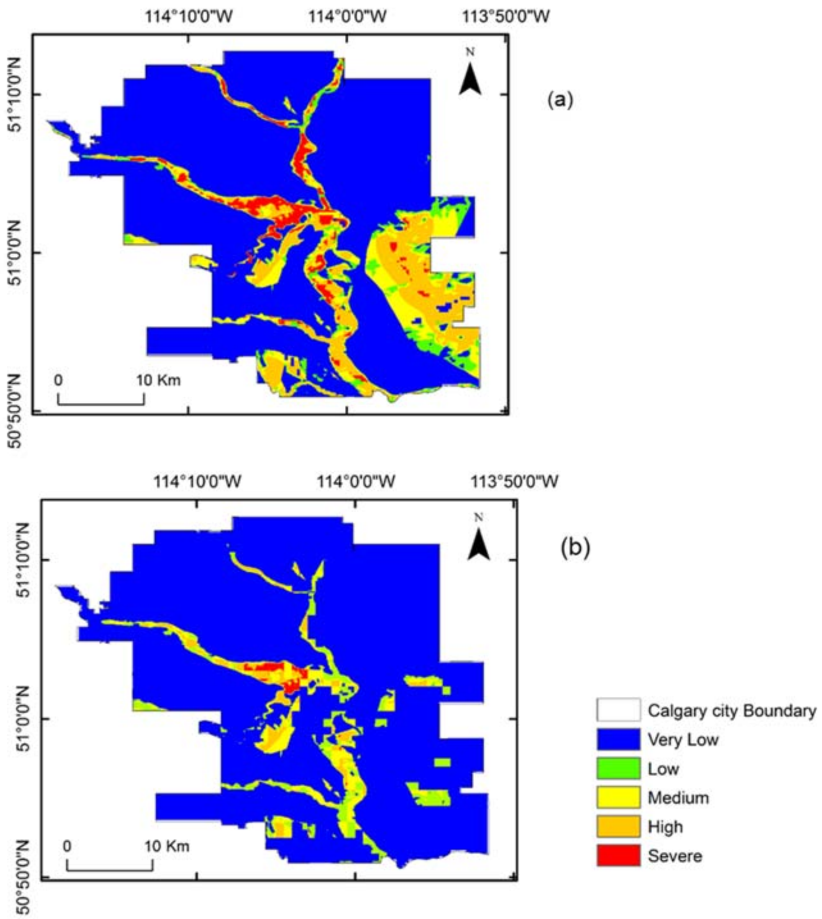

Figure 4: Flood risk map of Calgary, (a) without population, and (b) with population.

To evaluate the large extent flood hazard maps against local area hazard maps obtained using detailed hydraulic modeling, a qualitative comparison was carried out between the CFHM and the PFHM. The CFHM that contained the study reach was extracted from the larger map that contained all of Canada, and the PFHM and the CFHM for a small reach along the Qu'Appelle River is presented in Figure 7. A visual comparison between the two maps indicate that the hazard level "severe" has a slightly wider extent in comparison with the PFHM. The PFHM shows extent of flood on the Qu'Appelle River alone, whereas the CFHM takes into account other streams that flow into the Qu'Appelle River.

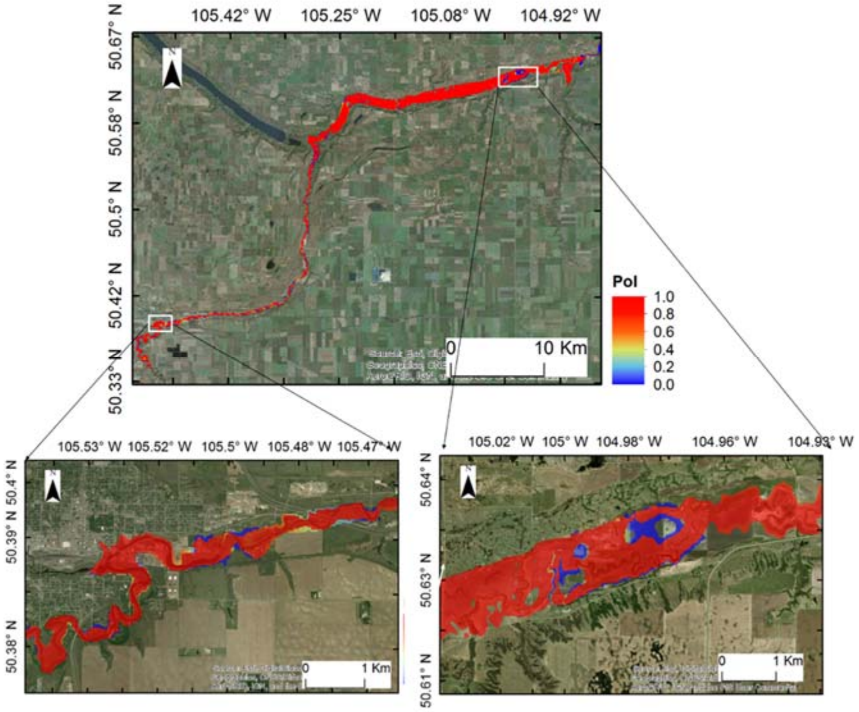

Figure 5: Probabilistic flood hazard map for the entire reach (top) and enlarged portions at a location along Moose Jaw River (bottom left) and along the Qu'Appelle River (bottom right).

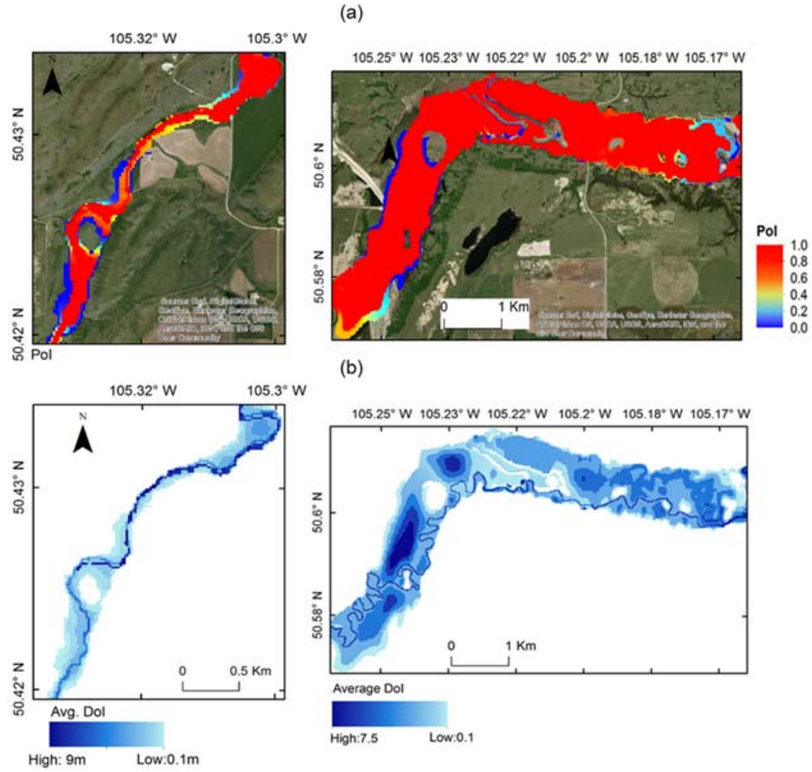

Figure 6: (a) Probability of inundation along the Moose Jaw River (left panel) and the Qu'Appelle River (right panel), and (b) average depth of inundation (DoI) along the same reaches.

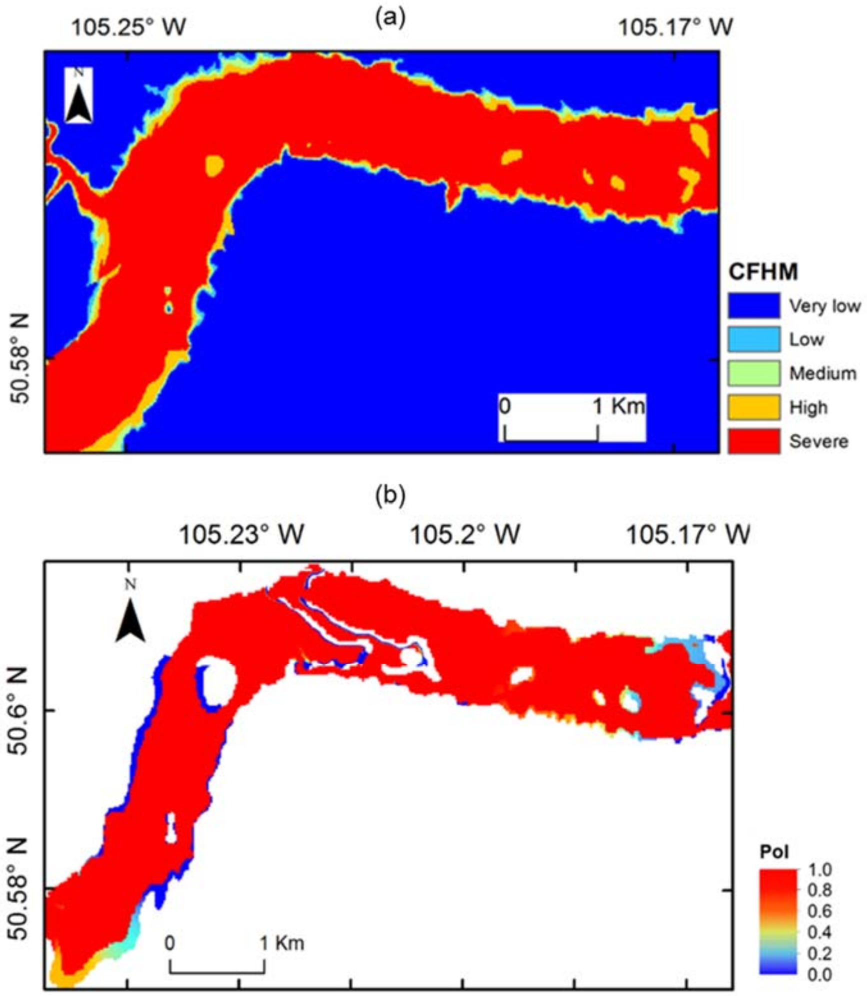

Figure 7: (a) The classified flood hazard map along the Qu'Appelle River, and (b) the probabilistic flood hazard map showing the probability of inundation (PoI) for the same stretch.

It is important to note here that land depressions in the prairies retain a significant amount of surface runoff and significantly affect the streamflow. During snowmelt or heavy rainfall events, these land depressions are interconnected, resulting in landscape flooding. Traditional hydraulic models have limited or no capabilities to simulate such a pluvial flooding pattern over the landscape dominated by land depressions. A new modelling framework is currently underway to simulate the landscape flooding by coupling a rule-based model that utilizes topography data with a simplified hydrological bucket model. The rule-based model is a grid-based simulation approach that can simulate flooding pattern over a certain area by minimizing the differences of water elevation in the surrounding grid cells. The rule-based approach handles the overland flow movement using Manning`s equation, while the bucket model handles the hydrological processes for surface runoff generation. This framework enables determining the quantity and the overland path of surface runoff and shows potential in predicting flooding patterns and the actual connectivity between land depressions using terrain data.

The comparison provided in this paper between the CFHM and the PFHM is a starting point to convert the CFHM of Canada into actual hazard map, where flood zones are related to flood frequency; e.g. 100-year flood. Flood frequency curves at various gauging stations provide stremflow values that correspond to a selected frequency, and consequently, the corresponding water level can be estimated using local rating curves. Spatial interpolation techniques can be used to create water elevation as a continuous surface, which can be used to delineate the inundated area using ArcGIS. Such a product can be used, along with local information on property value, to estimate flood dame and suggested flood insurance premium, which can be a useful flood risk scoring tool for the public and policy makers. As part of the FloodNet, it is planned to produce a web-based tool for flood risk scoring across Canada.

5 CONCLUSION

The topography- and nightlight-based approach adopted in this study for flood risk assessment on a national scale is both useful and practical. Without detailed hydraulic modeling, the flood hazard map of Canada can provide a reliable preliminary assessment of the flood hazard level anywhere in the country. The flood risk map, which integrates both hazard and exposure, including nightlights, is the most useful product as it allows for evaluating the spatial distribution of the expected flood damage, and thus can help in prioritizing government intervention and strategic resource allocation. The severe and high flood hazard areas in Canada are spread over all regions of the country; however, the severe and high flood exposure and risk are concentrated in the southern part of the country around urban centres.

A probabilistic framework to flood mapping, by accounting for uncertainties in inflow hydrographs and roughness parameters, was applied in the present study. The Qu'Appelle River that is prone to frequent floods in the Canadian prairies was selected and a hydrodynamic model was developed for a reach of the river. The variability in the depth of inundation (DoI) was found to be low at locations with high DoI and vice versa, indicating less uncertainty at locations where the DoI is high. The sensitivity analysis results indicated that the influence of channel roughness on flooding extents is more at locations characterized by steep slopes and unidirectional flow, whereas the flood extents were insensitive to roughness parameters and boundary conditions at locations where the channel had a mild slope and flat floodplain characterized by small depressions that retain water during high flows.

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