Response letter to the Reviewers of "Topography- and nightlight-based national flood risk assessment in Canada" – HESS-2016-524.

Reviewer 1

The authors would like to thank the anonymous reviewer #1 for providing a very thoughtful assessment and very useful suggestions. We are providing here below our detailed response to each remark.

1. *The authors have used what they consider to be a static entity like topography through two quantities "elevation above nearest drainage" and "distance from nearest drainage" to create a flood hazard level for each grid cell. The floods in the Bow and Elbow Rivers in Calgary, Alberta in 2007 for example, (one of the locations the authors use to verify one of the maps) significantly affected drainage to the point that it changed the rivers' locations, meander and moved a significant amount of sediment. While this would not likely affect a product that is based on a resolution of over 300 metres (at best) because these rivers may not change bank locations by more than 100 metres in one flood, it does beg the question of how often should this product be updated, maintained, etc. Products like this should be given technical support but there is no suggestion of technical support. This is fine because I don't think the development of a product is something that is suitable for publication in HESS and perhaps the authors are more interested in providing an approach leading to a potential product. Well in that case, a much more rigorous evaluation of that approach is required and that is lacking here. What is currently presented is really nothing more than a simple GIS exercise, which I might suggest is not suitable for HESS and thus, the work needs greater discussion, validation and verification if the ultimate objective is indeed to suggest an approach.*

R1. We would like to emphasize that the approach we are adopting here proposes for the first time the integration of detailed topographic information, in the form of distance and elevation from streams, with hydrologic and human settlements information to assess flood risk. What is obtained here is much more than a flood inundation map, as we integrate information on hazard and exposure, therefore moving a step forward towards large scale estimation of flood risk. Actually, what is intended here is both an approach that can be followed in any place across the globe and a product (for Canada). Therefore we believe that the article is presenting significant innovation. For example, many developing countries can benefit from this as global remotely sensed data are becoming increasingly available. We agree with the reviewer that a rigorous evaluation of the approach is needed. Accordingly, we revised the manuscript (Page 10, line 13 – page 11, line 15) to make the validation of the hazard map quantitative. We also added another qualitative assessment (Page 18, lines 13-21 and Figure 5) to compare the flood hazard mapping approach against an aerial photo showing the actual extent of 2013 flood in the Qu'Appelle river.

We agree that big floods may change the river course and therefore an update of the results from any hydraulic model may be needed after an extreme event. Actually, our approach can be easily updated when significant topographical changes happen in the landscape and this information is updated into the DEM being used. In this regard, updating the product proposed here can be easier than reconducting detailed hydraulic modeling. We believe little technical support is needed as we can provide relevant codes and GIS layers that can be re-run when significant changes happen in topography or landuse.

__2.__ Page 7 lines 12-19 – The authors need to state in greater detail what they are doing with the comparison around the City of Calgary. Is this a validation or verification? It seems like none of these, than what is this comparison for? If you want to make a comparison, it should be quantitative, instead it is entirely qualitative.

__R2.__ It would be useful if the reviewer clarified what is meant by validation and verification, as these terms are sometimes used in hydrology with different meanings with respect to what is defined, for instance, in the ISO 9000 rule (for more details please see https://en.wikipedia.org/wiki/Verification_and_validation; see also Biondi et al., 2012). Our application to the city of Calgary is intended to be a validation, according to the following definition of the term: "Validation is the assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers". To meet the above requirements, in hydrology validation is often performed by referring to independent set of data, as we did in our case. We clarified in the revised version of the paper that we are providing a validation according to the above definition.

As mentioned in the previous comment, we already provided a quantitative comparison in the revised manuscript, and also added another qualitative assessment.

__3.__ Page 8 – The Canada DEM resolution is reported as 326 metres. This is the spatial resolution – what is the elevation resolution and accuracy – 1 metre? 50 cm? What are the implications of this error on flood risk or hazard? The authors combine two topographic indices to create a skewed topographic index and call this flood hazard. I don't necessarily agree that this is flood hazard – what it definitely is, is a new topographic index related to position from a "drainage point". If the authors want to suggest a surrogate for flood hazard that is easy to create, then they would have to verify that surrogate but that has not been conducted here. At this point, the authors should be true to what they have presented and not label that products as flood hazard but simply the product of two topographically related indices.

__R3.__ We respectfully disagree. There is no universal measure of flood hazard. Typically, probability of occurrence is used. Here we are assuming that our proposed classification of the landscape, in the surrounding of the rivers, based on topography reflects its probability of being flooded, and thus, reflects hazard. We reproduced the entire work using DEM-20 that has a vertical accuracy ranging from zero to 10 m for more than 90% of the entire country (Natural resources Canada, 2013; Beaulieu and Clavet, 2009). Information on metadata and errors is now provided in the revised manuscript (Page 8, line 20 – Page 9, line 6). Therefore, the reliability of the DEM is not a question and, in general, does not affect the validity of the approach and the assumption that flood hazard can be inferred from landscape topography. Others have related flood hazard maps to topography, e.g. Lugeri et al. (2010), which is cited in our manuscript. As this approach can be followed using any elevation dataset, readers could reproduce these maps with improved accuracy in the presence of more accurate and finer DEMs/DTMs.

4. *Page 9 – the authors state "horizontal distance" from nearest drainage network. What is this exactly? Are the authors referring to a buffer like distance? If so, why not just create a buffer? A "horizontal distance" makes no sense in a GIS context, the authors must be careful with their terminology and provide greater detail. For example, in the definition of EAND, the authors intention I suspect is the nearest drainage cell, or point on the drainage network defined by the ArcGIS. But if a point is equally distant from two drainage points, how is the choice made? Details like this should be noted as well as metadata information, errors in the data, etc.*

R4. We are referring to a buffer like distance while describing DFND. However, in GIS, the term "buffer" is usually applied to concentric distances to a feature (line, point or polygon) in vector format. For the present study, the stream network was retained in raster format to maintain consistency in all subsequent calculations. Horizontal distance refers to the Euclidean distance between the drainage cells and adjoining cells that are estimated using the "Euclidean distance" tool in ArcGIS, followed by reclassification using the limits mentioned in Table 1. Hence, the word "buffer" was avoided and "horizontal distance" used instead. The term horizontal was used as this measure considers only the distance and not the elevation difference between the drainage cells and the adjoining cells. The reviewer is right that in EAND, the elevations to the nearest drainage cell is estimated as described in section 3.1. Additional metadata information on the DEM and errors, as well additional details to clarify the procedure, is included in the revised manuscript (Page 8, line 20 – Page 9, line 6).

5. *Page 9 – line 2 – the authors state that they developed a drainage network as the river network from the ARCGIS tools. Even with a filled DEM, etc, as the authors report, it is well known that a river network derived from a topographic map can often deviate from the actual river network because of errors in the DEM. Given the scale of the DEM used and the size of many of the rivers in Canada, it is possible for drainage points on the DEM derived drainage network not to coincide with actual river locations. Surely this is a problem so why wouldn't the authors use the actual river network for Canada or at least correct their product for actual rivers?*

R5. Some of the Reviewer's concerns were already addressed as we presented everything using the DEM-20. Even the river network made available through Environment and Climate Change Canada (ECCC) is generated using DEMs, and is based on even coarser DEM than 20 m. To verify this, the stream network delineated using the 20m DEM (Blue lines) and the stream network available from ECCC (Red lines) were overlaid on Satellite imagery available in Google Earth at different locations in Canada. Results for two such locations are presented in the following figures (L1 and L2). It can be clearly seen that the stream network delineated using the 20m follows that actual path of the streams and also captures any meandering whereas the readily available stream network presents only as straight lines cutting through the terrain.

Fig.L1 Comparison of river network obtained from the 20m DEM (Blue lines) with the river network given by ECCC (red lines) in the Greater Toronto Area, ON

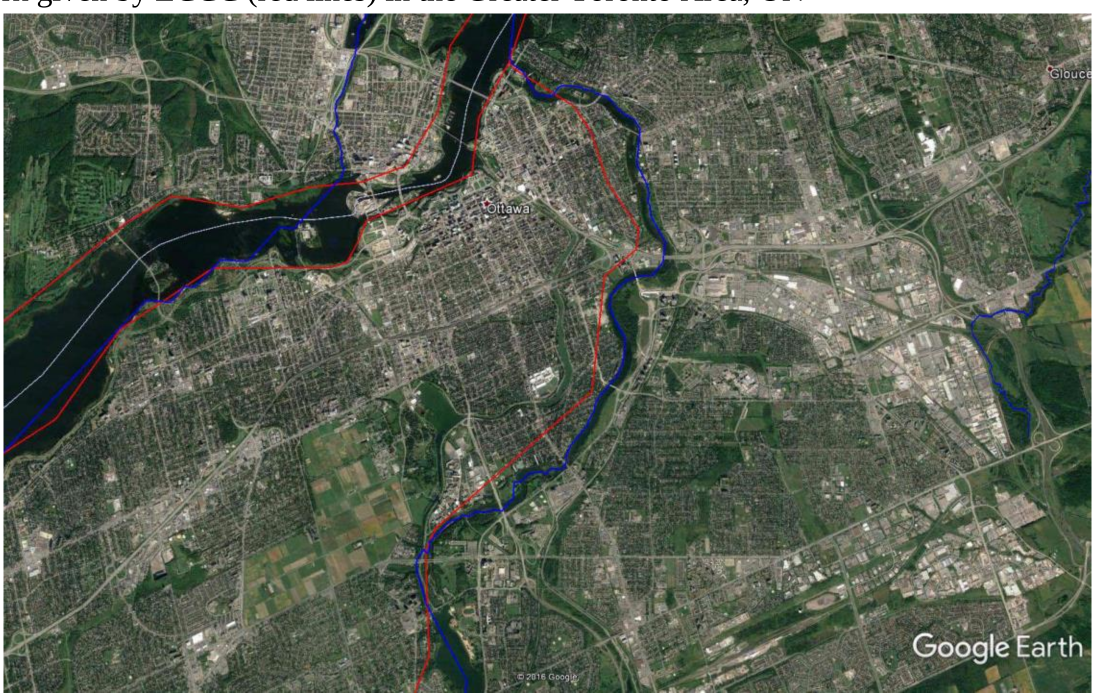

Fig.L2 Comparison of river network obtained from the 20m DEM (Blue lines) with the river network given by ECCC (red lines) in Ottawa, QC

6. *One of the reasons why the authors went with such a resolution was because they felt that it made the problem tractable but with "reasonable" detail. But because of the large expanse of this country with little population, there are large areas of the maps with no interest because there are no urban areas. Page 12 refers to Table 2, which shows that the percentage of Canada covered with land use 4 and 5 is less than 6%. The nightlights confirm the enormous area with little population and therefore, with little interest in products like this. It makes me wonder why the authors would create a product that covers all of Canada. Why not create a higher resolution produce that just focuses on urban areas and simply cut out all the rest? The authors state how problematic political borders are to watershed management. Well then why not create products in only the most hazardous areas? Why not eliminate all the region that is of no interest and not display them? Instead we get maps of the entire extent which has a lot of information that does not have to be displayed or provided. Because the authors rely on visual representation of their work, these visual representations are all that can be critiqued.*

R6. We respectfully disagree with the Reviewer as this suggestion contradicts the purpose of our work. Several municipalities attempt to model or use consultants to hydraulically model the few kilometers river reaches that pass through urban areas, but the bigger picture of an entire province or basin is missing. Development of new areas is moving fast in Canada and encroachment into flood hazard areas is happening (as we presented the case of Fort McMurray) because such areas were not modeled as they were not populated! The flood hazard map indicates that larger areas of Canada are in significantly high flood hazard areas, but the exposure is, of course, centered around urban areas because of the adopted definition of exposure. We need to highlight hazard areas to help planning and future developments, and also indicate the flood hazards in agricultural areas, important heritage areas, transportation infrastructures, such as roads crossing unurbanized areas, vulnerable ecosystems, etc. It is not just about urban centres. To demonstrate this, we present the figure L3. The figure is for a location north of Edmonton, Alberta, where the exposure map indicates "very low" to "low" exposure. However, a road network map overlaid on top of it indicates that there is a dense road network connecting different locations within the area. The hazard map for the same area also indicates a dense network with hazard levels "severe" and "high". Roads were flooded in major Canadian flood events and hampered rescue efforts.

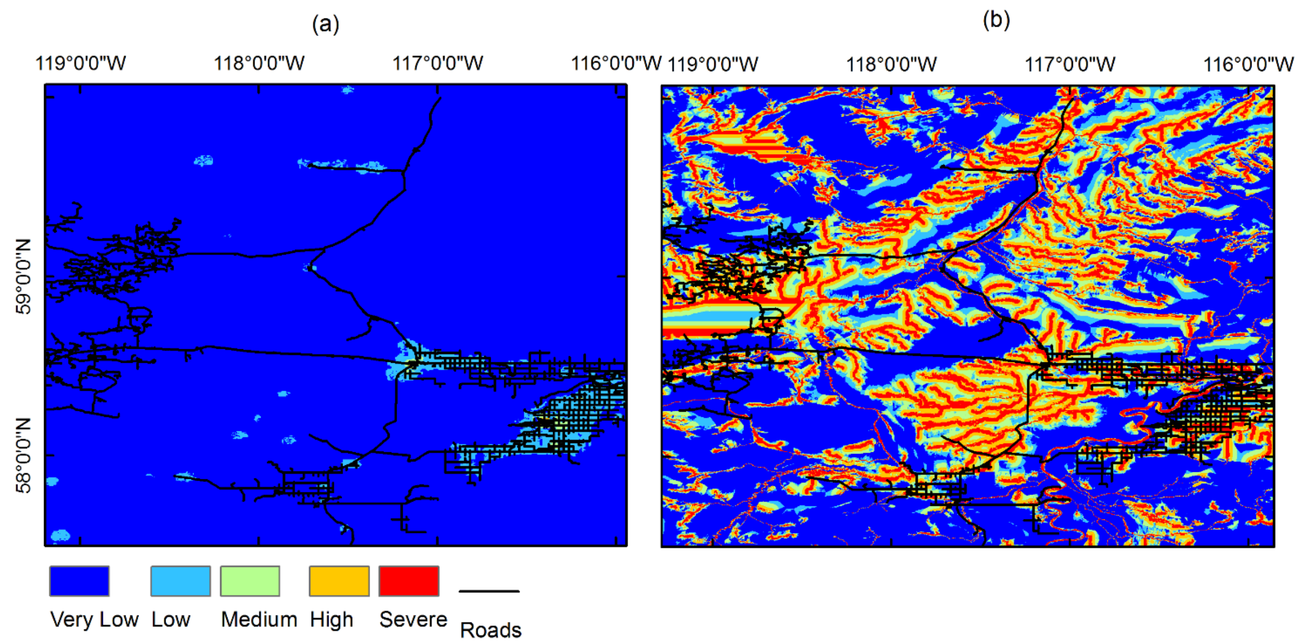

Figure L3: Exposure (left panel) and hazard (right panel) maps overlaid with road network.

7. *In Table 3, the percentage of areas covered by high and very high luminosity is tiny in comparison to the rest of the country. The nightlight DN value between 0 and 63 with resolution of one is now descritized into five classes each separated with the same value – one. The authors lump DN values from 11 to 63 for medium to very high luminosity in three out of five classes. Why not instead descretize those regions of interest (medium to very high) into five classes because ultimately you create a skewed product (when you multiply this five level classification with another five level classification scheme) that ignores the detailed information (nightlight, population, land use) and distribution that resides within the two most important classes. In doing this, the authors relegate two whole classes out of five for the bulk of the country that is of no interest. It would make more sense for the authors to focus in on the regions of interest and have five maybe 10 levels of classification within areas of interest. Why did the authors choose five levels of classification and not two, or four or 10?*

R7. We believe this is related to the earlier point of focusing on smaller urbanized part of Canada or doing the entire country. Our choice and preference is the latter, but other researchers are free to take our approach and focus on any area they prefer, and also other hazard classifications in number of classes and ranges.

8. *The risk product combines a 326 metre resolution DEM with a 30 arc second DEM. At the Canadian-US border this resolution is probably around 600 metres. So what merging algorithm* *did the authors use when combining two grids of differing resolutions? What is the ultimate resolution of their product?*

<u>R8.</u> In the revised manuscript, DEM-20 (20 m resolution) was used in the preparation of risk map for the entire country. The 30 arc second resolution corresponds to the Nightlight dataset that was used to prepare the exposure map. The nightlight images were resampled to match the resolution of the DEM within the entire study area and the final risk map was produced by combining the hazard and exposure map. The final product was a risk map of 20 m resolution. This clarification has been been added to the revised manuscript (Page 13, lines 18-20).

<u>9.</u> *Page 13 lines 14 - 15, the authors state that "airports and industrial and commercial areas are highly luminous but the census data show low or no population". Floods create numerous environmental hazards that are equally as lethal as is the potential for floods to drown people. If that is what the flood exposure map is about – human harm, then I would argue, it is incorrect to negate the potential human health risk associated with flood waters having moved through an industrial site simply because no one is living there at night. Flood waters in urban areas are more polluted than sewage and carry harmful hazardous waste that can be extremely harmful if people are exposed. The authors ignore this and simply acknowledge residential areas. This is the general problem I have with this approach.*

<u>R9.</u> We agree, we just wanted to show that census data showing zero population do not mean no human presence. There is still capital investment. Human lives are disturbed at a different level when homes are impacted, more than having a place of work impacted, but certainly human harm could still happen in industrial areas. We clarified this by a statement on Page 15, lines 17-18.

<u>10.</u> *There are too many figures and few that are actually useful. Figure 1 really is not very useful. If you really want to use up valuable journal paper space then why not superimpose (a) and (b)? I would just remove (a).*

<u>R10</u>. Figure 1 is now modified by combining old figures 1(a) and 1(b) and relevant write up is now provided in page 6, Lines 1-7.

<u>11.</u> *I would appreciate better attention to semantics. For example, on line 13 page 6. How is sufficient defined here by Apel or the authors?*

<u>R11.</u> It is subjective term that relates to "acceptable" level of accuracy and representation. Different users and uses dictate different levels of acceptability.

<u>12.</u> *Page 14 refers to Figure 2. Again (a) and (b) are both not necessary – just have (b). Figure 3's caption should be revised to read "resulting from EAND X DFND" because this is not a flood hazard map but a map of that index. The topographic index defined by the authors contributes to* *one kind of flooding but there are others that are equally as hazardous that are not well represented. British Columbia suffers from severe flash flooding that moves enormous amounts of debris yet there seem to be few hazards associated with this type of flooding that is mostly in mountanous regimes showing up in the map because of the way the authors have chosen their index. Can the authors comment on the universality of their choice in Canada? The authors clearly state early in their paper that extreme flooding in Canada is the result of many factors like ice jams, etc. This is very true and thus, the index defined by the authors cannot in fact be toted as a flood hazard by virtue of the fact that what leads to sudden high streamflow – the really danger - is not simply a flat area close to a stream bank. But if that's what the authors want to create, that's okay but then it requires a good discussion of why the approach is novel for defining a flood plain and what the benefits are (like computational ease), then they need to report the computational cost of creating these maps and report a quantitative comparison with things like the 1/100 year flood plain map in Calgary. Figure 5 refereed to on page 15 shows areas of overlap between the product and the flood plain map. This is again qualitative. A more quantitative comparison is required with even something simply like number of grid cells overlapped versus not overlapped to start with.*

R12. Figure 2 (a) and (b) help the readers see the difference that reclassification into 5 classes cause to the map. As discussed earlier, we disagree on the issue of Hazard definition. The issue of debris from the mountain can be just another index added to Hazard based on proximity to erodible mountains in the headwaters. However, it should be noted that the commonly used, and widely accepted, flood hazard maps based on flood frequency do not take into account factors, such as debris flow. The issue of ice jamming is true as a cause of flooding, but inundated areas first impacted are the lowlands and lands close to the stream, we cannot see how ice jams negates the universality of our proposed hazard index. Our approach simply prioritizes areas expected to be flooded first, then second, and so on.

13. *This brings me to my next point. Large municipal urban centres already have information on high flood risk regions. What information does this product bring them that they don't already have at a better resolution? Risk of fire is largely a problem when it starts encroaching on an urban area and not generally at the same time as a flood risk so how can this low resolution product be helpful to Calgary?*

R13. Based on this revised manuscript with DEM resolution of 20 m, we believe that this product is no longer a low resolution product. We believe that we addressed this point earlier, and also in the manuscript. What an approach like this brings is different. This approach helps prioritize areas for detailed modeling, help development planning, and other studies, such as investigation of various population groups and their vulnerability to certain hazards, which is useful for resource allocation. Recognizing the areas exposed at high flood hazard is a urgent priority in many regions of the world, we believe that our approach is a significant step forward.

14. *The discussion is lacking in many regards in this paper particularly where figures are produced. Page 16 for example refers to figure 6 but honestly, there is nothing really discussed or noted of significance here. Figure 7 is too coarse a resolution to be useful. Figure 8 is an "enlarged" version of an area for better visual interpretation but if they don't provide the exact area in space (not just with hatchmarks but perhaps with an areal photo showing the flood plain in the area) it is not a useful figure. This figure also has little discussion.*

R14. We believe that enough discussion is provided for Figure 6 (New figure 5). Discussion on Figure 7 has also been expanded (page 19, line 23 – page 20 – line 4) in the revised manuscript. While providing maps for a large country like Canada, the details are lost in the main figure. We have enlarged a small area and presented it to improve the interpretation. Addition of aerial photos over risk map (Figure 8) results in too many layers that would not be easily interpreted. Hence we avoided including additional layers.

15. *The authors don't provide a rigorous enough evaluation of their product at this stage. In Figure 10, the authors refer to reduced levels of social risk for commercial regions. Again I disagree with this but perhaps this is due to a lack of rigerous definitions on the part of the authors as to what is "social" – human residential impairment? The authors should revise all their captions to state what is truly shown. Also, there were numerous areal photos of flooded regions within Calgary during the 2013 floods. Why not use this valuable information to compare to their product? That would be a much better evaluation and would demonstrate the deficiencies and limitations of the product in an actual flood that was not 1 in 100 but with an extent that was outside the 1/100 year flood plain.*

R15. The issue of population in residential and commercial/industrial areas was discussed earlier. We compared with 100-year flood modeling in Calgary because a georeferenced map was made available to us, and the hydraulic modeling is supposed to be the "accurate and scientific" way of mapping flood inundation. Therefore, enough information is available to perform a validation of our results. However, we also managed to obtain a high resolution aerial photo of the 2013 flood in the Qu'Appelle River Basin, which is one of the most challenging areas in Canada for hydrologic and hydraulic modeling – the Canadian Prairies. We compared our product with this photo and the results are very good, and this is now presented and discussed in the revised manuscript (Page 18, lines 13-21, Figure 5). We thank the reviewer for bringing this up because it gave us the opportunity to conduct another compelling validation of our approach and product.

16. *Page 17: line 17, the authors refer to the "average" effect. Why would they be integrated in the first place? Why is "average" in quotes? My point is that this work is really a GIS exercise and the GIS community understands the issues and limitations with combining data of different resolutions, etc., yet I'm concerned with the lack of attention to terminology or basic GIS concepts used in the discussion. A more formal language is preferred along with greater detail on what was actually created and how.*

R16. Simply what we meant is that integrating two aspects in one can mask the individual effects. Sometimes integration is a must, and we did it, for example, with EAND and DFND, but in case of effect on population we wanted it to be explicit. As suggested, and as discussed earlier, additional details on the GIS-related analysis were provided in the revised manuscript with regard to handling maps with different resolutions and the accuracy of the metadata. We agree that the application of the work is basically a GIS exercise, which however makes use of an innovative idea and provides innovative information.

17. *I really do think products like these are good ideas but it's not just what is novel that must be shown but how it is useful and why it is needed. Unfortunately, I do not feel that the reader is given a full understanding of how this approach or product is useful. There is some attempt but more depth is needed. For example, on page 18, line 15, the authors state: "In other regions, and depending on the topography, the 100 year flood might cover two or three of the flood hazard classes." I don't mean to sound curt but so what? How is this useful to a planner that is required by most by-laws to deal with the 100 year flood or design with the 5, 10 or 30 year flood in Canada? Typographical errors: Line 13, Page 6 – insert "data" after "remotely sensed" Page 8 – insert "an" or "the" before "eight" Page 11 – line 9 replace "from" with "for" Page 32: Spelling eerror in the caption of Figure 8 (should be severe not sever)*

R17. We believe that our approach is indeed presenting an original contribution, and we also believe that it is very useful. It allows the identification of critical areas, where subsequent detailed analyses should focus on. For example, local authorities may want to relate flows at different flood frequencies (e.g., 100 year) to water stage (can be done using rating curves available locally). The stage of different floods will indicate clearly which of our hazard classes will be inundated. This way local authorities can convert our map to flood frequencies. This clarification was added to the revised manuscript on Page 22, lines 6-10. Typographical errors were corrected.

Reviewer 2

The authors would like to thank Reviewer #2 for providing a review. We are providing here below our detailed response to each remark. Some of our remarks are copied from our response to the first Reviewer wherever the reviewer's comment is similar to one made by the first reviewer.

1. *I miss a clear statement of the research problem and what is novel with the purposed study. The structure of section one and two could be improved by avoiding jumping back and forth between topics.*

R1. The paragraph on Page 2, Lines 15-23 and Page 4, Lines 7-12 state clearly the problem and the aim of our work. We would like to emphasize that our approach here proposes for the first time the integration of detailed topographic information, in the form of distance and elevation from streams, with hydrologic and human settlements information to assess flood risk. We cannot see eye to eye with the reviewer the issue of jumping between topics, however, we reviewed this carefully, and we could not identify the problem.

2. *[Page 8-9] To create the EAND and DFND classes, a drainage network was created using ArcGIS hydrology tool on a coarse resolution DEM. This can produce many errors - why not use an already existing drainage network, or at least verify against one?*

R2. In the revised manuscript, we presented everything using the finest scale-resolution DEM available for Canada (20 m). Even the river network made available through Environment and Climate Change Canada (ECCC) is generated using DEMs of a coarser resolution. We used Google Earth to compare the river network we generated against actual rivers, and the comparison, which validates the use of the 20 m DEM, was already shown in our response to Reviewer 1.

3. *[Page 9, Lines 12-13] The classification process for the different maps produced is not clear. For example, the hazard class intervals were selected somewhat arbitrarily. I would like to see more thought behind this, e.g., do they represent floodplains, and why five classes?*

R3. The five hazard classes selected can represent different hazard levels across the country as the topography is different across the country. However, as we explained on Page 18, this can be adapted locally to different types of representation; e.g. flood frequency. As the reviewer pointed out, the intervals for DFND and EAND were decided taking into consideration that flooding extent in floodplains would be much larger than in hilly areas. In hilly areas, EAND governs the hazard mapping, thus reducing the extent of hazard. For the study over the entire country, the 5 classes considered were deemed adequate.

4. *[Page 12, Lines 6-8] The exposure map based on nightlight data indicate that 98% of Canada's area has absent or low human activity. This leads to the following question –is a national flood risk assessment useful?*

R4. Yes, very useful. Majority of the population is in southern areas, however, hundreds of thousands of Canadians are spread across the Canadian landscape. Some of the northern population groups can be even more socially vulnerable than others, and floods in their regions are critical. In addition, major infrastructures, including roads which are important element for mobilizing rescue efforts are spread across what seems to be areas with low nightlight luminosity, which is now presented by the modified flood hazard and exposure maps in the revised manuscript (Figures 3 and 7). This work aims to highlight these issues. Because of the large area of Canada (almost equivalent to the area of Europe), visually, it looks like most of the country is dark at night, but zooming in can reveal more details. The availability of our product in a digital form with 20 m resolution allows for investigating issues at finer scales.

<u>5.</u> *[Page 12, Table 2 and 3; Page 31, Figure 7; Page 32, Figure 8] The land-use classes and the nightlight classification used for the exposure map give northern communities very low or low exposure level by default, resulting in very low or low flood exposure, and very low flood risk in areas above 60^o N. Is this national flood risk map useful for residents above 60^o N? I am missing a discussion around how the classification process affects the end product.*

<u>R5.</u> The first part of the question was addressed by our response to the previous comment. The classification process and selection of number of classes are usually arbitrary and subject to the judgement of the analysts. However, it is more convenient to fix the number of classes of the various maps. Increasing the number of classes would not be of much help as decision makers would eventually prefer to lump a few intermediate classes for easier interpretation. Five land-use classes are sufficient as one can even associate an average dollar value to each class.

<u>6.</u> *[Page 14-15, Lines 14-21, 1-5] A coarser DEM is chosen for the study to keep computational costs low, but results show that a finer resolution DEM (20 m in this case) gives better results and a more reliable flood hazard assessment. Floods are usually analyzed and managed at the provincial level in Canada where local information is important, why is a national flood risk assessment needed?*

<u>R6.</u> The idea is a way to address flood risk at large scale, and we addressed the importance of this earlier. Even at the provincial level where one province in Canada (e.g., Quebec is more than twice the area of France) is too large for detailed flood mapping based on hydraulic modeling. Our approach is useful even at the provincial level, especially in light of the fact that we reproduced the maps using 20 m resolution.

<u>7.</u> *[Page 15, Lines 16-20] It is suggested that hazard levels can be reclassified locally to match floods with different return periods in areas where flood inundation using hydraulic modeling is available. But, how useful are local topography-based flood hazard maps where flood inundation maps based on hydraulic modeling already exist? Also, topography-based flood hazard maps does not account for backwater and other hydraulic effects on areas upstream of flood protection. One related question is also how useful flood hazard maps with different return periods are if many floods are caused by ice-jams [Page 7, Lines 7-8; Page 18, Lines 11-14]?*

R7. We meant that areas where hydraulic modeling was done can be used as key locations to identify the water stage that corresponds to certain flood frequencies, which can be also simply approximated using rating curves). When flood stages of different flood frequencies are estimated, they can replace our hazard classes. Perhaps our map can be also used for practical extrapolation over larger areas based on finding match between our map and modeling-based inundation maps at some key locations. The issue of backwater curve not captured by our approach is certainly acknowledged in our manuscript (Page 19, lines 10-14).

Ice jams do cause floods. However, this is not a universal phenomenon. At locations where information on ice-jams are available, floods can still be translated to flooding depths and the same map can be used to determine the associated hazard upstream of it, independent of return-periods.

8. *[Page 16-17, Lines 23-24, 1-3] The authors bring up the issue with overglow effect when analyzing nightlight data. Have potential overglow effects been analyzed for the 2013 nightlight data used in this study, e.g., in comparison with previous years?*

R8. Overglow effect is inherent with nightlight images for all years. We did not carry out any comparison study on overglow variations in nightlight images as the decision was to use the latest nightlight imagery for the study. The classification of DN into different classes alleviates the overflow effect to some extent.

9. *[Page 17, Lines 10-19] There is a discussion that population data should be used together with nightlight data to separate social and economic impact, as airports and industrial areas show high luminous values but low population density. I will argue that although these built-up areas have low population density, they have high social impact, e.g., airports.*

R9. We agree with the reviewer. The purpose here was to show that using only census data might not be enough to determine social impacts as zero population according to census do not mean no human presence. There is still capital investment and human lives, which are disturbed at different levels when homes, workplace, or transportation are impacted. A sentence about this was added in the revised manuscript (Page 15, lines 17-18).

10. *[Page 19, Lines 12-16] There are many uncertainty aspects with the classes identified and some of the methods used – is the final product really useful and practical [Page 20, Lines 6-7] - also when considering the shortcomings the authors have presented?*

R10. The classes identified and methods used do have a degree of uncertainty with them and we have identified and provided discussion on them in the manuscript. The final product is still useful and practical as it is easy to obtain these maps for any part of the country. The shortcomings do not affect the methodology as much as it affects the end product. With the provided approach, the product can always be subject to improvements when finer/accurate data become available.

However, it should be noted that in this revised manuscript, the product itself is improved as it was redeveloped using much finer-resolution DEM, and both quantitative and qualitative validation are provided in the revised manuscript.

11. *The article has 10 figures, are all of them needed? For example, Figure 1 – a and b should be combined if to be included at all. Also, is both a and b in Figure 2 needed, they show the same information. Figure 5 – exclude enlarged figures, and visually improve the main figure.*

R11. Yes, we agree regarding combining Figure 1 a and b in one piece, and we did so in the revised manuscript. Figure 2 is important to show, at least visually, the effect of classification of nightlights. As for figure 5 (New figure 4), the enlarged portions are shown to discuss visual comparison and is now further supported by quantitative comparison.

12. *Minor issues: [Page 1, Line 13] The authors state that the study uses datasets at reasonably fine resolutions to create flood risk maps – what is considered reasonable?*

R12. This statement was modified to "The study focuses on using global and national datasets available with various resolutions to create flood risk maps."

13. *[Page 9, Line 4] What do you mean by horizontal distance?*

R13. We are referring to a buffer like distance while describing DFND. However, in GIS, the term "buffer" is usually applied to concentric distances to a feature (line, point or polygon) in vector format. For the present study, the stream network was retained in raster format to maintain consistency in all subsequent calculations. Horizontal distance refers to the Euclidean distance between the drainage cells and adjoining cells that are estimated using the "Euclidean distance" tool in ArcGIS, followed by reclassification using the limits mentioned in Table 1. Hence, the word "buffer" was avoided and "horizontal distance" was used instead.

14. *[Page 9, Line7] EAND instead of EFND*

R14. Thanks, we corrected it.

15. *[Page 11, Lines 19-22] It is stated that the average values of all nightlight satellites were used in this study, but there is only one available for 2013.*

R15. As the reviewer pointed out, data for 2013 is only from a single satellite. The sentence referring to this was modified in the revised manuscript (Page 13, line 21). The availability of data from more than one satellite is true for some years for which data are available and we were referring to that.

16. *[Page 17, Line 17] What is the "average" effect?*

R16. Simply what we meant is that integrating two aspects in one can mask the individual effects.

17. *[Page 21, Line 31] De Moel should be de Moel.*

R17. It is now corrected in the revised manuscript.

18. *[Page 23, Line 25] The reference Schanze is not found in the text.*

R18. It was removed from the reference list in the revised manuscript.

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List of changes made in the revised manuscript

- All flood hazard related maps were reproduced using the DEM-20, and lakes (major water bodies) were marked in black color;
- Figure 1a and 1b were combined into one part;
- Old Figure 4 was removed and subsequent figures renumbered;
- Figure 5 is new in this revised manuscript;
- Figure 7 was modified;
- Text changes on Pages 22, 25, 26, 27, 29, 31, 33 – 38 according to the page numbers in this document.

Topography- and nightlight-based national flood risk assessment in Canada

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Abstract

In Canada, flood analysis and water resource management, in general, are tasks conducted at the provincial level; therefore, unified national-scale approaches to water-related problems are uncommon. In this study, a national-scale flood risk assessment approach is proposed and developed. The study focuses on using global and national datasets available ~~at reasonably fine~~with various resolutions to create flood risk maps. First, a flood hazard map of Canada is developed using topography-based parameters derived from digital elevation models namely Elevation Above Nearest Drainage (EAND) and Distance From Nearest Drainage (DFND). This flood hazard mapping method is tested on a smaller area around the city of Calgary, Alberta, against a flood inundation map produced by the City using hydraulic modeling. Second, a flood exposure map of Canada is developed using a land-use map and the satellite-based nightlight luminosity data as two exposure parameters. Third, an economic flood risk map is produced, and subsequently overlaid with population density information to produce a socioeconomic flood risk map for Canada. All three maps of hazard, exposure, and risk are classified into five classes, ranging from very low to severe. A simple way to include flood protection measures in hazard estimation is also demonstrated using the example of the city of Winnipeg, Manitoba. This could be done for the entire country if information on flood protection across Canada were available.

The evaluation of the flood hazard map shows that the topography-based method adopted in this study is both practical and reliable for large-scale analysis. Sensitivity analysis regarding the resolution of the digital elevation model is needed to identify the resolution that is fine enough for reliable hazard mapping, but coarse enough for computational tractability. The nightlight data are found to be useful for exposure and risk mapping in Canada; however, uncertainty analysis should be conducted to investigate the effect of the overglow phenomenon on flood risk mapping.

Keywords: flood hazard, exposure, risk, nightlights, Canada.

1 Introduction

Rivers, and water bodies in general, have always been the most attractive landscape feature for humankind. Historically and to date, rivers have provided people with water for drinking and agriculture, food, an inexpensive mode of transportation, a natural drain for their effluents, and fertile land for agriculture in the floodplains. Consequently, most populous cities in the world are built around rivers. Interestingly, even recent studies show that people are still moving closer to streams in various regions of the world (Ceola et al. 2015). The increased flood hazard comes as a natural consequence of encroaching on floodplains.

Globally, floods are among the most feared natural hazards as they can inflict large scale economic and social damage, cause panic, and disrupt essential services. Annually, thousands of lives are lost due to floods, with 5200 lives, for example, claimed in 2011 alone (Balica et al. 2013). The most recent 2016 floods in Louisiana, USA, claimed 13 lives and left 40,000 homes under water. In Canada, flood damages exceeded 7.4 billion US dollars over the recent five years (2010-2015), with 9 lives lost and more than 100,000 individuals directly affected, according to the CRED/OFDA International Disaster Database (http://www.emdat.be/database). This has led the

Canadian government to establish FloodNet – a Canada-wide strategic research network for flood forecasting and impact assessment.

Floodplains and low-lying lands are typically areas with high levels of flood hazard due to their elevation and proximity to rivers; however, society makes such areas more exposed by inhabiting them and establishing valuable economic investments, with insufficient measures to contain vulnerability in most cases, and thus, increasing flood risk as the product of hazard, exposure, and vulnerability (Balica et al. 2013; UNISDR, 2009; Samuels et al., 2009). Some argue that areas that have not been flooded for a long time tend to be encroached by the society, causing the damage from future floods to be higher than expected, whereas areas that were recently damaged by floods seem to encounter lower than expected damages when another flood occurs (Di Baldassarre et al. 2015). It has been suggested that social memory plays a significant role in flood vulnerability as societal preparedness can be different based on the recent history of floods. This emphasizes the importance of developing a systematic flood risk assessment approach that helps societies, insurance companies, water managers, and policy makers make informed decisions.

National flood risk assessment approaches are useful but challenging as data required to develop realistic approaches can be extensive, and detailed hydraulic modeling without proper prioritization of high risk areas can be unjustifiably costly. In recent years, there has been an increasing use of remotely sensed and global datasets in water resources as they can make such studies on a national scale possible. For example, GRACE (the Gravity Recovery and Climate Experiment) has been shown to provide data on water cycle and groundwater reserve that are needed for water management (Famiglietti and Rodell, 2013). Satellite-based data, e.g., snow cover data, have proven valuable for calibrating hydrological models (Parajka and Bloschl, 2008) and for flood detection and mapping (Brakenridge and Anderson, 2006). Ceola et al. (2014; 2015) used 1-km resolution nightlight datasets to show human interaction with streams as well as exposure to floods, based on the fact that nightlights reflect human activities. As nightlights can indicate the spatial distribution and temporal trends, in certain regions, of human activities around rivers, we reiterate that they are of obvious relevance to flood risk assessment studies, especially on a large scale.

Ceola et al. (2014) relied mainly on the proximity of population to rivers to assess exposure to floods. However, a research question that has been left unaddressed by previous studies that used nightlights relates to the datasets that are needed, in combination with nightlights, to establish flood risk assessment approaches that are realistic and feasible. The aim of this study is to integrate several and relevant sources of information to develop a flood risk assessment approach for Canada, which will lead to national flood hazard and risk maps that benefit from topographic information, remotely sensed nightlight data and, as an option, local information to estimate vulnerability. The end product should be flexible, easily updatable, and help stakeholders assess areas that require further attention through, for example, detailed hydraulic modeling.

2 Flood hazard, exposure, vulnerability, and risk

The terms of flood hazard, exposure, vulnerability, and risk are sometimes confusing to readers as they may have different meanings for different users. The four terms may even be used interchangeably to refer to the same thing. Following the definition provided by UNISDR, 2009; IPCC, 2012; Colleantuer et al., 2015, flood risk is given by a combination (e.g. the product) of hazard, exposure, and vulnerability (Equation 1).

Flood risk = flood hazard × flood exposure x flood vulnerability (1)

Hazard is used by some researchers to mean the flood disaster itself or its potential occurrence (Gilard, 2016; UNISDR, 2009, Colleantuer et al., 2015), identified more precisely (Sayers et al., 2002) by two main components – source (e.g. rain) and pathway (e.g. flood extent and depth). This definition is appropriate and usually quantified from an engineering perspective as the probability of occurrence of a flood event (Balica et al., 2013; de Moel et al., 2009). Intuitively, a low-lying area that is close to a river has a higher level of flood hazard (impacted by more frequent floods) than an area of higher elevation that is far-removed from the river. In this study, *distance* from, and *elevation* above, the river are used as two indicators of the flood hazard level of any land pixel.

Exposure (i.e. elements at risk) 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 can be indicators of flood exposure. *Vulnerability*, following Adger (2006) and Colleantuer et al. (2015), is defined as the capacity of the society to deal with the flood event, namely the state of susceptibility to harm from exposure to an undesired event, floods in this study, associated with environmental and social change and lack of capacity to adapt. Lack of flood defenses or protection of economic values and human lives susceptible to floods are indicators of vulnerability. Obviously, the product of exposure and vulnerability reflects an integrated measure of the environmental and socioeconomic consequences of floods. The main reason for the increase in losses due to floods is the increase in the population and people's preference to reside in flood prone areas, which makes them exposed to floods (Jonkman, 2005; Ceola et al. 2014). An example of the policy and social dimension of exposure is depicted in Figure 1 for the city of Fort McMurray, Alberta, Canada and its surrounding areas, which shows how the society encroached into areas of higher level of flood hazard over the years. Increase in exposure is indicated by the spatial expansion and increase in nightlight luminosity from 1999-2013, which is considered a proxy for socioeconomic activities (Doll et al. 2000), overlaid with the flood hazard map showing only high hazard areas. The hazard was calculated based on elevation above and distance from the nearest rivers, details of which are provided in the forthcoming sections. The figure is obtained after combining and reclassifying the two maps to show that significant development has occurred over the years in high hazard areas.

~~The increase in exposure is indicated by the spatial expansion and increase in nightlight luminosity from 1999-2013, which is considered a proxy for socioeconomic activities (Doll et al. 2000). For the simplicity of display, the flood hazard map was classified into three levels of hazard based on elevation above and distance from the nearest rivers. Land-use, nightlight, and population are used in this study as indicators of flood exposure.~~

In the literature, frameworks or guidelines for flood risk assessment at the national level are limited. A classic example is the work of Hall et al. (2005), who conducted a national-scale flood risk assessment in England and Wales for the purpose of prioritization of resources for flood management. The methodology of Hall et al. (2005) benefited from rich information available on the standard of protection, condition and location of flood defences, as well as flood extent maps, occupancy, and asset values in England and Wales. de Moel et al. (2009) noted that flood extent maps are the most commonly produced flood maps in Europe, and that only very few countries have developed flood risk maps that comply with the European Directive (2007/60/EC). Later, Lugeri et al. (2010) developed a flood hazard map of Europe, identifying low-lying areas adjacent to rivers, and used it with land-use data and a damage-stage relationship to identify flood risk. A coarse global scale flood risk assessment was also developed by Ward et al. (2013) using global hydrological and hydraulic modeling. The work presented in this paper is at a finer resolution, and using different types of data based on topography and remote~~ly~~ ~~sensed~~sensing, which lead to a low-cost flood mapping product that is relevant at a national scale.

The level of detail required for flood risk analysis is an important issue, which is obviously related to the spatial scale of the study area. Even in urban areas, Apel et al. (2009) found that a medium-level complexity model for both hazard and exposure is sufficient. One could expect that on national scale for large countries, aggregate measures and index-based approaches might be the feasible choice. When compared with a physically based modeling approach, a parametric approach, which uses flood hazard and exposure indices, can direct decision makers to simplified usage and simpler understanding of the risk, and thus, better allocation of resources and investments for flood management and protection (Balica et al. 2013).

As the second largest country in the world, the continental extent of Canada from 41.7^{o} to 83.111^{o}N and from 52.619^{o} to 141.010^{o}W, encompasses different topographies ranging from flat prairies to mountains and different climates from semi-arid to wet. On an average annual basis, Canadian rivers discharge 9% of the world's renewable water resources (Whitfield and Cannon, 2000). Fluvial floods in Canada can happen as a result of excessive rainfall, similar to the 2013 flood in Alberta, however, high water levels often result from reduced channel capacity due to ice and debris jams (NRCC, 1989). Therefore, water levels and extent of floods may not reflect the conventional return period associated with the flood discharge. Floods are usually monitored, analyzed, and managed at the provincial level, which makes a Canada-wide unified flood modeling, mapping, and analysis, as well as flood-related data accessibility laborious tasks.

3 material and methods

To develop a national-scale framework for flood risk assessment in Canada, parameters representing the concepts of hazard and exposure were identified and subsequently, a flood risk index was developed based on the integration of both hazard and exposure. All three types of maps – hazard, exposure, and risk – are presented separately as they each contain distinct and useful information. In a subsequent step that is developed for the city of Winnipeg, Manitoba, we show how flood protection measures, as might be represented within hazard or vulnerability, can be incorporated.

3.1 Hazard parameters and mapping

It is common to define and classify flood hazard based on flood magnitude and/or frequency (Apel et al. 2009; Balica et al. 2013), but classification based on depth is also used (Masood and Takeuchi, 2012). The frequency and magnitude of floods, along with their associated inundation depth, are constantly changing due to economic development and climate change (Milly et al. 2002), which challenges the estimates and definition of flood hazard and risk on a range of scales (Merz et al. 2010a). Therefore, classifying hazard levels on a national scale based on topography (Lugeri et al. 2010) is both realistic and sound, as it can be converted locally to other types of classification as will be discussed here in the results section.

In this study, flood hazard was estimated using two parameters: elevation above the nearest drainage (EAND), which is similar to HAND (height above nearest drainage, Rennó et al. 2008) and distance from the nearest drainage (DFND). These two parameters define the topography of an area and thus, help in determining the relative position of a place with respect to the stream. Both parameters were derived from a Canadian digital elevation model (DEM) obtained from

Natural Resources Canada (http://geogratis.gc.ca/site/eng/extraction). The CDEM is derived from the Canadian Digital Elevation Data, which were extracted from the hypsographic and hydrographic elements of the National Topographic Data Base (NTDB)~~ at the scale of 1:50 000~~, the Geospatial Database (GDB), various scaled positional data acquired by the provinces and territories, or remotely sensed imagery. The CDEM is available for download at various resolutions ranging from 0.75 arc second (~20m at the equator) to 12 arc seconds (~326m at the equator) as tiles that are consistent with the National Topographic System (NTS; Official division and identification system for the base topographic maps of Canada). The vertical accuracy of the DEM varies with location, with a ~~ with a ~~measured altimetry accuracy of under 5 meters per tile for most parts of the country (Natural Resources Canada, 2016).

EAND is a terrain descriptor, which produces a new normalized DEM where pixel values represent altitudes relative to the local drainage instead of the mean sea level. To allocate elevation values to the pixels with respect to local drainage, we first identified the drainage network by using the ArcGIS hydrology tool. The DEM, available in raster format, was initially filled by identifying pits and raising their elevation to the level of the lowest pour point. After obtaining the filled DEM, the second step was to generate flow direction. There are a total of eight valid output flow directions, corresponding to the eight adjacent cells into which water may flow. The flow direction tool follows the eight directions flow model, which was presented by Jenson and Domingue (1988). After identifying the drainage network for Canada, a new raster was created using the Euclidean allocation tool available in the spatial analyst toolbox of ArcGIS. All pixels within this raster were assigned the new values of elevation, which were the elevation values of the nearest drainage pixel based on Euclidean distance. Finally, this output was subtracted from the original elevations to obtain the EAND map for the study area. Also, for each pixel, the DFND – the horizontal distance from the nearest drainage network – was calculated. Negative values of EAND could be observed because there were depressions lower than the nearest stream. EAND and DFND were classified into five different ~~EFND~~ EAND and DFND classes as shown in Table 1. The lower values of EAND and DFND were assigned the higher class values as they indicate the low-lying and close areas to the streams, respectively, and thus, the highest level of flood hazard. The hazard value was calculated based on the product of EAND and DFND classes; e.g. a hazard level of 20 could result from EAND class 4 and DFND class 5 (or vice versa). Finally, hazard values were reclassified into five different hazard classes as shown in Table 1. The class intervals were selected somewhat arbitrarily in this study. However, depending on the topography of the study area, other hazard class intervals can be selected.

Table 1. Classes of elevation above nearest drainage (EAND), distance from nearest drainage (DFND), and the resultant 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	4	1001 – 2500	4	16 – 20	4	High
4.1 – 6	3	2501 – 5000	3	11 – 15	3	Medium
6.1 – 8	2	5001 – 10000	2	6 – 10	2	Low
> 8.0	1	> 10000	1	1 – 5	1	Very low

The topography-based hazard mapping approach developed in this study was ~~evaluated~~ validated quantitatively against flood inundation map developed using hydraulic modeling by the city of Calgary (Government of Alberta, 2013) for an area of Calgary to evaluate the utility of our approach. Validation is meant to assess that the product does provide useful information for locating the areas at higher flood hazard (Biondi et al., 2012). Two performance measures were selected for validation: Sensitivity and specificity (Altman and Bland, 1994). Sensitivity and specificity are measures that indicate the probability of correctly classifying a pixel within the flooding extent as flooded or non-flooded. The measures are easy to calculate and have been used in classification studies in the past (e.g. Murtaugh, 1996; Cutler et al., 2007). Sensitivity (Sv) is defined as,

$$S_v = \frac{F_p}{F_{ap}} \qquad (2)$$

$$S_v = \frac{F_p}{F_p + F_{op}}$$

Where F_p, F_{ap}, and F_{op} are the number of truly predicted flooded pixels, the total number of actually flooded pixels, and the number of pixels actually flooded that were predicted as not flooded, respectively. Here, "truly predicted" refers to the pixels in hazard level *severe* in the hazard map, and "actually" refers to pixels in the flood inundation map used for validation. Sv ranges from 0 to 1, with values closer to 1 indicating high probability of correctness in classifying a flooded pixel. Specificity (Sc) is defined as,

$$S_c = \frac{NF_p}{NF_{ap}} \qquad (3)$$

$$S_c = \frac{NF_p}{NF_p + NF_{op}}$$

Where NF_p, NF_{ap}, and NF_{op} are the number of truly predicted not-flooded pixels, the total number of actually not-flooded pixels, and the number of pixels actually not-flooded that were predicted as flooded, respectively. Sc ranges from 0 to 1 where values closer to 1 indicate high probability of correctness in classifying a pixel as a non-flooded pixel. –A qualitative assessment of the flood hazard mapping was also conducted against an aerial flood photo in Saskatchewan, Canada. Another important parameter that affects the flood and its impact on the floodplain is the existence of flood protection or defence measures. Including flood protection within hazard or vulnerability can be debatable. However, the approach we adopt in this study depends on the type of the flood protection. Structural flood protection measures that affect the flood runoff itself (Mays, 2011), such as dikes and dams, are included within hazard assessment as they affect the flood stage-discharge and discharge-frequency relationships. Non-structural measures, such as zoning, insurance, rearranging spaces, and raising buildings, are included within vulnerability assessment because they affect the susceptibility of the floodplain (UNISDR, 2009) rather than the flood water (Mays, 2011). When such information on flood protection is available for the whole country, flood protection can be included as the third hazard parameter to identify the final hazard level or as a separate vulnerability parameter. Flood protection can be included as a binary parameter, i.e. protected/unprotected or in the form of various levels of protection. For the current study, complete information on flood protection across Canada was not made available to us; however, we investigated how to consider protection on a smaller regional scale around the city of Winnipeg, Manitoba, and it will be shown in the results section.

3.2 Exposure parameters and mapping

As reflected in most flood studies, there is no doubt that land-use is the most relevant flood exposure parameter as it indicates the land or property value, e.g. urban development or agricultural land. In this study we also used a *land-use* map for Canada available through the North American Land Change Monitoring System (NALCMS; Latifovic et al. 2012), which is available in raster format at a spatial resolution of 250 m and can be obtained through http://www.cec.org/tools-and-resources/map-files/land-cover-2005. The original land-use data taken from NALCMS define 19 land-use types for North America, out of which there are 15 types found in Canada. These types were further reclassified for the purpose of this study into five types as shown in Table 2. There are no agreed upon global rules for land-use classification, however, for the purpose of national-scale flood risk assessment, these five types were judged to be sufficient, and also bear some similarity to the European Corine Land Cover classes (http://uls.eionet.europa.eu/CLC2006/CLC_Legeng.pdf). The reclassified land-use types were then assigned values between 1 and 5 according to their economic value, with the values of 5 and 1 assigned to urban areas and water bodies, respectively.

The second flood exposure parameter considered in this study is *nightlights*. Nightlight satellite imagery has been investigated as a proxy for human activities, and has been used in various studies ~~from~~ for different domains (Raupach et al., 2010; Zhou et al., 2014; Gomez et al., 2015; Townsend and Bruce, 2010). Ceola et al. (2014) explored nightlights to examine human exposures to floods worldwide, using HydroSHEDS data, based only on proximity to streams. The study included 175 regions covering 168 countries with the exception of Canada, Russia, and part of northern Europe. The nightlight values, 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 (NC) as shown in Table 3. The nightlight data were obtained from the National Oceanic and Atmospheric Administration (NOAA) of the United States (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html). The spatial resolution of the dataset is 30 arc-seconds (corresponds to roughly 1 km near the equator, and around 600 m^2 over the populous southern Canada) and the data are available for the period 1992-2013. When datasets with multiple spatial resolutions were used, the maps with coarser resolution were resampled to correspond with the finer resolution, and thus, the final product has the finer resolution. The most recent available data of 2013 were used for our analysis, and the Canadian nightlight map of the year 2013 is shown in Figure 2. ~~Usually data from more than one satellite are available and, similar to Ceola et al. (2014; 2015), the average values of all satellites were used in this study.~~

Table 2. Classes of land-use types in Canada along with their percent of area covered.

Land-use type	Reclassified land-use	Land-use class (LC)	% of area covered
- Wetland *(marshes, swamps, mangroves);* - Water *(open water);* - Snow and Ice *(perennial cover)*	Water bodies	1	16
- Barren land; - Sub polar or polar barren moss - Temperate or sub-polar grassland; - Sub polar or polar grassland	Wasteland/ Grassland	2	28.2
- Temperate or subpolar needle leaf forest; - Temperate or subpolar broad leaf forest; - Mixed forest; - Temperate or subpolar shrub land; - Subpolar or polar shrub land	Forest	3	50
Cropland	Agriculture	4	5.7
Urban and built up	Urban	5	0.1

Table 3. Classes of nightlight luminosity in Canada from 1 – 5. The exposure classes were selected based on the product of nightlight and land-use classes.

Nightlight value (DN)	Nightlight class (NC)	Nightlight level	% area covered	Exposure	Class	Exposure level
0 – 5	1	Very low luminosity	93.6	1 – 5	1	Very low
6 – 10	2	Low luminosity	4.4	6 – 10	2	Low
11 – 30	3	Medium luminosity	1.4	11 – 15	3	Medium
31 – 59	4	High luminosity	0.5	16 – 20	4	High
60 – 63	5	Very high luminosity	0.1	21 – 25	5	Severe

The ranges of the first two classes (having DN $\leq$ 10) were kept narrow because they are spread over most part of Canada (about 98% of Canada's area). They indicate absent or low human activity and, hence, from a flood exposure perspective they are less important. Accordingly, low nightlight class values were assigned to them. The range of DN values 11-30 is significant as it is mainly found in parts of the forest and agricultural land that possess more important resources than the first two classes. The DN range of 31-59 is found in the outskirts of cities and towns, and represents mostly agricultural lands and small establishments. The pixels having DN values of 60 and above fall within city boundaries and contribute up to 80% of the nightlights of the city. Therefore, 60 and above were kept as a separate class (NC=5), highlighting urban centers, which are the most flood exposed areas. Similar to the calculation of the hazard index, exposure was also calculated as the product of land-use and nightlight classes, leading to values ranging from 1 – 25. The exposure values were further reclassified into five classes as shown in the last three columns of Table 3, and a flood exposure map of Canada was produced.

Finally, and based on equation (1), flood risk was calculated as the product of hazard and exposure, as local vulnerability information was not available, and was reclassified into five risk classes as shown in Table 4. In the absence of population data, nightlights might be taken as a surrogate for population. However, our investigation reveals that both datasets may differ in some places. This is expected as nightlights are more representative of economic investment and activities, which can be different from population. For example, airports and industrial and commercial areas are highly luminous but the census data show low or no population. Human harm can still happen in areas indicated by census data as "zero-population". The nightlight data capture such areas. However,~~Moreover,~~ population data, especially when associated with qualifiers regarding different groups and income can be distinctively used to assess social vulnerability or exposure to floods (Adger, 1999). As floods may have different impacts on the relative well-being of individuals and groups, which is not reflected by classic economic exposure, it is important to identify the impact of floods on population separately, without integrating or averaging with other exposure parameters. Therefore, in this study the physical flood risk map of Canada was produced first, then it was overlaid with the population information to allow reclassification of the risk map based on the distribution of population.

Table 4. Classes of flood risk in Canada, which results from the product of hazard and exposure.

Flood risk value	Risk class (RC)	Risk level (RL)
1 – 5	1	Very low
6 – 10	2	Low
11 – 15	3	Medium
16 – 20	4	High
21 – 25	5	Severe

4 Results

4.1 flood hazard mapping

The topography-based (EAND and DFND) flood hazard map of Canada, developed and classified based on the method explained in the previous section, is shown in Figure 3. Large areas of the country are classified under high and severe levels of flood hazard due to their low elevation and proximity to rivers. However, most of these areas have negligible human presence and economic investments. The flood hazard map can be useful for large-scale planning and development, where avoiding encroachment into flood hazardous area is recommended. In support of identifying the flood information needed for flood insurers to assess their exposure to floods and to price the flood elements at risk, Sanders et al. (2005) identified the availability of fine-resolution DEMs as the key obstacle for such analysis. For the national-scale analysis in this study, we ~~used~~ tested the

DEM-326~~ m DEM resolution~~, as it is computationally tractable for a country like Canada. However, a comparison between hazard mapping using the ~~326 m and a much finer resolution of 20 m~~DEM-326 and DEM-20 was conducted on a smaller area around the city of Calgary, Alberta. Even though ~~Figure 4 shows~~ an overall reasonable visual match between both flood hazard maps produced using the different resolutions was found, there ~~are~~ were important differences~~ to be observed~~. The stream network itself, generated using the DEMs, ~~can~~ have significant differences, ~~depending on the resolution. Figure 4(b), produced using the 20 m DEM, shows~~and a more realistic representation of the ~~Elbow River and its confluence with the Bow River~~rivers, compared to ground truth, ~~and thus, a more reliable flood hazard assessment for the area around downtown Calgary~~was achieved using DEM-20. ~~Other areas, such as the top right corner of the city, appears only with the 326 m resolution as an artefact of the coarse DEM's resolution. Depending on the purpose and use of the flood hazard map, caution must be exercised with regard to the adopted DEM.~~All maps in this study were, thus, produced using the DEM-20.

A flood inundation map of an area in the city of Calgary was produced by the City (Government of Alberta, 2013), based on a 100-year flood determined by flood frequency analysis and using the hydraulic model HEC-RAS. This map was prepared for the reaches of Bow and Elbow River flowing through the city limits. A comparison between the topography-based flood hazard mapping method adopted in this study and the hydraulic modeling-based 100-year inundation map is shown in Figure ~~5~~4. Visually, ~~T~~there is good agreement between the model-based 100-year flood inundation (shown as hatched grey area) and the hazard level classified in this study as *severe* (Table 1). Two sections of the ~~Bow and Elbow Rivers~~reaches are enlarged, as examples, for better visual comparison between both methods. As shown in the main map (on top) in Figure ~~5~~4, there is good agreement in other sections as well, and there are small areas that do not match well. Some smaller areas of the 100-year flood are extended over the second highest hazard area defined in this study as *high*. This was expected, as our classes shown in Table 1 were selected somewhat arbitrarily across Canada. This agreement between the two maps were further analyzed based on performance indices (equations 2 and 3) to quantify the agreement between the inundation map and the hazard level *severe*. The sensitivity (Sv) was found to be 0.75 indicating that the hazard class severe is able to capture 75% of the area being designated as inundated by the 100-year flood inundation map. The specificity (Sc) was found to be higher at 0.85 indicating that the hazard map could be reliably used to identify an area that would not be inundated by a 1 in 100 year flood as determined by the inundation map. The locations where the discrepancy between the two maps exist can be identified visually. The most ~~obvious~~noticeable disagreement between the hazard map and the inundation map is just above the confluence of the Bow and Elbow rivers, where the *severe* hazard level is much wider than the modelled extent. The scrutiny of areal imagery of that area did not indicate the presence of any flood protection measures at that location. A specific reason could not be ascertained to explain the discrepancy, which could vary from the incorrectness of the DEM at that location to the modeling extent of the hydraulic model used to prepare the inundation map. Interestingly, a similar observation for the same location was made by Sampson et al. (2015) in their study wherein, their global hydraulic model also overestimated the inundation extent at the same location.

The hazard levels can be reclassified locally based on different values of EAND and DFND to match particular floods, e.g. 100-year, 200-year, in areas where flood inundation using hydraulic modeling is available. This way, the flood hazard map can be converted into approximate flood inundation maps for floods with particular return periods. To check if the hazard map can be compared against an observed flood, a qualitative analysis was also done by visually comparing the hazard map with an aerial imagery of the 2013 flood in the Qu'Appelle River located in the Saskatchewan province of Canada (Figure 5). The image was taken on 06/05/2013, a day after the annual maximum discharge was recorded in the river and the flooded extent is visible in the image. To compare across both maps, the hazard map is overlaid as a mesh on the aerial image. It can be observed from the figure that the flooding extent is well captured by the hazard level *severe* at most locations along the reach. This result further strengthens the relevance of the hazard map and its accuracy in identifying flooding extents.

Another important flood hazard parameter, which was not fully implemented here due to lack of information, is flood protection measures. However, an example using an area near the city of Winnipeg, Manitoba, is shown in Figure 6. The city of Winnipeg is protected from Red River floods using a floodway (appears in the figure in pink color) that carries part of the flood runoff around the city, and a dike (appears in the figure in yellow color) that prevents flood surface runoff from entering the city from the west side. The effect of flood protection of these structural measures is handled in our flood hazard mapping method by identifying the flood depth up to which the city is protected (flood design level), then assigning the design level to the DEM cells in the protected area. A hazard map with and without flood protection for the city of Winnipeg is provided in Figure 6, which shows the reduced level of flood hazard within the city limits. Usually, there are backwater and other hydraulic effects on areas upstream of flood protection, and such effects cannot be easily captured by the topography-based hazard mapping adopted here. Hydraulic modeling is recommended to investigate the effects of flood protection measures on upstream unprotected areas.

4.2 Flood Exposure and Risk Mapping

The flood exposure map of Canada, which integrates land-use and nightlight information, is shown as Figure 7. The areas of higher exposure is mainly concentrated around major urban centers in Canada. As expected, the exposure map is quite similar to the nightlight map (Figure 2b), because the distribution of nightlight matches to a great extent the land-use map; for example, urban areas are much more luminous than forests. However, it is useful to include both types of information as some major capital investments, reflected by high luminosity, can be situated within larger areas classified as agricultural, or forested areas. To demonstrate this, a small area within the exposure map is enlarged and overlaid with the road network map obtained from the National road network (http://geogratis.gc.ca/) and shown in Figure ~~5~~7. Although the exposure indicates “very low” to “low”, the hazard map for the same location indicates a significant area within the “severe” and “high” classes.- Roads were flooded in major Canadian flood events and hampered rescue efforts. Also, some large parks with lower luminosity can be found within the limits of urban areas. Furthermore, nightlights are quantified using the DN, which helps in using them as a proxy for economic investment/damage calculations in the absence of monetary values. It is important to note that one of the shortcomings of using nightlights is the phenomenon of “overglow” (Doll, 2008) – areas of low luminosity shown with false high luminosity due to reflections from surrounding areas with much higher luminosity. Small et al. (2005) listed three major causes for this phenomenon: coarse spatial resolution, large overlap between pixels, and errors in the geolocation.

By assuming that flood vulnerability is homogeneous over Canada, a flood risk map of Canada, which results from the product of flood hazard and exposure only, is shown in Figure 8. Even though severe and high flood hazard areas are spread spatially over the entire country, severe and high flood risk areas are concentrated in urban centers in the southern part of Canada. Severe and high flood hazard in northern areas assume lower levels of risk when integrated with lower levels of exposure in the north due to lack of human activities and urban centers. These maps are in 20 m resolution, which allows for assessing the flood hazard, exposure, and risk in details, which are not visible on a national map.

A key flood exposure and risk parameter, which was deliberately left out of the risk map, is population. Using the example of the Greater Toronto Area in Ontario, Figure 9 shows the differences that are represented by nightlights, population distribution, and land-use maps. The airport area, indicated by a grey triangle, and an industrial area indicated by a grey circle, are typical examples of urban/built-up areas (Figure 9c) with high economic investments that are highly luminous areas (Figure 9a), but very low – close to zero – population (Figure 9b). This confirms that nightlights and population distribution can differ at times, and it is important to include both parameters, but without integrating them in order to avoid the "average" effect.

To identify flood impact on people (social impact) and separate it from economic impact, we propose overlaying the flood risk map (Figure 8) with a population density layer. Figure 10 shows an example of such reclassification of the flood risk map with and without population on a smaller area (the city of Calgary, Alberta) for better visualization of the concept. The central part of the city with high-rise buildings and high population density remains within the highest levels of flood risk where both economic and social risks are at their highest levels. 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 (Figure 10b) in spite of having severe economic flood risk (Figure 10a).

5 Discussion

Even though flood hazard, exposure, and vulnerability maps are all important, the flood hazard map is of special interest to both the public and planners or decision makers. The flood hazard map allows the public to assess the situation of their properties with respect to floods, whether the property is residence, agricultural land, or commercial business. For planners and decision makers, flood hazard maps allow for assessing areas of future development, or locations of strategic establishments. As mentioned earlier, the flood hazard map developed in this study can be reclassified or converted to inundation maps of floods with specific return periods, e.g. 100-year flood, using hydraulic modeling, or even linked to particular recorded flood events, such as the known 1979, 1997, and 2011 floods in Manitoba. In some areas, like the city of Calgary (Figure 4), 100-year flood extent almost matches our severe flood hazard class (< 2 m). In other regions, and depending on the topography, the 100-year flood might cover two or three of the flood hazard classes. Furthermore, local authorities may relate flows at different flood frequencies (e.g., 100 year) to water stage (can be done using rating curves available locally). The stages of different floods indicate clearly which of the hazard classes, determined using the topography-based hazard mapping, will be inundated. This way local authorities can convert the flood hazard map to flood frequencies.

For prioritizing resource allocation and intervention for flood damage mitigation, flood risk is the important indicator as it integrates hazard, exposure, and vulnerability, and reflects the spatial distribution of expected damage. The general flood risk map, similar to Figures 8 and 10a, can be used for prioritizing intervention and estimating compensations based on economic flood risk, but flood risk maps with population, similar to Figure 10b, add an important sociopolitical dimension because they indicate where certain levels of risk affect more or less people. This type of socioeconomic flood risk map can be made public to collect feedback from all stakeholders. Certain groups falling under reduced levels of risk may raise issues of particular social exposure or vulnerability, and help water managers revise the classification or use differential spatial weights to produce more realistic socioeconomic flood risk maps. This approach of engaging both the public and water professionals in co-production of flood-related knowledge can be initiated using the risk maps (Lane et al. 2011).

The simple way presented in this paper for considering the effect of flood protection on the hazard (or vulnerability), and thus the risk, classification can be useful for quantifying the change in the spatial distribution of flood risk. This might prove useful for comparing flood risk with different types of societal risk, e.g. forest fires. This method allows for quick assessment of the value of flood protection measures, and the locations of critical need for such measures.

It is important to note that there are various uncertainties associated with the nightlight and topography-based approach suggested in this paper for flood risk assessment in Canada. The DEM's resolution is an important criterion, and sensitivity analysis might be needed to identify a resolution that is coarse enough for tractable computations, but fine enough for reliable identification of the stream network and the various hazard classes. The available nightlight data are of much coarser resolution (1 km) than the required DEM's resolution. This difference, along with the uncertainty stemming from the overglow phenomenon, can cast some doubts on the nightlight classification. Therefore, exposure and risk maps should be treated with caution when analyzing small areas. Finally, it is relevant to note the importance of local information for the estimation of flood hazard and vulnerability. While the flood risk map based on hazard and exposure may provide important indications to identify critical areas, information on existing flood protection is necessary in order to provide useful guidelines to decision makers. Therefore, obtaining local information is a fundamental step that can be carried out only by effectively cooperating with actors who have a refined knowledge at the local level, like for instance local water managers.

6 Conclusions

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. This low-cost product can be used for early stages of development planning. Identifying the flood hazard level of even areas such as wastelands might prove useful for planning and management of activities like mining in remote and undeveloped areas. 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 risk map, which typically reflects economic risk can be combined with population distribution maps to explicitly identify the social risk dimension as well as overall socioeconomic flood risk. It was shown in this study that nightlight luminosity and population distribution can differ at certain locations, and it is beneficial to use both types of information for flood risk assessment.

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 centers. Complete information on flood protection across Canada should be collected and integrated with the developed hazard and risk maps produced in this study in order for these products to be considered complete and ready to use. Some sensitivity analysis regarding the required DEM's resolution is needed to identify the resolution that is fine enough for reliable hazard mapping, but coarse enough for computational tractability. Both DEM's resolution and the nightlight's overglow phenomenon are possible sources of uncertainty in the maps produced in this study. Attempts should be made in the future to quantify such levels of uncertainty.

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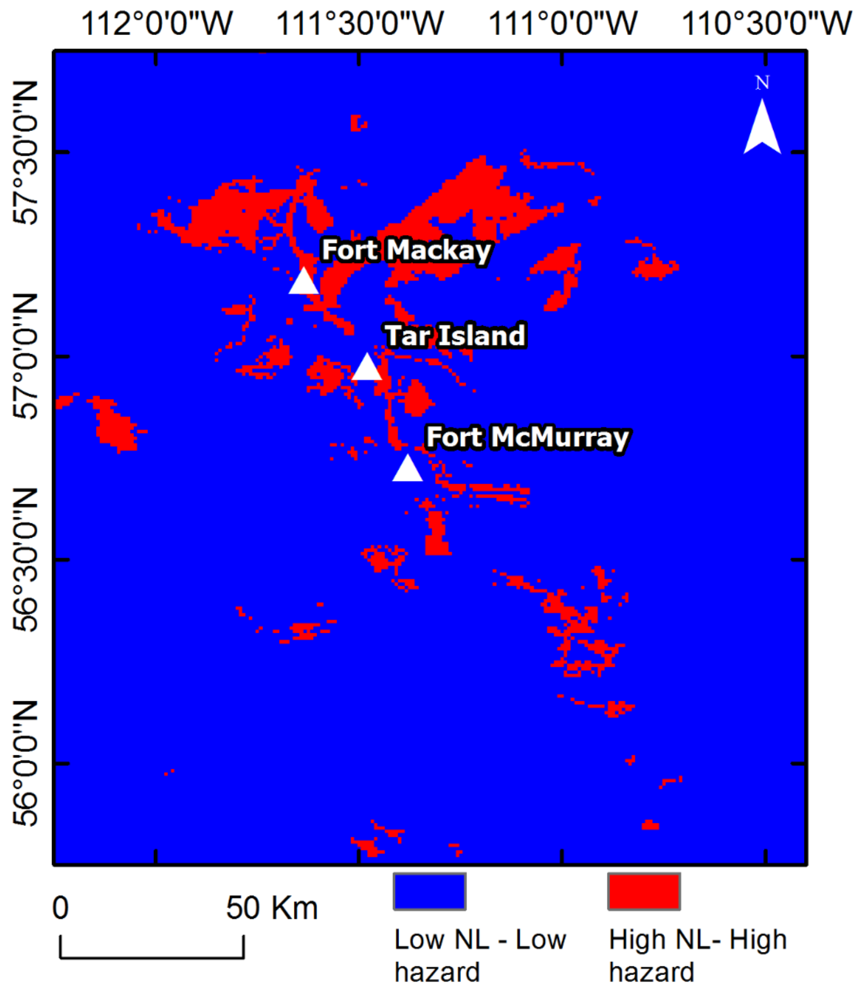

Figure 1: Locations indicating increase in nightlight (NL) activity over high hazard areas between the years 1992 – 2013 (DN_{2013}- DN_{1992})~~(a) Variation in nightlights around Fort McMurray, Alberta, Canada between the years 1992 – 2013 (DN_{2013}- DN_{1992}). Positive values indicate increase in nightlight luminosity; (b) Classified flood hazard map for the same area. The expansion of human activities over high flood hazard area are obvious.~~

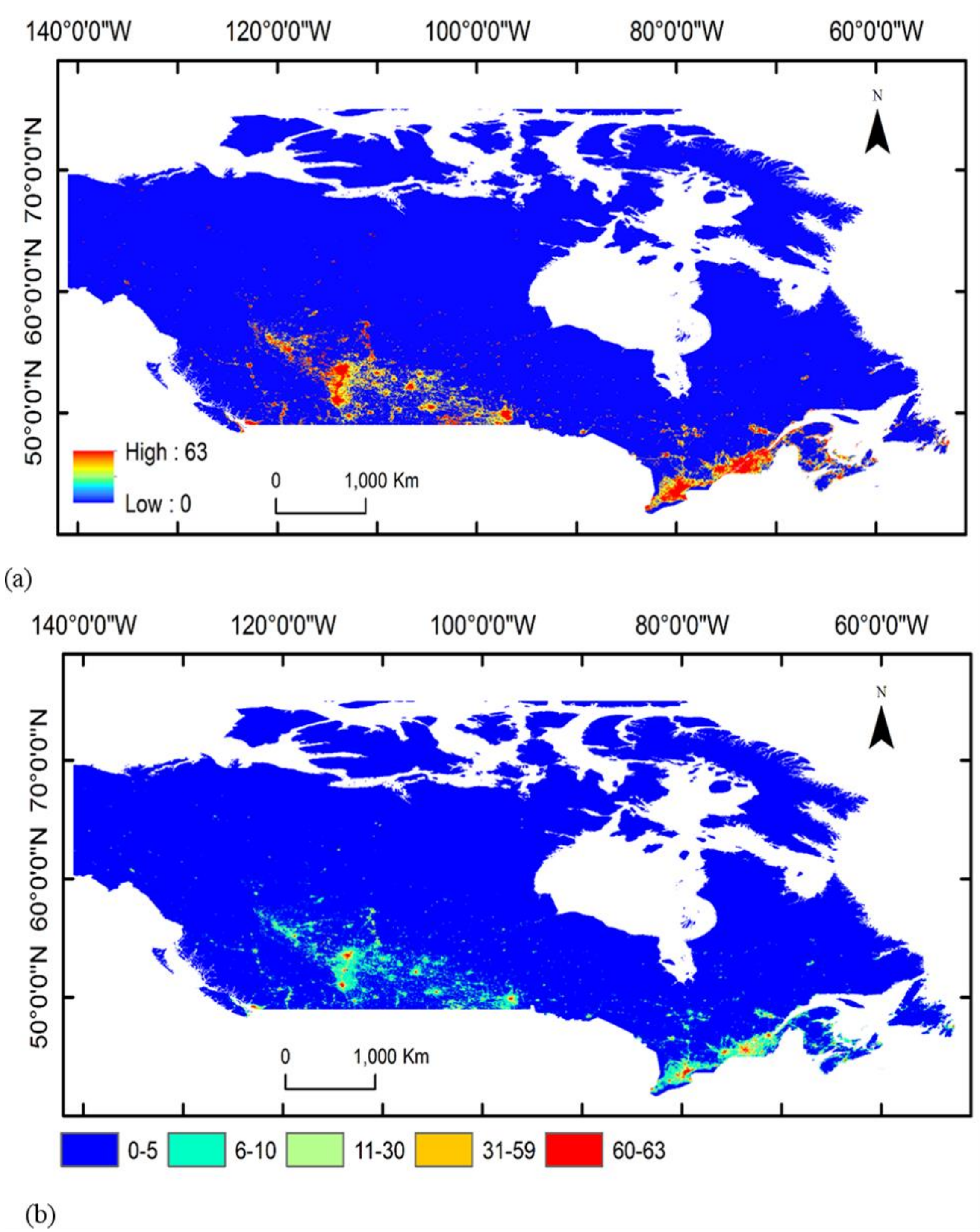

Figure 2: Nightlights over Canada shown as (a) Continuous spectrum and (b) classified as shown in Table 3 into very low luminosity (0-5), low luminosity (6-10), medium luminosity (11-30), high luminosity (31-59), and very high luminosity (60-63).

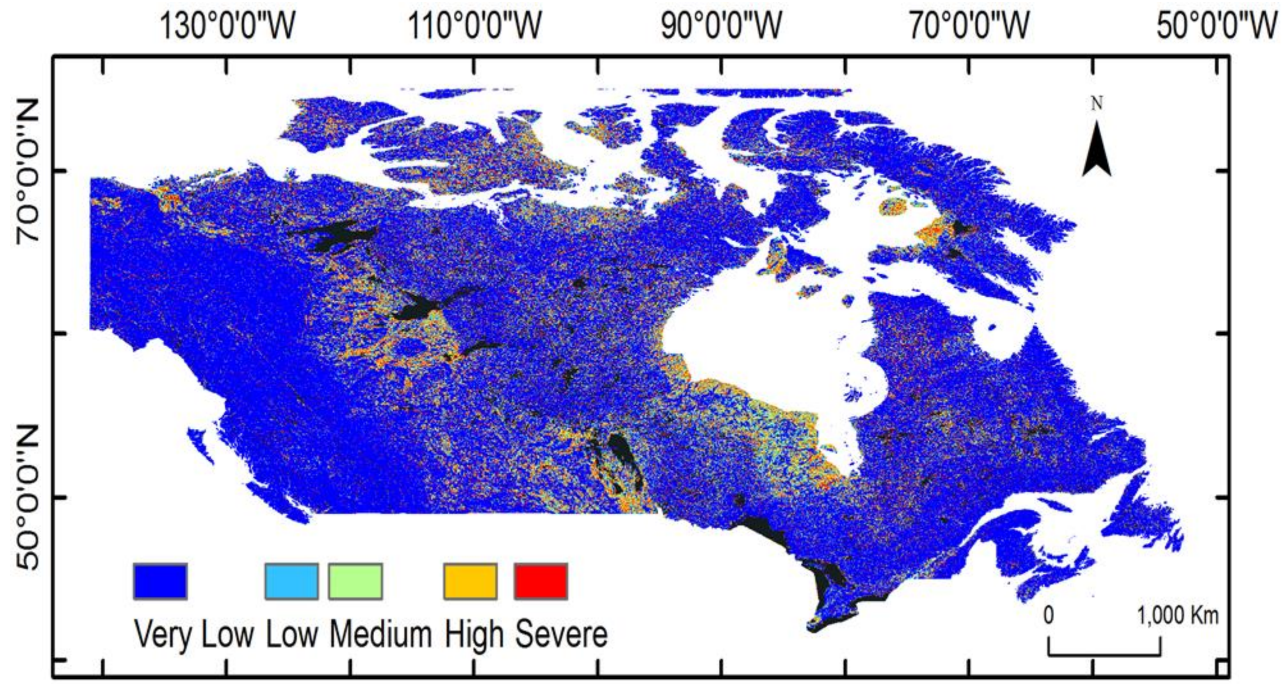

Figure 3: Flood hazard map for Canada obtained using the ~~326m~~ 20 m DEM. Large areas are classified under high- and sever-level flood hazard, but most areas have negligible human presence and investments.

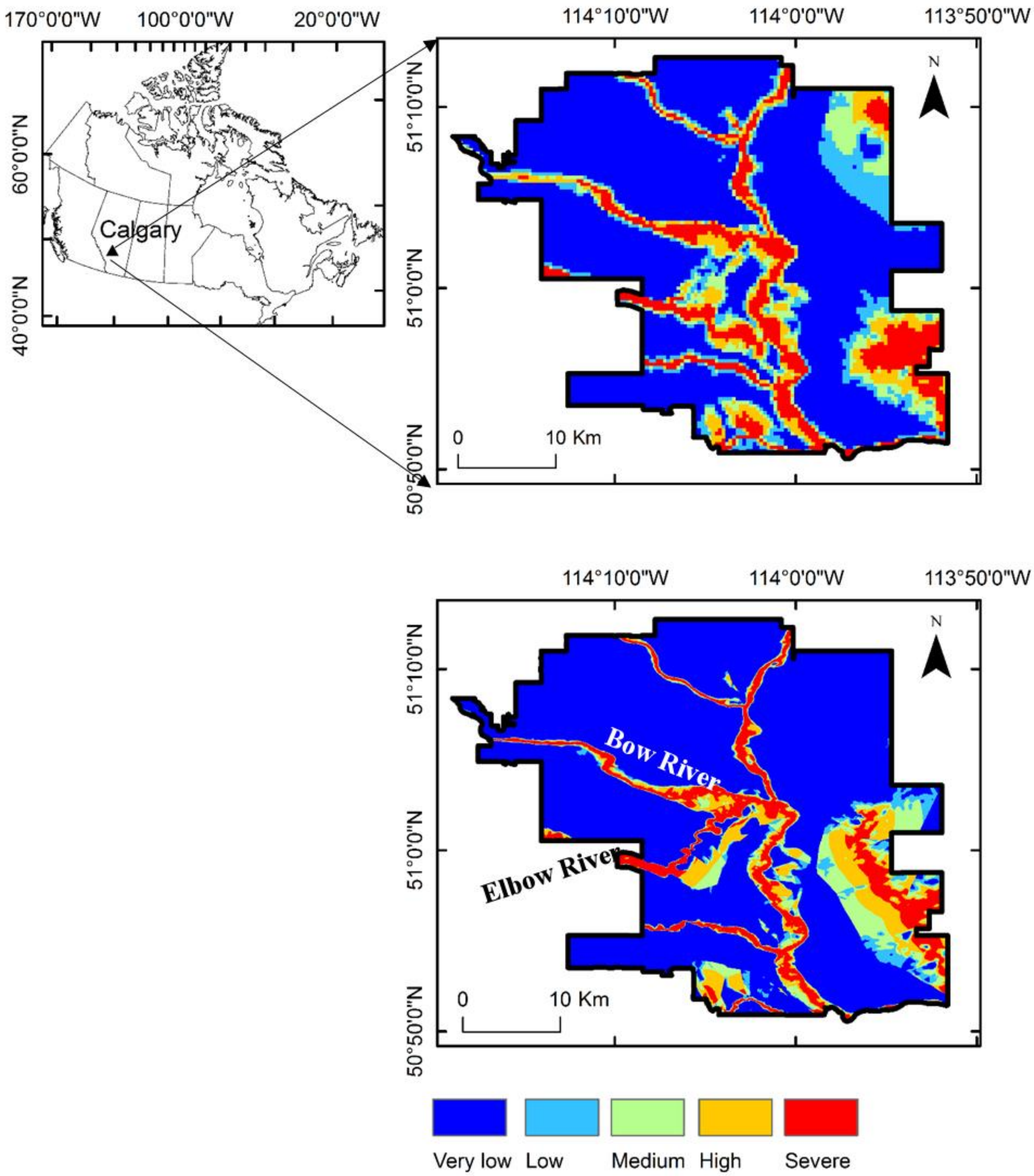

Figure 4: Effect of the DEM resolution on flood hazard map. Example of the flood hazard map for city of Calgary using two different DEMs with a resolution of (a) 326m and (b) 20m.

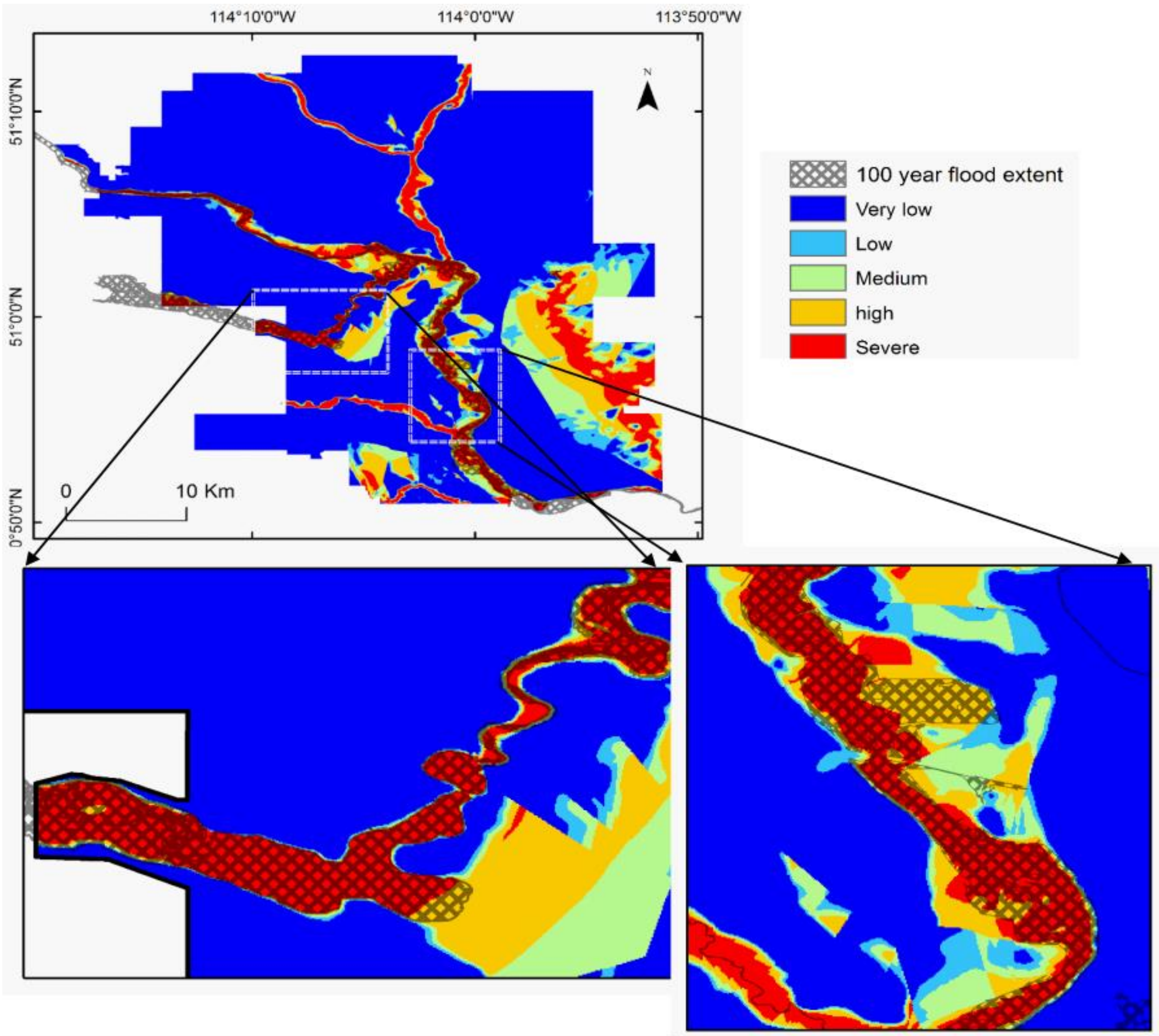

Figure ~~5~~4: Comparison of Hazard map obtained from the present study and a 100-yr flooding extent map prepared by the city of Calgary (Hatched portions). Portions of the reach along the Bow and Elbow rivers are enlarged to show the level of agreement between both maps.

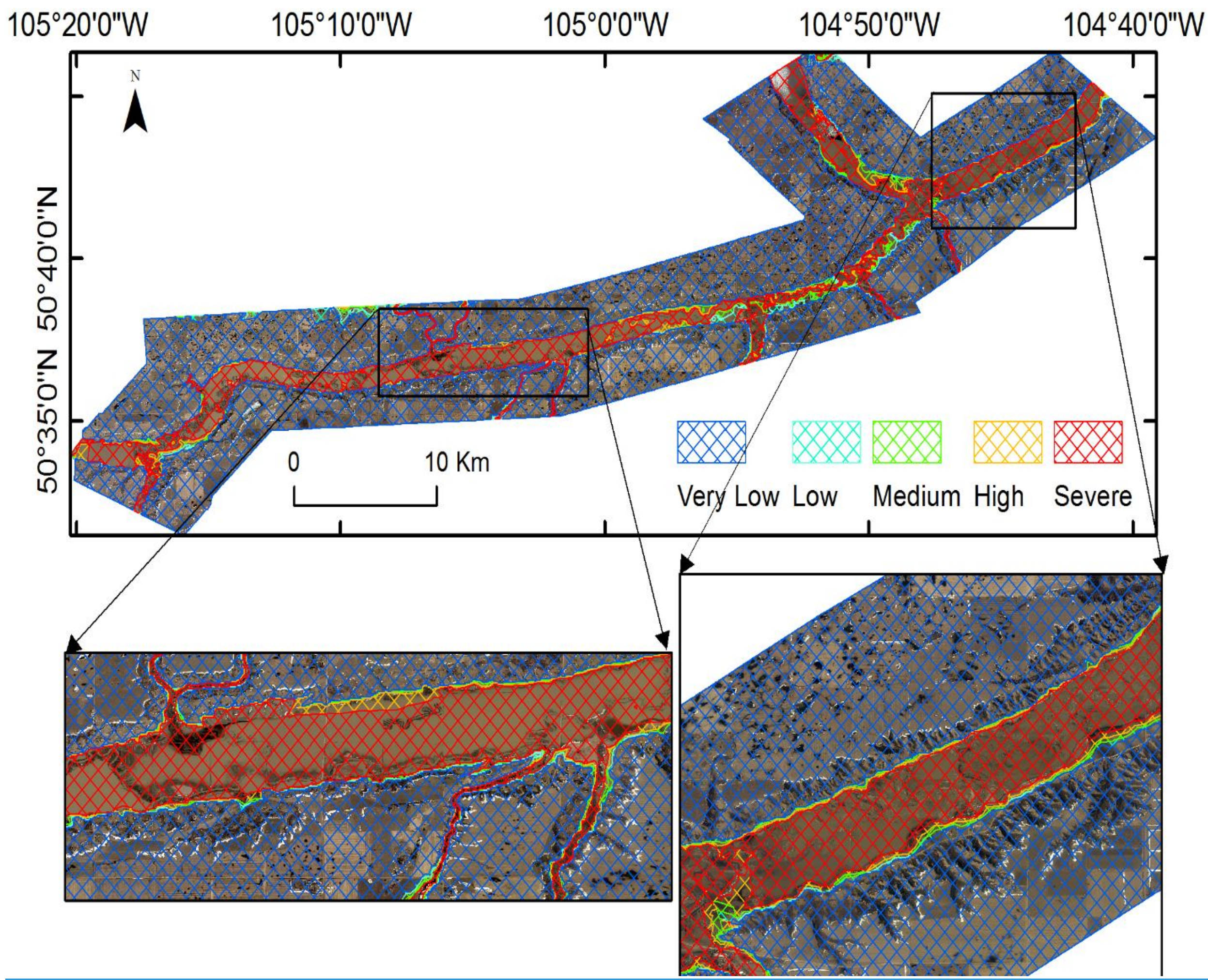

Figure 65: Comparison of hazard map with aerial image of a single flood event on the Qu'Appelle River, Saskatchewan (background). Date of image: 06/05/2013

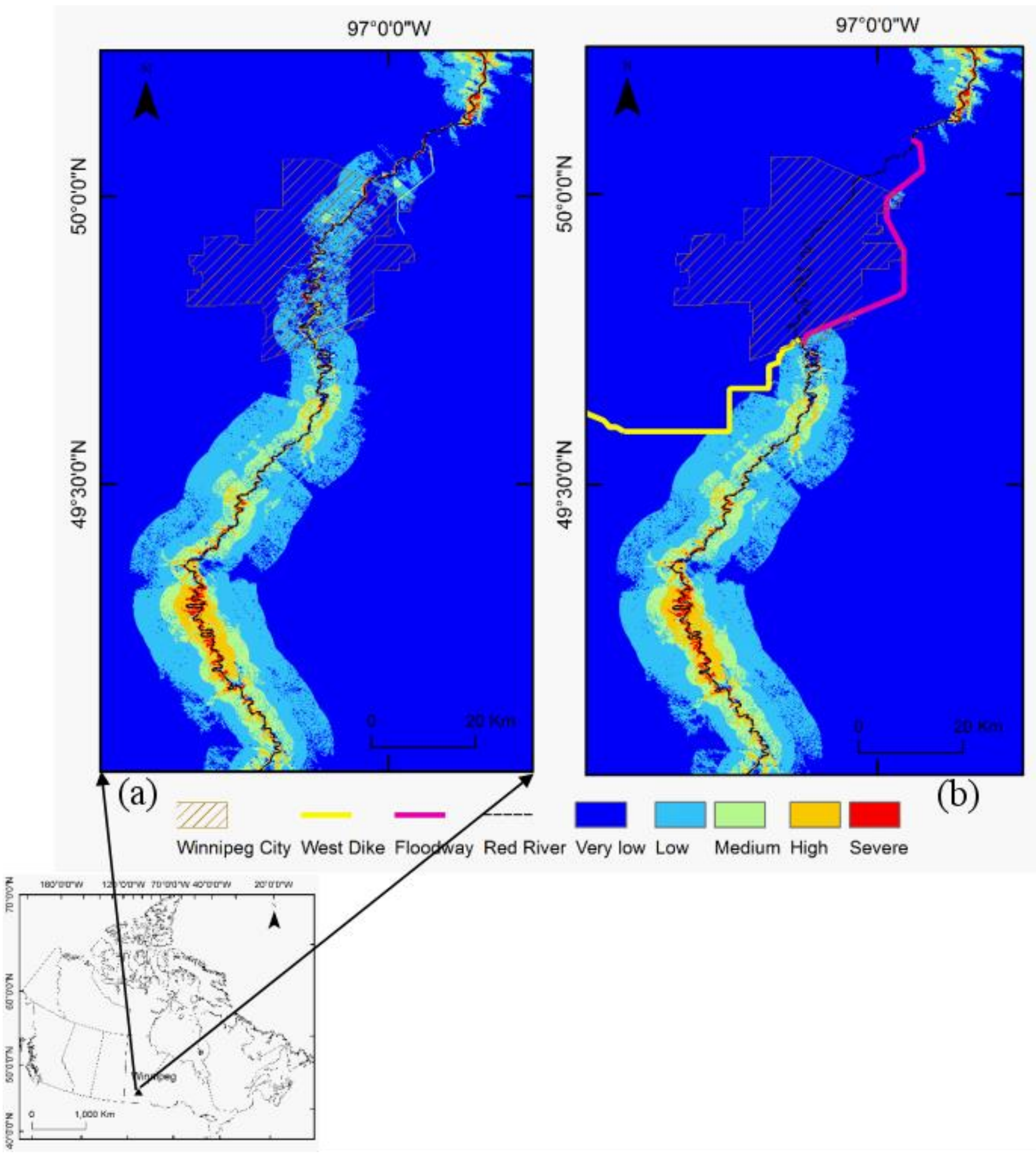

Figure 6. Hazard map for the Red River in Manitoba: (a) without considering flood protection structures in delineating hazard zones and (b) considering flood protection.

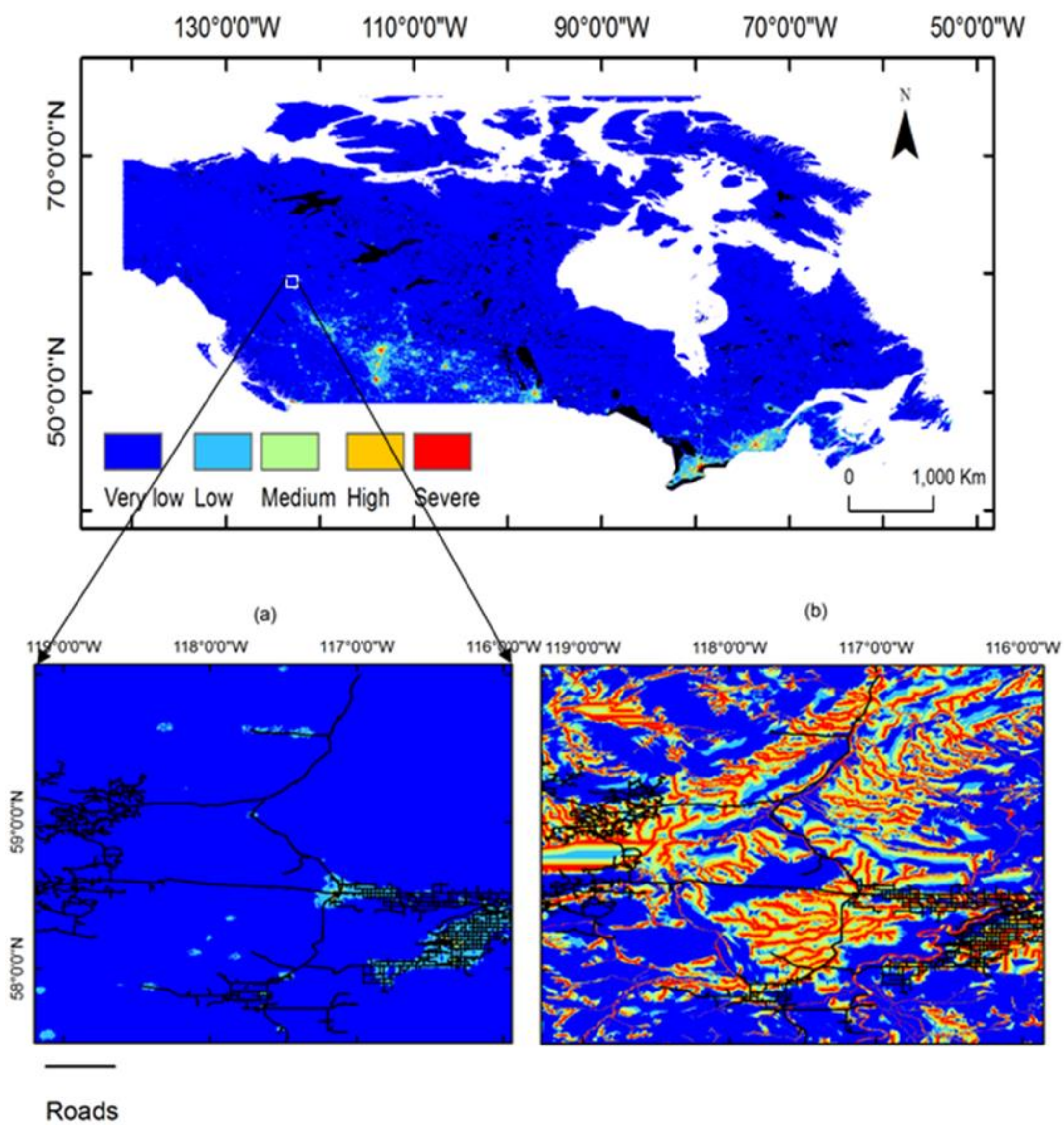

Figure 7: Classified Flood Exposure Map for Canada. Severe and high exposure are concentrated around urban centers in the southern part of the country. Enlarged portion shows road network overlaid over (a) exposure map and (b) hazard map.

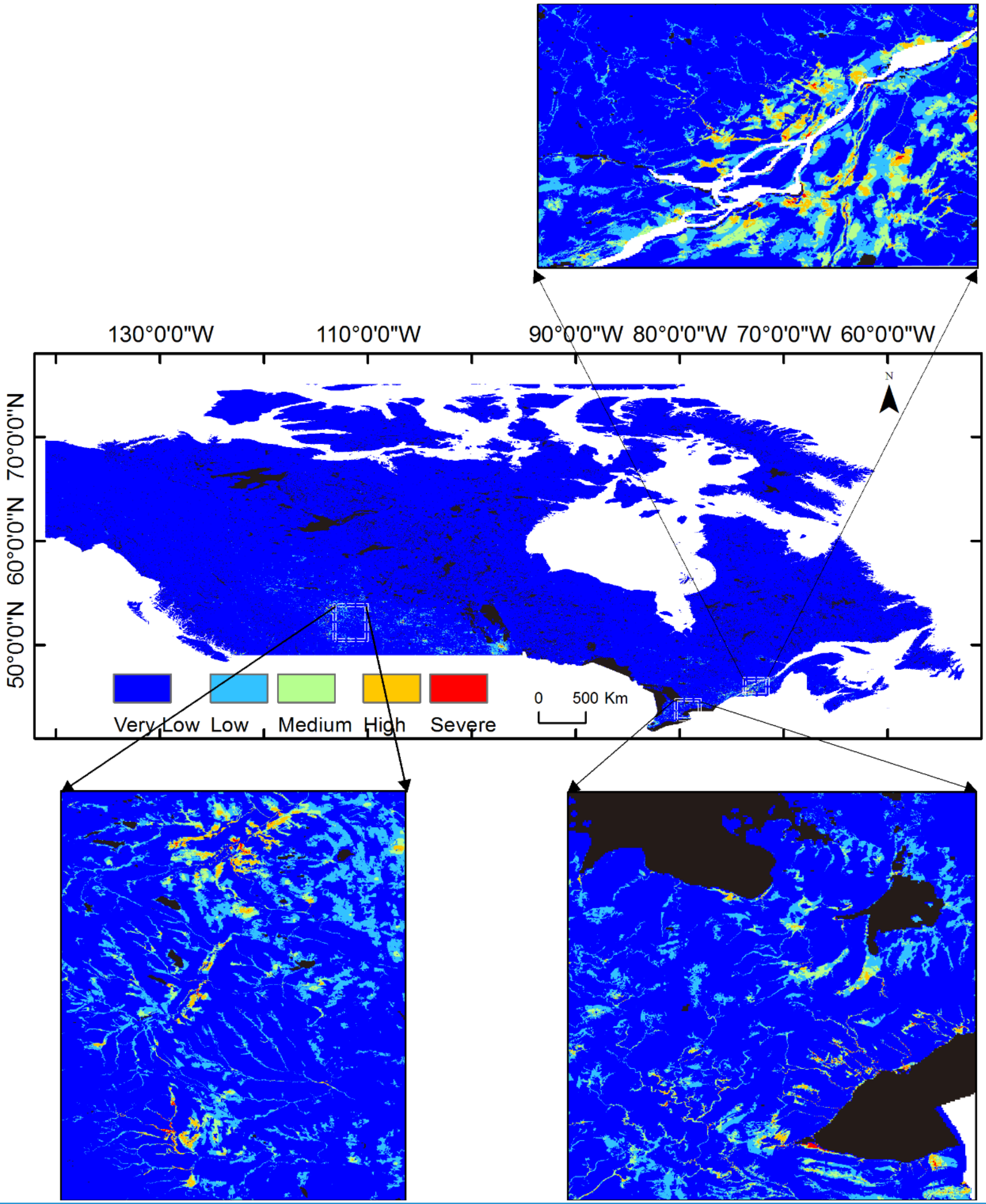

Figure 8. Flood risk map for Canada. Certain portions of the map are enlarged for better visual interpretation of the various levels of flood risk. The risk map is a product of hazard and exposure (flood protection measures are not included). Severe risk only occurs in areas of severe hazard and exposure, causing sever flood risk areas to be concentrated in urban centers.

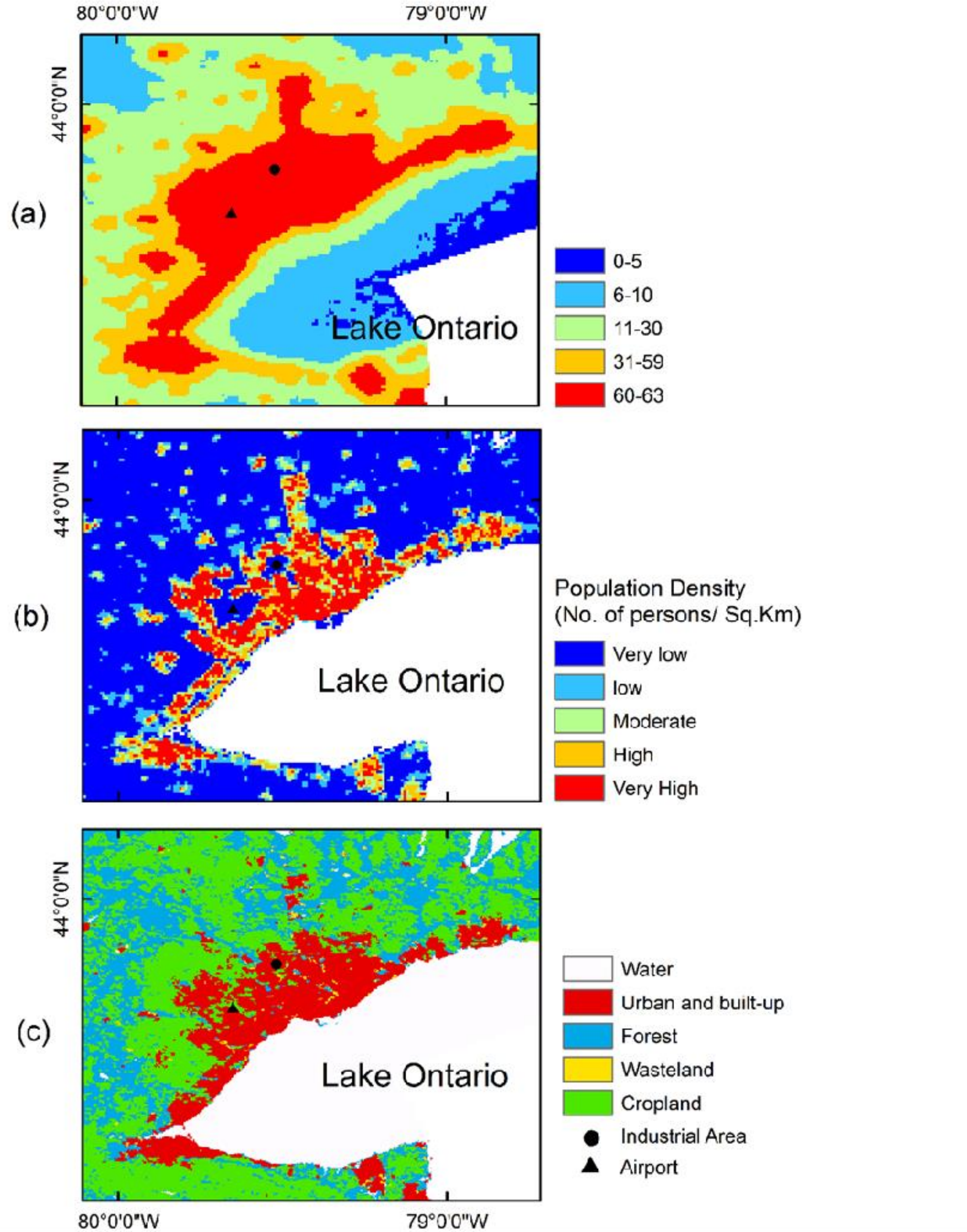

Figure 9: Comparison of population distribution and nightlights over Greater Toronto Area: (a) classified nightlights for the area with locations of the airport and a major industrial area; (b) population density over the area; and (c) land-use map of the area indicating urban extent.

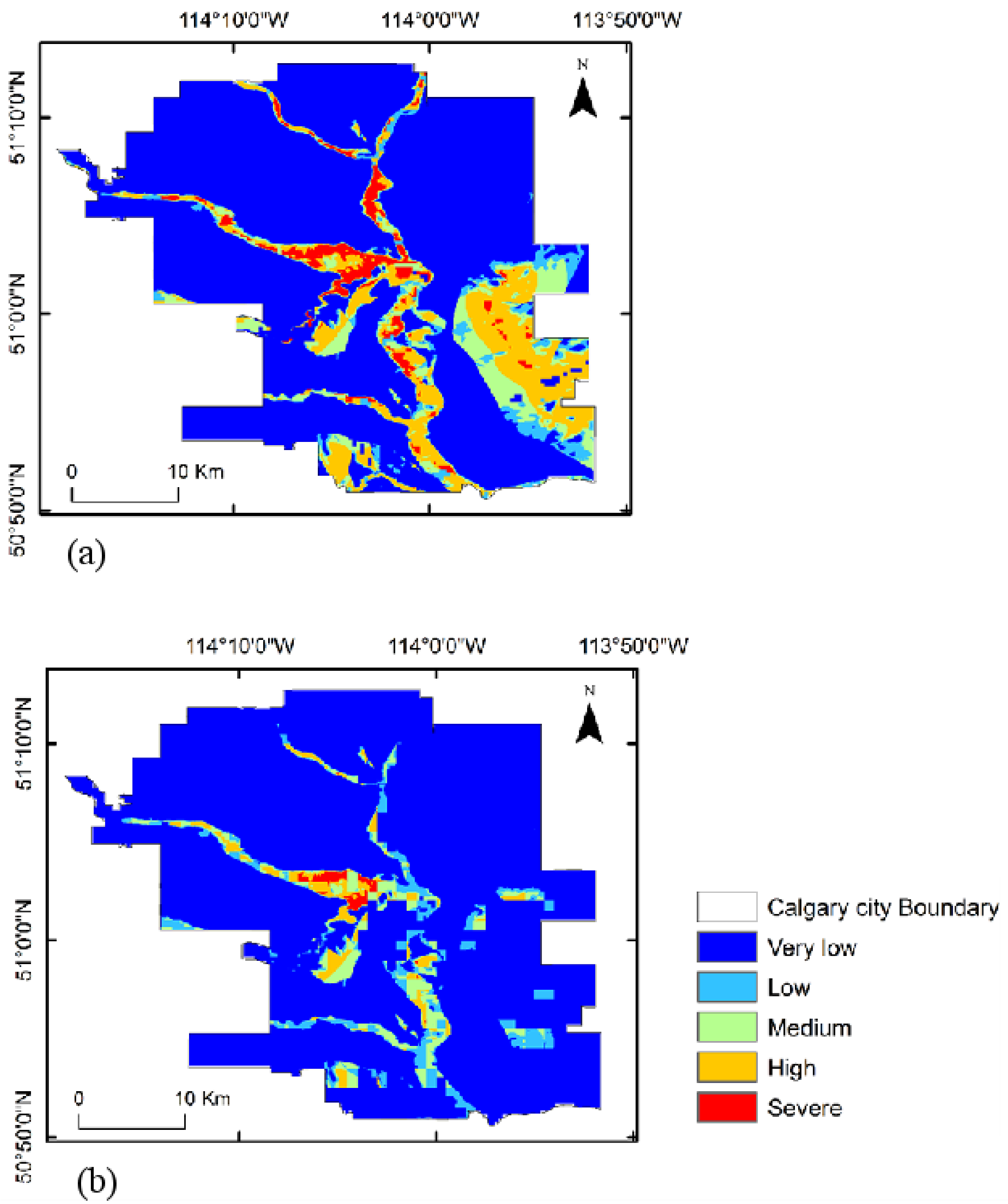

Figure 10: Flood risk map of Calgary; (a) without population information, and (b) with population. Areas around the center of the city with high rises and dense population remain in the severe risk category, whereas northern and southern parts, which are mainly commercial, change to reduced levels of social risk.