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Regional Analysis of Population Exposure to Flooding in Canada

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Executive Summary

Over the years, flooding is becoming more of a significant cause of casualties, economic loss, property & environmental damages all over the world due to climate change, severe precipitation, land use changes and numerous other factors. Studies have proven that flooding is predicted to occur even more frequently in the near future. With the rise of flood-prone areas in Canada specifically, it has now become more crucial than ever to consider floodplain mapping at larger scales which can help us identify different degrees of risk and vulnerability for unique locations. This process has become much easier with the availability of accurate global flood models such as CaMa-Flood, and the public release of a huge variety of datasets (including population datasets and reanalysis data). In this report, we will be analyzing how much of the Canadian population is exposed to floods and the risk factors. In doing so, we also present a pre-processed flood map that was formulated using the CaMa-Flood model and freely available NARR reanalysis data used as the input values. We also introduce different global population data sources and analyse differences between them, which are needed for the further assessment of impacts of flooding. Lastly, this study will touch upon what high and very high flood depths are based on the hazards they pose to humans, and how it is relevant to exposure analysis. This report demonstrates a detailed presentation of the process (split up into three experiments) needed to be followed on ArcGIS to properly assess the exposure of the Canadian population to flooding, where any user familiar with the content who has the software can follow along without any issues.

Keywords: Floodplain mapping; Flood risk; CaMa-Flood model; NARR Reanalysis data.

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Chapter 1: Introduction

Floods are one of the most frequent natural disasters that occur worldwide as a result of climate change (United Nations Environment Programme, 2020), intense precipitation (Denchak, 2019), socio-economic factors (De Silva & Kawasaki, 2020) and various other aspects (Gaur et al., 2019). These natural hazards have a severe impact on the population exposed and economy. Under such situations, it is crucial to practice floodplain mapping. Floodplain mapping is used to determine areas that are prone to flooding through a cascade of hydrologic and hydraulic modelling (Conservation Halton, 2020). The procedure in floodplain mapping is complex, as it is data intensive and involves rigorous computational simulations (Mohanty & Simonovic, 2020). Population exposure will be the prime focus of this report and is extremely important for assessing the flood risks and vulnerability to the public. Flood exposure can be mitigated by human intervention which includes population relocation, land use control, the building of flood banks, and many others to lower the overall risks of flooding to population and help with flood management (Qiang, 2019).

1.1 Review of Flooding in Canada

Floods are the most common natural disaster in Canada that have affected hundreds of thousands of Canadians and are found to be the costliest in terms of property damage (Public Safety Canada, 2015). In Canada's history, many of the worst floods occurred on major river systems that pass through urbanized areas (Burton, 2006). The Canadian Disaster Database (Public Safety Canada, 2007) reports that there have been 241 flood catastrophes in Canada between the years 1900 to 2005, which is five times higher than the next most likely natural disaster (**Figure 1.1**).

Notable historical flooding catastrophes that occurred in Canada include; the Red River flood in 1950 and 1997; the 1996 flood in Saguenay, Quebec; Alberta flooding in 2005 and 2013; and the 2011 flooding in Manitoba and Saskatchewan (Dangerfield, 2019). One of Canada's most flood-prone areas is that of the Red River in Manitoba. The 1950 flood in Manitoba overflowed many valley towns and one-sixth of Winnipeg, in which more than 100,000 people had to be evacuated and four of eleven bridges were destroyed (Burton, 2006; Dangerfield, 2019). The total cost of the damages was about CAD $125.5 million in 1957 dollars (Dangerfield, 2019).

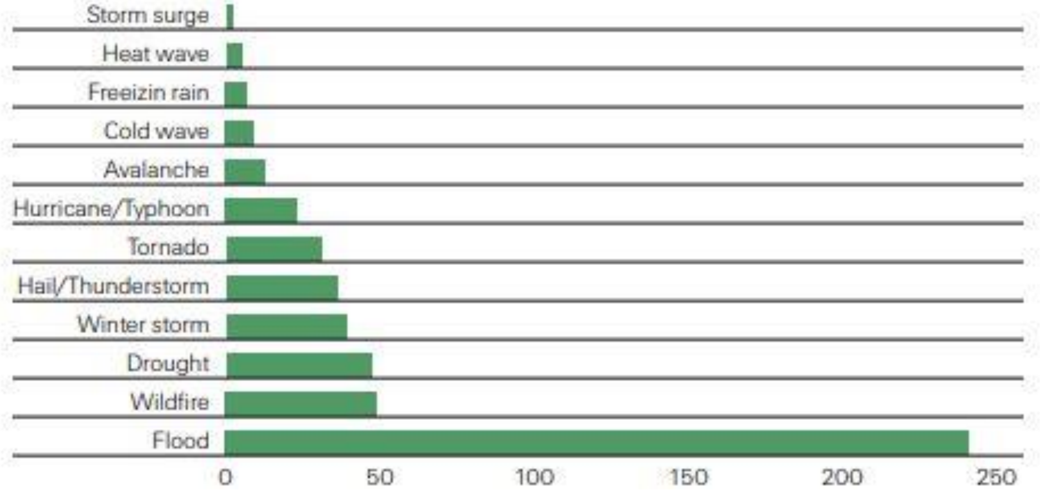

Figure 1.1: Meteorological and Hydrological Disaster Incidences in Canada, 1900–2005 (Source: Public Safety Canada, 2007)

Almost five decades later in 1997, another flood arose, so severe that it was given the name "*The Flood of the Century*" due to the province being hit by a blizzard across the Red River Valley (Dangerfield, 2019). According to Environment Canada, just a year before the 1997 Red River Flood, the 1996 flood in Quebec broke the record for Canada's first-ever billion-dollar disaster that resulted in a total damage cost exceeding CAD $1.5 billion. In 2005, three major storms lead to the historic flooding that inundated southern Alberta towns and forced thousands of residents to evacuate, with damages reaching more than CAD $400 million (Dangerfield, 2019). Just a few years later, the 2013 flooding in southern Alberta became one of Canada's most expensive natural disasters, with estimated costs of around CAD $6 billion (Pomeroy et al., 2016). In 2011, the flooding in Manitoba and Saskatchewan from the Assiniboine River produced the highest water levels in Canada's history and the total cost of the damages was close to CAD $1 billion (Dangerfield, 2019). Consequently, an approach for a national flood risk mapping framework has been promoted by the Canadian government to reduce future damages from flooding (Henstra & Thistlethwaite, 2018). The federal government plays a primary role in ensuring a broadly consistent national approach to flood mitigation, even though specific flood mitigation measures are principally the obligation of provincial/territorial and local agencies (Mohanty & Simonovic, 2020). In consultation with provincial and territorial partners and key stakeholders, the federal government has developed new documents in the Federal Flood Mapping Guidelines Series that will help advance flood mapping across Canada (Public Safety Canada, 2019). The framework consists of Flood Hazard Identification and Priority Setting, Hydrologic and Hydraulic Procedures for Flood Hazard Delineation, Geomatics Guidelines for Floodplain mapping, and Risk-based Land-use Guide with Floodplain mapping being the central component (Mohanty & Simonovic, 2020). For more details, visit https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgtn/ndmp/fldpln-mppng-en.aspx.

1.2 Impacts of Floods in Canada on Population

The Canadian Encyclopedia (2006) states that scientists predict an increase in flooding over the next few years linked to climate change. However, an element of this that has to be considered is the constant population growth in Canada, as the majority of citizens live in known floodplain areas. The new IBC flood risk model shows that "20% of Canadian households could be qualified as high risk and about 10% of those households would be considered very high risk, which is about

1.8 million households" (Meckbach, 2016). Not only do floods have a negative effect on the economy due to the extremely high costs of property damage, but additionally can have various health impacts on the population such as mortality, hypothermia, increased mental health issues, deterioration of seniors/patients who required emergency transportation, homelessness, and many others (Burton, Rabito, Danielson, & Takaro, 2016). In general, the public is affected extremely negatively when flooding events occur because a larger part of Canadian homeowners do not have insurance coverage for damages caused by groundwater and overland flooding (Sandink et al., 2010). For example, although there were no mortalities, the Red River flood in 1997 destroyed over 800 farms, ruining farmers' years of work and inundated some of the richest soil in the country, meanwhile over 25,000 residents had to flee their homes (Came, Eisler, Macdonald, & Stewart, 2003). Another example is the 1996 flood in Saguenay that killed seven people and forced 16,000 residents from their homes (Branswell, 1996). Even five months after the incident, parts of the infrastructure remained in ruins and most of the evacuees still could not return to their homes (Branswell, 1996). The 2013 flood in southern Alberta lead to one of the largest evacuations across Canada, with around 100,000 Albertans that had to flee their homes and five mortalities (Environment and Climate Change, 2017). It is important to understand that floods do not only affect infrastructure but can leave life-lasting effects on the population hence, why the constant use of floodplain mapping is so crucial.

1.3 Floodplain Mapping Using Public Data Over Large Regions

Floodplain mapping refers to the use of data and mathematical models to predict regions that will be covered by water, the peak flow depth, the elevation that water would reach or the flow velocities to demonstrate where the flooding hazards are (Environmental Water Resources Group Ltd., 2017; Mohanty & Simonovic, 2020). These types of maps are critical for understanding and reducing risks to public safety, damages to infrastructure or the environment, and emergency planning and response. In Canada, floodplain maps are usually conducted at the local and provincial level whereas flood analysis and water resource management on the national-scale and global-scale are infrequent (Moel, Jongman, Kreibich, Merz, Penning-Rowsell, & Ward, 2015; Mohanty & Simonovic, 2020). On the other hand, extending these inundation maps to a larger scale is catching the attention of more and more scientists around the world (Carnacina & Jemberie, 2014). However, models must be adequately detailed, must require a highly accurate dataset and have huge computational simulations to precisely account for hydrologic variation, which is difficult when dealing with large scale flood inundation mapping (Jongman et al., 2012; Yamazaki et al., 2013; Carnacina & Jemberie, 2014). Nowadays, floodplain mapping over large regions has become much easier with the public accessibility to global data sets; that may include meteorological, hydrological, topographic and demographic data (Dottori et al., 2016; Mohanty & Simonovic, 2020). For example, inputs for this type of global-scale mapping may be retrieved from remotely sensed topographic data such as Shuttle Radar Topography Mission (SRTM) DEM (Yang et al., 2011) and Advanced Land Observing Satellite World 3D-DEM (AW3D-30) (Tadono et al., 2015; Mohanty & Simonovic, 2020). A detailed list of freely available data sets for download can be found on https://freegisdata.rtwilson.com/ or refer to Appendix A of https://www.eng.uwo.ca/research/iclr/fids/publications/products/109.pdf.

1.4 Characteristics of Population

When analyzing the population exposed to flooding in Canada, it is necessary to thoroughly evaluate the specific demographics and other characteristics of the Canadian population such as the age structures in various regions, the density of citizens in certain areas, urban versus rural population, etc. (Tarsi & Tuff, 2012) in order to determine which groups are more vulnerable to flooding events. Despite having to deal with similar circumstances, certain groups may face different challenges and have distinct needs from others that would affect their ability to respond efficiently to emergency situations (Dotto et al., 2010). Currently, there is an estimated population of 37,742,154 in Canada at mid year (Worldometers, 2020) but not all these people are affected by the floods that occur. As mentioned before, one of Canada's most flood-prone regions is that of the Red River in Manitoba (Burton, 2006) principally during the spring as snow melts and river ice breaks up, which flows north through southern Manitoba and into Lake Winnipeg (Newton, 2008). Manitoba has an estimated population of 1.272 million while its capital city, Winnipeg is home to about 60% of the provincial total population (World Population Review) and are at highest risk to flooding. Other vulnerable areas include provinces of high population density such as Prince Edward Island, New Brunswick and Ontario (Statistics Canada, 2017) because when people are of closer proximity, a flooding event will have a greater impact than if the population is more dispersed. According to a study done by Fraser Institute, Vancouver is found to be Canada's densest city with 5,493 people per square kilometre, followed by Montreal with 4,916 people per square kilometre, and Toronto with 4,457 people per square kilometre (Vella, 2018). The Atlantic provinces have the highest concentration of senior population with Nova Scotia having the most at 16.6% of its total population, followed by New Brunswick at 16.5% of its population (Kembhavi, 2012). These two provinces would also be considered vulnerable to flooding because the elderly population is more dependent on others during emergency situations and a majority generally live on fixed incomes, making it more difficult for them to move to a safer location. Finally, changes in land use associated with urban development increases vulnerability to floods by a large amount. In 2019, the total Canadian population that lived in urban areas was 30,628,482 compared to 6,960,780 that lived in rural areas (Macrotrends, 2020). Overall, analyzing the characteristics of population is very much needed when assessing flood impacts.

1.5 Objectives of the Study

The main objective of the present study is to portray the amount of people in various areas of Canada that are being exposed to flooding provided using various population data sources and inundation modeling with CaMa-Flood to essentially help with further mapping of the overall risk to the population. The population data sources that were used for this study are Statistics Canada (the reference that the other data sources were compared to), Global Human Settlement, Gridded Population of the World, LandScan and Worldpop, further discussed in **Section 3.2**.

This report provides a detailed description on performing floodplain mapping and various comparative analyses of flood impacts on the Canadian population. **Chapter 2** focuses on the methodology used to assess these flood impacts while thoroughly explaining the structure and importance of floodplain mapping using the CaMa-Flood model, the processing of these public population data sources, and a detailed presentation of the ArcGIS process used for this assessment (**Appendix A** shows this process in even more detail). **Chapter 3** focuses on floodplain maps and a specific description of the different data sources and how the data was downloaded and prepared for the further assessment. **Chapter 4** shows the procedure used to attain the objectives and was split into various experiments (all produced using ArcGIS):

- Comparison of all population data sources for the common year 2015 over Canada
- Population exposure analysis with all population sources for 2015 floods over Canada
- Exposure analysis with all population sources for a 1:100-year and a 1: 200-year event floods over Canada and test regions

- Exposure and vulnerability analysis from 2006 to 2019 with Statistics Canada, and identification of the most severely affected census sub-divisions

Finally, **Chapter 5** shows the results of all the experiments mentioned above.

Chapter 2: Proposed Methodology for the Assessment of Flood Impacts on the Canadian Population

The proposed methodology for producing floodplain maps and assessing the impacts in Canada related to flooding are discussed in this section using various population data sources with the detailed CaMa-Flood model sub-divided into three major points in the following paragraphs.

2.1 Floodplain Mapping Using CaMa-Flood Model

The CaMa-Flood (Catchment-based Macro-scale Floodplain) model is a widely used global-scale distributed river routing model (GRM) to realistically describe river routing considering floodplain inundation dynamics over large regions (Yamazaki et al., 2011, 2013, 2014b). This global hydrodynamic model has the ability to calculate water river discharge, flood inundation, water levels, velocity, and water storage for early flood warning (Yamazaki et al., 2017). The river basins are discretized into unit-catchments based on high-resolution flow direction maps (Lehner et al., 2008) and digital elevation maps (DEMs; Farr et al., 2007) and are each assumed to have a river and floodplain storage (Yamazaki et al., 2017). The relationship between water storage, water level, and flooded area in the model is based off sub-grid topographic parameters using a 1 km resolution digital elevation model (Yamazaki et al., 2011). The parameters and variables used in CaMa-Flood are listed in **Table 2.1**. River discharge and flow velocity along the river network at each unit-catchment is calculated by the local inertial equation (Bates et al., 2010; Yamazaki et al., 2013) as provided in Equation 1:

$$Q^{t+\Delta t} = \frac{Q^{t} - \Delta t g A S}{\left(1 + \frac{\Delta t g n^{2} |Q^{t}|}{z^{4/3} A}\right)} \tag{1}$$

where $Q^{t+\Delta t}$ is the discharge between time-period 't' and 't+Δt', Q^t is the discharge at the previous time-step, A is the channel cross-sectional area (m^2), ƶ is the flow depth (m), g is the gravitational acceleration (ms^{-2}), n is the Manning's friction coefficient (m$^{-1/3}$ s), and S is the water surface slope between the upstream and downstream unit catchments (Yamazaki et al., 2017). This equation notably represents backwater effect and improves the representation of shallow water physics (Yamazaki et al., 2017). That being said, the principal advantages of the CaMa-Flood model include: its high computational efficiency, its capacity to provide more reliable predictions of flood stage and river discharge at finer resolutions, its ability to simulate bifurcating flows in deltas and floodplains (which other GRMs are unable to do), and its suitability for parallel processing (Teng et al., 2017; Yamazaki et al., 2017).

2.2 Processing of Publicly Available Population Databases

Current estimates of global and regional flood exposure are made using population datasets that provide an estimate of the population that lives in certain areas and floodplains. Population maps are a key component of assessing flood risks and exposure. Population data is generally collected via nationally organized census studies such as government agencies or non-profit organizations which usually enable users to download for free. However, results have shown that in most cases, existing demographic datasets struggle to represent concentrations of exposure, with the total exposure being spread over larger areas (Smith et al., 2019). It is clear that the most accurate population estimates based off high-resolution satellite imagery are needed for assessing flood exposure in Canada. The datasets that were analyzed before beginning the assessment of the exposed population are shown in **Table 2.2**.

Table 2.1: Parameters and Variables Used in CaMa-Flood Model (Source: Mohanty and Simonovic, 2020)

Symbol	Name	Unit
Parameters		
L	channel length	m
W	channel width	m
B	bank height	m
Z	surface altitude	m
X	distance to downstream cell	m
A_c	unit catchment area	m^2
n	Manning's roughness coefficient	m-1/3s
Variables		
S	total water storage, $S_r + S_f$	m^3
S_r	river channel water storage	m^3
S_f	floodplain water storage	m^3
D_r	river water depth	m
D_f	floodplain water depth	m
H	effective river depth	m
A_f	flooded area	m^2
R	runoff from land surface model	m/s
Q	discharge	m^3/s
Rup	maximum 30 day upstream runoff	m^3/s
v	river flow velocity	m/s
i_o	riverbed slope	
$isfc$	water surface slope	
i_f	friction slope	

Table 2.2: Key Features & Characteristics of Various Population Data Sources

Data Sources	Type of Information Provided	Spatial Resolution	Temporal Resolution	Data Format	Past Studies	Comments
Statistics Canada https://www150.statcan.gc.ca/n1/en/type/data?HPA=1	Statistics Canada is not only population specific but focuses on many other topics including economy, income, various age groups, immigration, travel, housing, agriculture and many others. Under the population section there are additional subtopics such as births, migration, mortality and future population estimates per region which could be beneficial for our work. Various articles, tables, thematic maps and public use microdata are provided.	250m, 1km, spatial resolution varies	1991-2020	ArcGIS, GML, and MapInfo formats	• Official website of the Government of Canada uses these datasets • Various Canadian universities use these datasets for their research	Statistics Canada is a very reliable source used by the Government of Canada which is available to the general public. I found that many of the datasets were archived for certain years, which could be a problem if we are looking for a longer time sequence for our work. Additionally, there is not as many maps as other data sources have.
Worldpop https://www.worldpop.org/geodata/listing?id=29	Worldpop shows the spatial distribution of the population for almost any country, including Canada from years 2000-2020. The projection is Geographic Coordinate System, WGS84. The units are number of people per pixel. It also provides other	3 arc (approx. 100m at the equator)	2000-2020	GeoTIFF	• United Nations has conducted various studies using these datasets • Worldpop presented their population mapping work to the government and	Although Worldpop is not a Canadian-specific source, it provides reliable population data that has been used by many government officials globally. This could be a

	specific information about the population in various countries such as age & sex structures, internal migration, births, urban change, etc.				president of Afghanistan • Population mapping in Nigeria to support polio elimination • UNITAR-UNOSAT uses datasets to assess numbers during natural disasters	potential data set we use as the source is very well organized and it is quite easy to find every year we need to analyze, and is available in GIS formats.
Global human settlement https://ghsl.jrc.ec.europa.eu/download.php?ds=pop	This data sources lists all the GHS datasets that are available for download which includes GHS-POP. GHS-POP is a spatial raster dataset that depicts the distribution of population, expressed as the number of people per cell for target years.	250m, 1km, 9 arcsec, 30 arcsec	1975, 1990, 2000 & 2015	VRT file (with GeoTIFF tiles) or GeoTIFF files	• European Commissions have used these datasets • This data has been used extensively in urban land cover related studies at global levels	This data source has shown to be high-resolution and reliable however, only 4 years are shown which would be hard to use to predict future estimates.
ESRI world population data https://www.esri.com/about/newsroom/arcnews/map-gives-new-insights-into-global-population/	This data source is available on ArcGIS online and its method combines information from datasets on global land cover, roads, and place names to produce a probability surface calibrated using census data.	150m at equator	2013, 2015, and 2016	Available on ArcGIS online and other GIS formats	• World Population Estimate (WPE) • ESRI releases ready-to-use US census Bureau data	ESRI data is different from other data sources as it uses accurate census data that displays where people live and where people do not live. However, not enough temporal resolution is used as it is a newer source and would make it harder for us to make future

						estimates using only three years of data. All data is available on ArcGIS, which makes it easier for us to use.
GPW https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11	The Gridded Population of the World consists of estimates of human population (number of persons per pixel), consistent with national censuses and population registers for the years 2000, 2005, 2010, 2015, and 2020 with various maps and documents.	30 arc-second (~1 km at the equator),2.5 arc-minute, 15 arc-minute, 30 arc-minute and 1 degree resolutions.	2000, 2005, 2010, 2015, and 2020	GeoTIFF, ASCII (text), and netCDF format	• Columbia University has conducted studies based on these datasets	Not enough information about other population factors such as age and income in certain regions is available on this source. Additionally, there are no consecutive yearly data sets which may make it harder to predict future estimates.
UNEP Environmental Data Explorer http://geodata.grid.unep.ch/ results.php	This data source focuses on much more climate change data sets rather than population, but still includes various future estimates of the population.	3” (~90 m)	1950-2050 (some years are skipped)	GeoTIFF, Comma Separated File, HTML, Microsoft Excel & ESRI Shapefile	• United Nations have conducted past studies with these datasets more for climate change	I found that this data source is hard to navigate and find specific data sets. It also does not show much information regarding demography. However, it may be useful as it already shows future estimates of population.

HRSL http://ciesin.columbia.edu/ data/hrsl/#data	The High Resolution Settlement Layer (HRSL) provides estimates of human population distribution at a resolution of 1 arc-second (approximately 30m) for the year 2015 for various countries in the world.	1 arc-second (approximately 30m)	2015	GeoTIFF	• Columbia University	Does not provide data sets for Canada and only shows one year, so this would not be useful for our work.
LandScan https://landscan.ornl.gov/	LandScan is the finest resolution global population distribution data available and represents an ambient population (average over 24 hours) and is essentially a combination of locally adoptive models that are tailored to match the data conditions and geographical nature of each individual country and region.	1 km (30″x 30″), 30 arcsecs	1998, 2000-2018	ESRI grid format, raster format, cloud-based web mapping service (WMS)	• Studies using GIS at the University of Waterloo using these datasets • Population distribution for the southeast United States	LandScan shows where people are located on average over a 24-hour period, which essentially shows where people are during the day but not where they live at night which could differ quite a bit.

Nonetheless, all these datasets were not chosen for further analysis due to not having Canadian-specific data, insufficient years provided, unavailability in Geo TIFF formats or lack of precise spatial resolution. The population data sources that were used include: Statistics Canada (basis for comparison), Worldpop, LandScan, Gridded Population of the World (GPW), and Global Human Settlement (GHS). To open each specific dataset in ArcGIS, it is necessary to first visit their official websites (provided in **Table 2.2**), then download the data only provided in TIF format relevant for Canada in all the years available. It is very important to note that the data collected should all have the same geographic coordinate system or there will be complications with projecting the data in ArcGIS. Note that we may have to change the geographic coordinate system later. The final step for processing this publicly available data would be to make separate folders for each data source with each year available and save all the relevant data. From here, it will be quite easy to open the data in ArcMap for further analysis.

2.3 Assessment of the Exposed Population

To be able to assess the population exposed to flooding, there are multiple steps that were taken before getting to the results. The process used in ArcGIS is described below:

- **Step 1: Laying the Foundation**

In this step, users must insert a boundary map of Canada that outlines the country with each province. This map should be in the SHAPEFILE format that can be easily found on the Internet (on various databases).

- **Step 2: Adding Data**

For this step, users must add the specific dataset for the year desired (i.e. Statistics Canada) by clicking the "Add Data" option in ArcMap. Certain datasets are only available showing world-wide data, which must be cut down to match the Canada boundary map (it is only necessary to assess the exposed population in Canada, not other parts of the world. This can be done in various ways, but the easiest approach would be to use the "Extract by Mask" option found in ArcToolbox found under "Spatial Analyst Tools" ---> "Extraction." In this step, the input raster would be the dataset in TIF format (ie. Statistics Canada) and the input raster or feature mask data would be the Canada boundary map in SHAPEFILE format. This option would then extract the data to exactly match the boundary map, without messing up any projections.

- **Step 3: Adding the Flood Map**

This step is similar to Step 2 as adding the flood map (also in TIF format) is done using the same "Add Data" option in ArcMap. The flood map used must be for the same year as the dataset inserted. In this study, the year 2015 is used which is later explained in **Chapter 4**. The flood map would be processed prior explained in **Section 3.1**. As mentioned above, the flood map must match the Canada boundary map and the specific dataset.

- **Step 4: Overlaying the Data**

The simplest step of all would be to overlay the dataset onto the flood map. This is done by checking all layers found under the Table of Contents on the far left of ArcMap which include: the Canada boundary map, the flood map for the specific year, and the population data for the same year.

- **Step 5: Finding the Exposed Population to Flooding**

Finally, for the last step when the data is overlaid, to find the exposed population to flooding, users must use the "Zonal Statistics" option also found in ArcToolbox. Zonal Statistics would calculate how much of the population is affected by flooding in each specific area. The "Zonal Statistics as

Table" option would fulfill the exact same process but would put the results in the form of a table, which may potentially be easier for users to compare the population exposed.

- **Step 6: Exporting Data**

When the steps above are completed, the user must save the map of the exposed population. This can easily be saved using the "Export Map" option found under "File" in ArcMap.

Note: The process of how to add a legend and frame around the map is not explained in this section. For a complete detailed example with screenshots along the way, see **Appendix A.**

Chapter 3: Data

In this section, the data that was used for the assessment of the population exposed will be described in more detail including the floodplain maps (**Section 3.1**) and the various population data sources (**Section 3.2**).

3.1 Floodplain Maps

As mentioned before in **Chapter 1**, floodplain maps outline areas that may be at risk for flooding during heavy rainfall and severe storms and are used to reduce overall risks to public safety, infrastructure and environmental damages, and help provincial and national emergency planning and response. An example of a floodplain map of Canada for the year 2015 is shown in **Figure 3.1**. In our case, the floodplain map that was used was based off a reanalysis dataset. Reanalysis is a systematic approach that produces data sets that show how weather and climate are changing over time, enabling several climate processes to be studied all at once (Dee et al., 2016). The specific dataset used was North American Regional Reanalysis (NARR), which is a high-resolution atmospheric and land surface hydrology dataset (Mesinger et al., 2006; Mohanty & Simonovic, 2020). NARR contains an extensive amount of observational data to produce a long-term representation of weather over North America. The NARR system uses a 221 (32-km) domain with an output timestep available every 3 hours (from 1979 to present at a grid resolution of 0.3°) and a 3D-VAR assimilation approach to illustrate flooding to a detailed extent (Essou et al., 2016; Mohanty & Simonovic, 2020). The grid-wise runoff values on flood maps for 100 and 200-year return periods are generated by fitting the Generalized Extreme Value (GEV) distribution (a statistical tool to analyze flood frequency) on the continuous time-series (Lettenmaier & Potter, 1985; Castellarin et al., 2001). The GEV distribution which has its upper limits can be depicted using the function:

$$F(x) = exp\left\{-\left[1 - \frac{k(x-\mu)}{\sigma}\right]^{1/\xi}\right\}, k \neq 0 \tag{2}$$

$$F(x) = exp\left\{-exp\left(-\frac{x-\mu}{\sigma}\right)\right\}, k = 0 \tag{3}$$

where μ, σ, and k are the location, scale and shape parameters (Mohanty & Simonovic, 2020). These runoff values are then inputted into the CaMa-Flood model to determine the maximum flood depth (in meters) and the inundation ranges (in kilometers squared) for all of Canada (Mohanty & Simonovic, 2020). These characteristics can also be seen on the flood map in **Figure 3.1** which is at a 1 km resolution. To quantify the degree of hazard caused by flooding, the maximum water depths are discretized into five classes based on the degree of severity to humans and economic destruction, represented in **Table 3.1**.

Table 3.1: Discretization of Maximum Water Depth Values (Mohanty et al., 2020)

Value of maximum water depth (m)	Flood hazard class	Description of hazard
0 to 0.2	Very Low	Generally safe for people, vehicles and buildings
0.2 to 0.6	Low	Unsafe for vehicles, children and the elderly
0.6 to 1.5	Medium	Unsafe for people and vehicles
1.5 to 3.5	High	Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
>3.5	Very High	Unsafe for vehicles and people. All building types considered vulnerable to failure

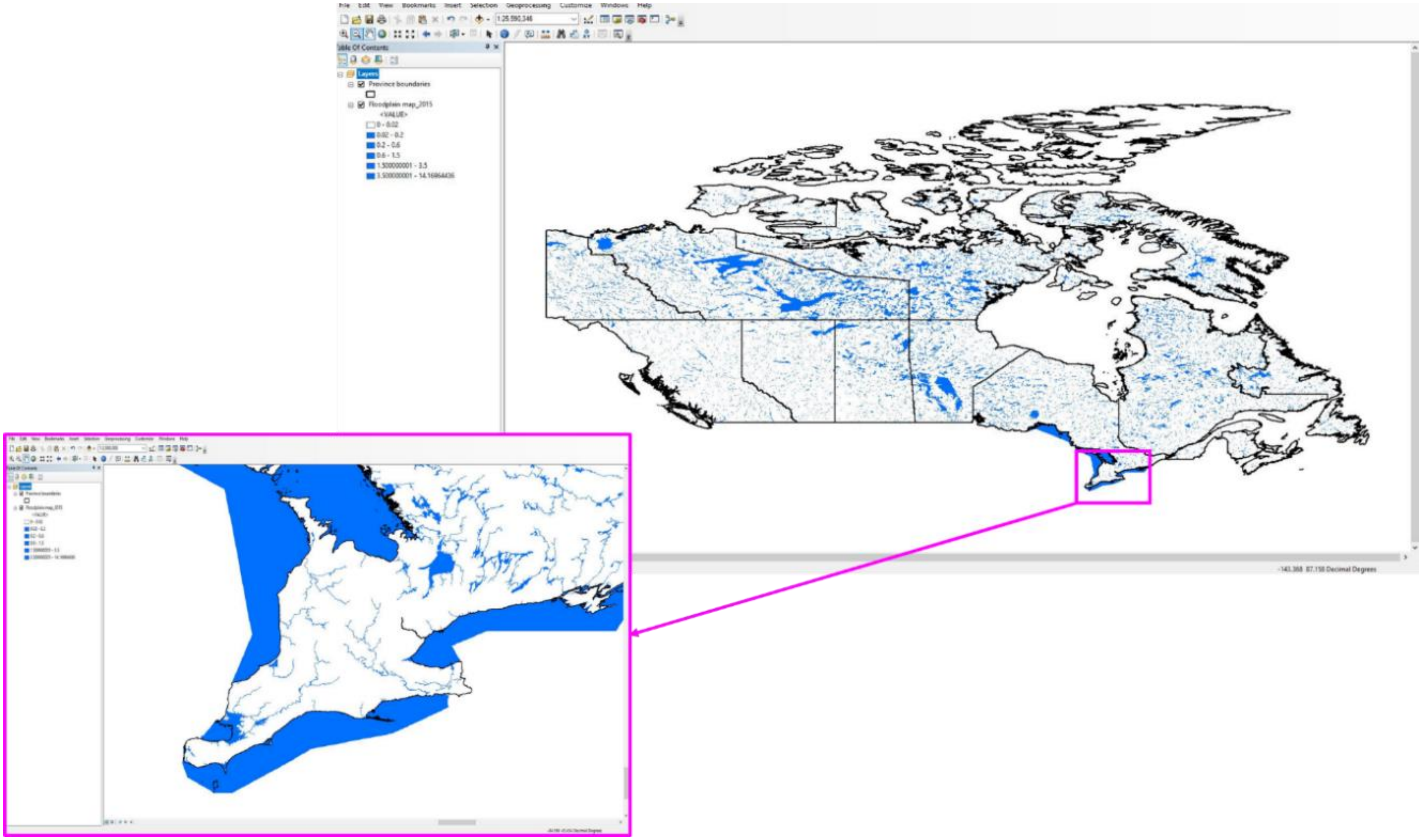

Figure 3.1: Floodplain Map of Canada for the Year 2015

3.2 Population Data

The reference population data source that was used as the basis of all the comparisons and for the further assessment of exposure to flooding was obtained from Statistics Canada. Statistics Canada is the best choice to use as the threshold of all datasets because it is the Government's official website, meaning that it must have the most accurate data and has the biggest variety of population & demography data available for download (Statistics Canada, 2012). Since the 2011 Census, a new methodology has been used to collect census data referred to as the wave methodology which involves contacting non-respondent households at key times to remind them to take part in the census and to encourage them to complete the questionnaire (Statistics Canada, 2019). Every Canadian household is required by law to answer the census questions, limiting the overall presence of any errors (Statistics Canada, 2019). This data source additionally has data for other topics out of the population horizon including economy, income, various age groups, immigration, travel, housing, agriculture and many others. Under the population section there are additional subtopics such as births, migration, mortality and future population estimates per region (Statistics Canada, 2020). When downloading the data, there were multiple spatial resolutions available however, only the 1 km was needed. It is important when comparing different datasets, that they have the same grid size/spatial resolution in ArcGIS or else users will have to deal with a lot of problems regarding the projections in ArcMap. Therefore, the same spatial resolution for all five datasets was downloaded (1 km). Even though a wide range of temporal resolutions were available for Statistics Canada (from around 1991-2020), it was extremely hard to find the population data because a lot of the pages were archived on the website and unavailable in TIF format and needed to be converted. The next population data source that was used is: World Pop, which is a globally used website that shows the spatial distribution of the population for almost any country, including

Canada from years 2000-2020 (World Pop, 2020). There were only two options for grid sizes: 1 km and 100 m hence, 1 km was used for download. World Pop is an extremely organized website where it is quite easy to find every year needed for analysis, all available in ArcGIS formats such as TIF. Global Human Settlement (GHS) was also used and had three options for spatial resolution: 0.25km, 0.27km, and 1km for the years: 1975, 1990, 2000, and 2015 also all available in TIF format (Global Human Settlement - European Commission, 2016). The only issue with this data source was that there was not enough data for other years and that the years available were too spread out, making it harder to differentiate the yearly change in population. The last two population sources used were: Gridded Population of the World (GPW) and LandScan. Both datasets were accessible in TIF format and had the 1 km spatial resolution. The Gridded Population of the World consists of estimates of human population, consistent with national for the years 2000, 2005, 2010, 2015, and 2020 while LandScan represents an ambient population (an average population count over 24 hours) for the years 1998, and 2000-2018. For a more detailed description of these five data sources with their official website URLs, refer to **Table 2.2**. From there, it will be quite simple to obtain all relevant data as all the websites show you exactly where to download the datasets straight onto your devices. Users should keep in mind that downloading all the applicable datasets is a very time-consuming process. As mentioned in **Section 2.2**, all data must have the same geographic coordinate system in order for ArcMap to project the data properly. The process for preparing this data for the assessment of impacts is that users must add the specific dataset for the year desired (i.e. Statistics Canada or any other dataset) by clicking the “Add Data” option in ArcMap. LandScan, GHS and GPW are only available showing world-wide data on a map which must be cut down to match the Canada boundary map. The easiest approach would be to use the “Extract by Mask” option found in Arc Toolbox found under “Spatial Analyst Tools” -

--> “Extraction” which would then extract the data to exactly match the boundary map, without messing up any projections. The data would now be ready for the next steps needed to be taken to find the Canadian population exposed to flooding (See **Appendix A** for a complete example). Consequently, for the experiments that were done in this study, only the year 2015 was used to compare all of the datasets because this was the only year all the datasets downloaded had in common (even though the websites said otherwise) while the years 2006-2019 were used for the exposure and vulnerability analysis with Statistics Canada data in **Section 4.4** (Experiment 3).

Chapter 4: Analyses of Flood Impacts on Canadian Population

4.1 List of Experiments

The tasks were split up into three main experiments to analyze the flood impacts on the population in Canada:

- **Experiment #1: Comparing Different Population Data Sources for 2015**

  The distribution of population in 2015 observed in all five data sources and the difference in population in Canada between Statistics Canada and the other data sources. This experiment is only conducted to identify how each population data source varies from the others so that we are able to use the most accurate source when doing further analyses of impacts.

- **Experiment #2: Population Exposed to Flooding in 2015**

  The population exposure analysis with all the population data sources for flooding in 2015 over Canada and the exposure analysis for 1:100 and 1: 200-yr event floods over Canada and test regions: Assiniboine Basin, Bow and Elbow Basin, St. John Basin, Grand Basin, Lower Fraser Basin, and the Red River Basin. The objective of this experiment is to figure out how much of the population is being exposed to floods in 2015 and to illustrate the possibilities of flooding occurring with the use of 1:100 and 1: 200-yr event flood maps which represent that in any given year there is a 1% and 0.5% chance a flood risk area will flood.

- **Experiment #3: Exposure and Vulnerability Analysis from 2006 to 2019**

  The exposure and vulnerability analysis from 2006 to 2019 with Statistics Canada, and identification of most severely affected census sub-divisions. This task is crucial to show which areas are most affected and are at most risk during emergency evacuation and planning.

4.2 Experiment 1 – Comparing Different Population Data Sources for 2015

In this experiment, there were two main tasks involved in the comparison of different population data sources for the year 2015. As mentioned previously, 2015 was the only same year all these population data sources had in common because some of the years that were initially planned to be downloaded, were not available on certain data sources (i.e. a lot of pages on Statistics Canada were archived for some reason). However, for these two tasks (unlike previously mentioning keeping the population data sources in TIF files), we must convert all population data sources to shapefile format. The reason why we must do this is because there was no Statistics Canada data in TIF format that was not archived therefore, we must collect data over various census divisions into an Excel spreadsheet, which can then easily be converted into a shap efile. All other data sources that are already in TIF format must be converted into shapefile format through ArcGIS using geoprocessing tools. Since our data downloaded had only a single band of data (and a small number of "classes"), the tool that was used for conversion was the "Raster to Polygon" tool. Users will know when datasets are in shapefile format by the ability to open the attribute table by right clicking on the data, since TIF formats do not have this feature available. After all the datasets are converted, the first task of preparing 5 different maps (of each different data source) to show the distribution of population in 2015 may be started. The plotting of the original data on a map is a very simple step, since all you have to do is go into "Symbology" (by right clicking all population data and selecting layer properties) then, select the relevant column of data that you currently want to show from the drop down. From there, you must select 5 classes manually in Symbology and choose 5 shades/colours that are distinct from one another. Under "Classify," select a range that is uniform for all datasets (not changing the minimum and maximum limits). From there, all that is left to do is add a legend that shows the amount of population (that can be found under "Insert"), latitude & longitude, a North arrow, and a scale. The second task will be a very similar process to the first task other than the main difference of using the "Subtraction" tool (minus 3D-analyst) in ArcMap to make four maps, each comparing Statistics Canada (our basis) to every other data source. It is important to keep in mind that the geographic coordinate system for this entire experiment is GCS North American 1983 with a prime meridian: Greenwich. If for some reason, the data sources do not match, users must use the "Project" data management tool in ArcMap to make the data sources have the same coordinates and projections. "Symbology" is used again but this time, users will have to add 6 classes (again with 6 new distinct colours) and come up with a new range (which is uniform for the second task) without changing the maximum value. Once again, a legend, latitude and longitude, a North arrow, and a scale are needed for presentation. The "Zonal Statistics" in ArcMap would then be used to calculate the exact difference in population between Statistics Canada and each other data source. Our results for both tasks are shown in **Section 5.1**.

4.3 Experiment 2 – Population Exposed to Flooding in 2015

The exposure analysis was additionally split up into two smaller tasks: the total population exposed to floods in 2015 mainly focusing on 6 test regions of Canada with the five different population datasets, and the quantification of population exposed to floods in 2015 for a 1 in 100 and 1 in 200-year flood event in various population sources. For the first task, the 6 test regions chosen were the Assiniboine Basin, Bow and Elbow Basin, St. John Basin, Grand Basin, Lower Fraser Basin, and the Red River Basin. We have decided to choose the floodplains that are prone to flooding in Canada based on history and future predictions. The five previous datasets (Statistics Canada, GHS, GPW, Landscan, and World Pop) for the year 2015 were overlaid on the flood map of Canada for the common year further shown in **Appendix A**. Keep in mind that the datasets and flood map are all in TIF format for this experiment. From there, the “Zonal Statistics” tool in ArcMap was used to calculate the population exposed to all flood depths and specifically only high and very high flood depths. Lastly, a legend, latitude and longitude, a North arrow, and a scale are needed for presentation. We have assessed these results in both quantitative and qualitative techniques with the help of tables and maps shown in **Section 5.2**. As shown in **Table 3.1**, a value of 1.5 to 3.5 meters of maximum water depth indicates a high flood hazard while, a water depth exceeding 3.5 meters indicates a very high flood hazard. We have decided to use this method to identify areas and floodplains that are at higher risk than others hence, these areas must be protected against flooding to a greater extent. For the second task of representing the exposure to floods in 2015 for a 1 in 100 and 1 in 200-year flood event, we used statistical probability to put a context to floods and their occurrence. If the probability of a flood magnitude being reached or surpassed is known, then risk can be assessed. To determine these probabilities, all the annual peak streamflow values measured at a stream gage are examined with the help of the CaMa-Flood model. Generally, the meaning of a 1-100 year and a 1-200 year flood is misinterpreted as meaning a flood will only occur in the highlighted area once every 100 and 200 years however, it just defines that in any given year there is a 1% or 0.5 % chance a flood risk area will flood, similar to rolling a dice. The results of the population exposed for a 1 in 100 and 1 in 200-year flood event are computed quantitatively in a table that can be found in **Section 5.2**.

4.4 Experiment 3 - Exposure and Vulnerability Analysis from 2006 to 2019

For the final experiment, only Statistics Canada was used as the population dataset to portray the degree of exposure of population (ranging from very low to very high) from 2006 to 2019 at census sub-divisions in Canada. We represented the flood exposure based off the percentage of the population exposed to floods out of the total Canadian population, as shown in **Table 4.1**. We have prepared 14 qualitative maps for each year (2006 to 2019) of Canada showing all areas with very low, low, medium, high, and very high flood exposure, found in **Section 5.3**.

Table 4.1: Discretization of Flood Exposure (Mohanty et al., 2020)

Percent of population out of total population exposed to floods	Flood exposure
0 to 5	Very Low
5 to 10	Low
10 to 15	Medium
15 to 20	High
> 20	Very High

The maps were constructed by the addition of five classes (with five distinct colours to show the range in flood exposure) in “Symbology” in ArcGIS. Under “Classify” in the same section, a uniform range had to be selected for all years to accurately portray flood exposure. For this experiment, the Statistics Canada data was in shapefile format and contained the geographic coordinate system: GCS North American 1983 with a prime meridian: Greenwich. We have provided the quantitative values for the total population exposed to floods from 2006 to 2019 with Statistics Canada data, and list of census sub-divisions with high and very high exposure to floods in Canada with Statistics Canada, in **Section 5.3**. These values were calculated using the “Zonal Statistics as a table” tool found in ArcMap. This experiment is very essential because the results are established off the most accurate dataset used by the Government of Canada and shows a temporal change which is needed for future flood risk management.

Chapter 5: Results

5.1 Experiment 1 – Comparing Different Population Data Sources for 2015

Based on our results, it is clear that there are differences when it comes to population datasets, which we must keep in mind when further analyzing and constructing flood maps. This can be seen in the distribution of the population in **Figure 5.1**. There exist small inconsistencies in each dataset that lead to small differences such as in the maps below where a contrast in colours of the same areas occur from one dataset to another. A specific example of this would be examined if we take a close look at certain census sub-divisions in the maps below that vary from (a) to (e) (none of the maps look the exact same). However, there are no major dissimilarities in the population data sources used therefore, yielding to more accurate results in the assessment.

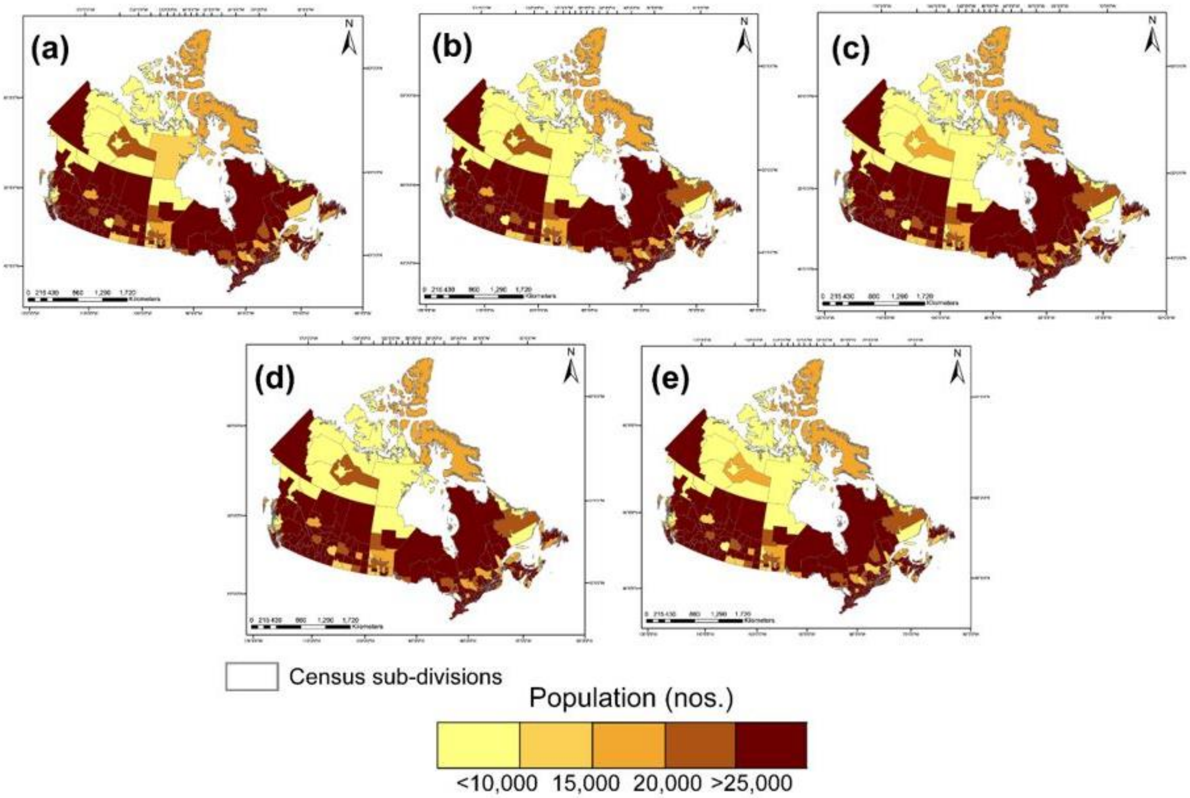

Figure 5.1: Distribution of Population in 2015 observed in (a) Statistics Canada, (b) Global Human Settlement, (c) Gridded Population of the World, (d) LandScan, and (e) World Pop

Based on our results from the second part of the experiment, we can conclude that the difference between Statistics Canada and (a) GHS and (b) GPW is a smaller range than between the other datasets (c) LandScan and (d) World Pop by simply looking at the maps in **Figure 5.2**. This signifies that these three data sources have more in common with each other (with the distribution of population) and should be more focused on for further assessment. Overall, there are a lot less bright red and blue areas in (a) and (b) and a higher amount of green and yellow areas that indicate a smaller discrepancy in total population.

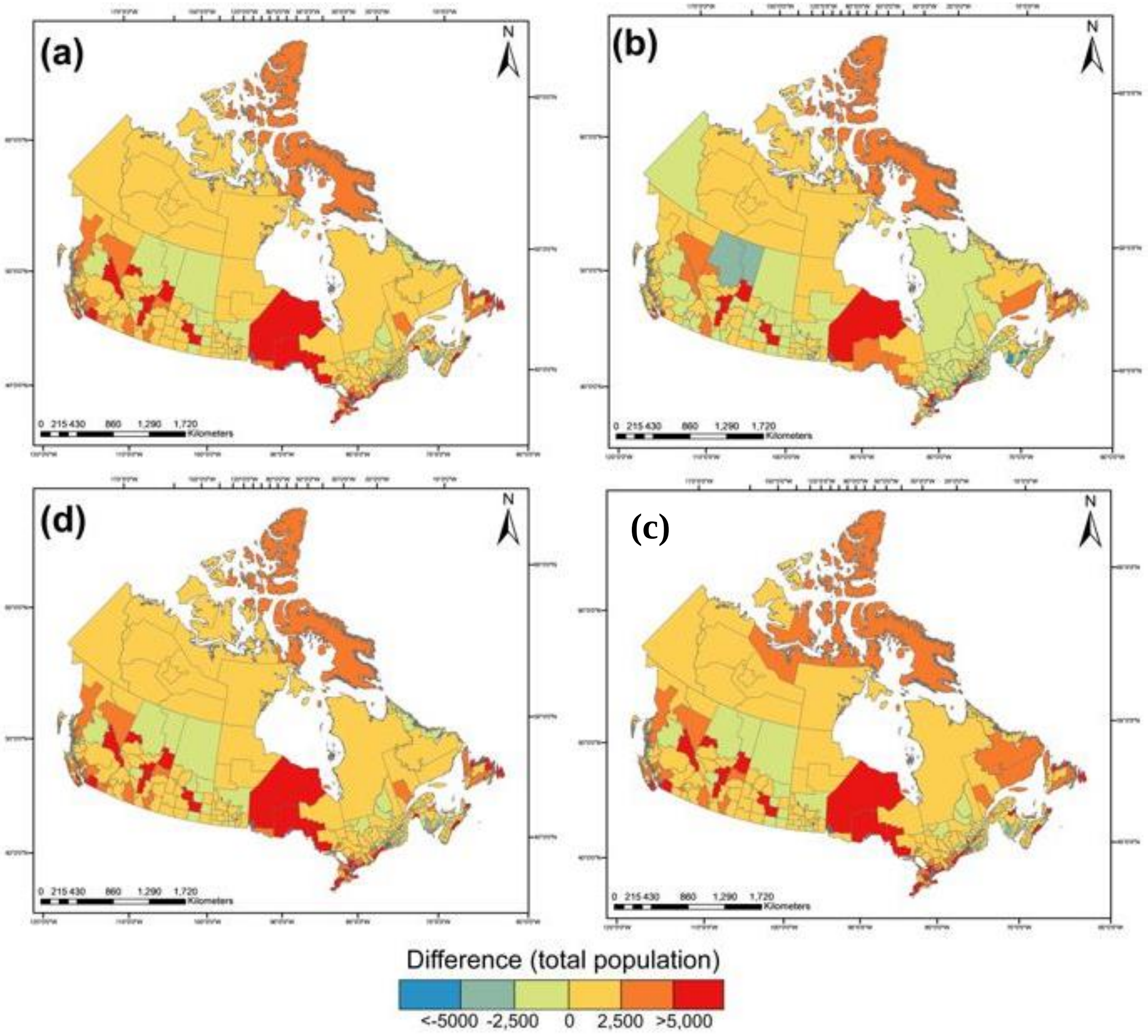

Figure 5.2: Difference of Population in 2015 between Statistics Canada and (a) Global Human Settlement, (b) Gridded Population of the World, (c) LandScan, and (d) World Pop

5.2 Experiment 2 – Population Exposed to Flooding in 2015

This experiment is one of the most significant components of our entire study. The results from **Figure 5.3** demonstrate a visual representation of the population exposed to inundation (all flood depths) in Canada which was achieved by the overlap of the flood map for the year 2015 and all the various population data sources. There is not too much variation seen in the maps below, other than there being more dark brown areas (more population exposed) specifically in the zoomed in areas with the yellow outline of the maps based on Statistics Canada data and Gridded Population of the World data.

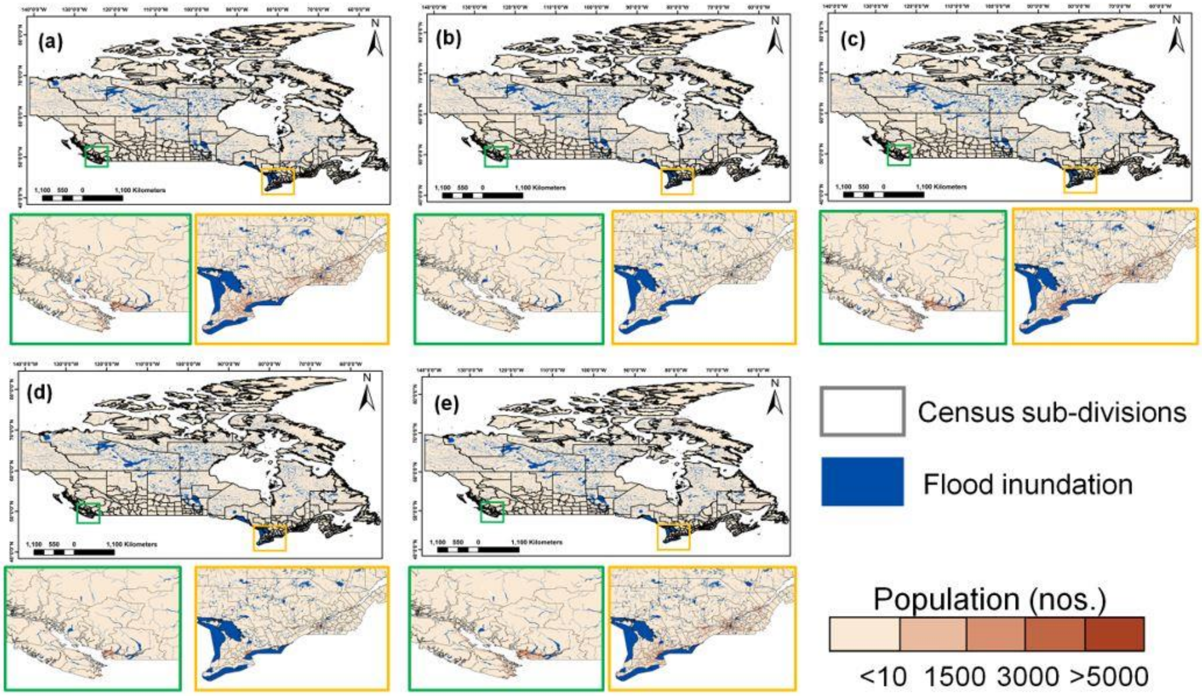

Figure 5.3: Population Exposed to Floods in 2015 with (a) Statistics Canada, (b) Global Human Settlement, (c) Gridded Population of the World, (d) LandScan, and (e) World Pop

Figure 5.4 provides the results of the population exposed to only high and very high flood depths for 2015 with various population data sources which outlines all of the areas that were affected and are more prone to severe flooding (which has a bigger impact on the population). The criteria used to determine what is considered a high and very high flood depth is previously demonstrated in **Table 3.1.** These results show that Statistics Canada data and Gridded Population of the World data again have more population distributed (represented by darker brown areas) at high and very high flood depths, meaning that they are at higher risk during severe inundations. The other population data sources may be underestimating the amount of people living in certain areas which could lead to an under-value of the population exposed to high and very high flood depths.

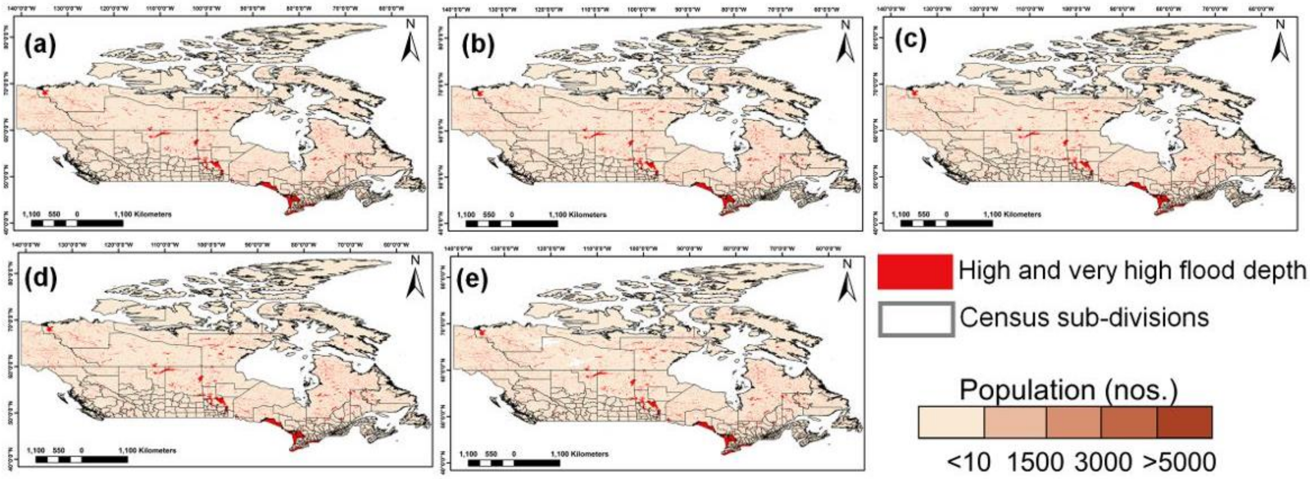

Figure 5.4: Population Exposed to Floods (Only High and Very High Flood Depths) in 2015 with (a) Statistics Canada, (b) Global Human Settlement, (c) Gridded Population of the World, (d) LandScan, and (e) World Pop

A comparison between the population exposed in 2015 for all categories of flood depths versus only high and very high flood depths between all population data sources is provided in **Table 5.1** below. It can be noted by looking at the quantitative data in the table that LandScan and World Pop show the lowest population exposed to all flood depths and only high and very high depths compared to Statistics Canada. This bit of information is critical for us to be aware of because now we must not consider these data sources for future assessment of flooding in Canada since, it will not yield such accurate results as Statistics Canada, Global Human Settlement, and Gridded Population of the World.

Table 5.1: Quantification of Population Exposed to Floods in 2015 with Various Population Sources

Population source	Population exposed in 2015 (in millions)	
	All flood depths	**Only high and very high flood depths**
Statistics Canada	2.23	1.52
Global Human Settlement	2.06	1.30
Gridded Population of the World	2.11	1.33
LandScan	1.97	1.27
World Pop	1.66	1

In the next part of the experiment, 6 flood-prone river basins were chosen for analysis which include: Assiniboine basin, Bow and Elbow basin, St. John basin, Grand basin, Lower Fraser basin, and Red River basin. Our results proved that the highest amount of the population exposed to floods (all flood depths and only high and very high flood depths) was over the Lower Fraser basin, while the lowest amount of exposure was over the Red River basin (see **Table 5.2** and **Table 5.3**) in 2015.

Table 5.2: Total population exposed to floods (all flood depths) in 2015 over 6 test regions with various population datasets

Population data	Assiniboine Basin	Bow and Elbow Basin	St. John basin	Grand basin	Lower Fraser Basin	Red River Basin
Statistics Canada	216072	20459	104967	122177	282177	2824
GHS	210321	18911	90261	119693	279693	2212
GPW	212850	19613	69272	121015	281015	2121
LandScan	211661	17554	85198	119331	279331	2230
World Pop	210228	16865	74705	119667	279667	2001

Table 5.3: Total population exposed to floods (only high and very high flood depths) in 2015 over 6 test regions with various population datasets

Population data	Assiniboine Basin	Bow and Elbow Basin	St. John basin	Grand basin	Lower Fraser Basin	Red River Basin
Statistics Canada	183661	15958	81875	100185	231385	2203
GHS	178772	14183	74014	98149	229349	1725
GPW	176666	15298	55417	94391	227622	1654
LandScan	179912	14043	66454	100238	223465	1739
World Pop	168183	12649	56028	93340	206953	1561

Another aspect that can be noted by looking at these tables is that Statistics Canada data always has the highest total population exposed to floods under each of the test regions. In this context, it would be safer to go with the results of Statistics Canada rather than having an underestimated population exposure, potentially leading to maps that show lower risks to flooding than intended. Finally, for the last task we made a comparison of population exposure to floods over Canada and the same 6 test regions with all data sources for a 1 in 100 and 1 in 200-yr flood event. The results we came across were very similar to the last task completed, where Statistics Canada had the highest population exposure in a 1 in 100 and 1 in 200-yr flood event and World Pop had the lowest population exposure (see **Table 5.4** for the quantitative values and **Figure 5.6** for a visual representation).

Table 5.4: Quantification of Population Exposed to Floods in 2015 for a 1 in 100 and 1 in 200-yr Flood Event in Various Population Sources

Population source	Population exposed (in millions)	
	1 in 100-yr	1 in 200-yr
Statistics Canada	3.31	3.90
Global Human Settlement	3.01	3.40
Gridded Population of the World	3.27	3.63
Landscan	3.01	3.40
World Pop	2.86	3.24

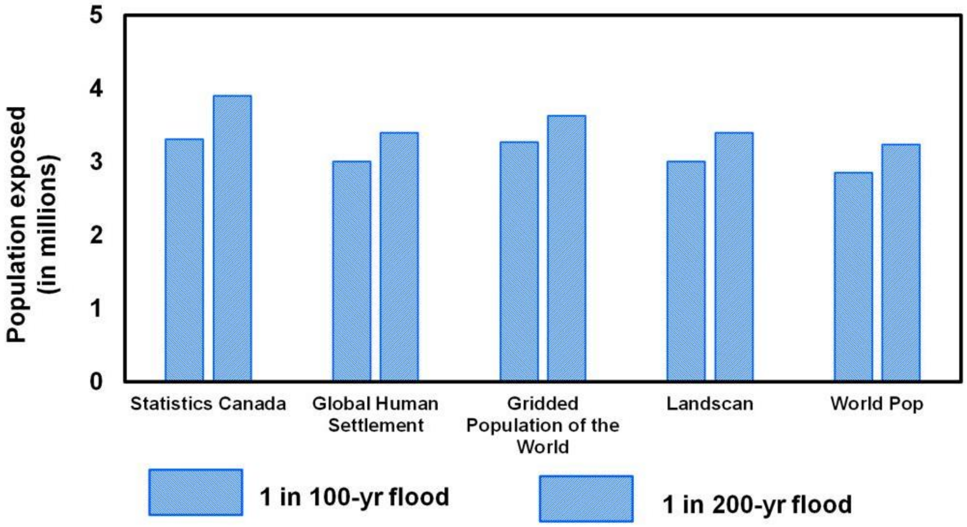

Figure 5.5: Total Population Exposed to Floods Considering a 1 in 100 and 1 in 200-yr Flood Event

5.3 Experiment 3 – Exposure and Vulnerability Analysis from 2006 to 2019

For experiment #3, the total population exposed to floods was found using “Zonal Statistics” in ArcMap with the Statistics Canada dataset (see **Table 5.5** for specific values) from 2006 to 2019. The table follows a specific trend: as the years go up, so does the population exposed to flooding as predicted. The temporal change in population exposure and vulnerability at specific census sub-divisions using Statistics Canada is provided in **Table 5.6**. Looking at this table, we notice that big cities such as Toronto and Montreal are classified as having a very high degree of exposure.

Table 5.5: Total Population Exposed to Floods from 2006 to 2019 with Statistics Canada Data

Year	Population exposure
2006	1981675
2007	2007103
2008	2035751
2009	2066293
2010	2096372
2011	2123128
2012	2153119
2013	2182618

Year	Population exposure
2014	2210976
2015	2232214
2016	2264740
2017	2299447
2018	2340603
2019	2383122

Table 5.6: List of Census Sub-Divisions with High and Very High Exposure to Floods in Canada

Census sub-division	Province	Degree of exposure
Brome-Missisquoi	Quebec	High
Huron	Ontario	High
Kings	Nova Scotia	High
Division No. 17	Alberta	High
Central Kootenay	British Columbia	High
East Kootenay	British Columbia	High
Cariboo	British Columbia	High
Muskoka	Ontario	High
Peace River	British Columbia	High
Beauharnois-Salaberry	Quebec	High
Dufferin	Ontario	High
Joliette	Quebec	High
Kenora	Ontario	High
Kings	New Brunswick	High
Division No. 13	Alberta	High
Division No. 12	Alberta	High
Comox Valley	British Columbia	High
Lanark	Ontario	High
Bruce	Ontario	High
Division No. 7	Manitoba	High
Arthabaska	Quebec	High

Division No. 16	Alberta	High
Saint John	New Brunswick	High
Gloucester	New Brunswick	High
Marguerite-D'Youville	Quebec	High
Kawartha Lakes	Ontario	very high
Cochrane	Ontario	very high
Perth	Ontario	very high
Division No. 2	Manitoba	very high
Division No. 1	Alberta	very high
Nipissing	Ontario	very high
Les Maskoutains	Quebec	very high
Okanagan-Similkameen	British Columbia	very high
Division No. 15	Saskatchewan	very high
Northumberland	Ontario	very high
Cowichan Valley	British Columbia	very high
North Okanagan	British Columbia	very high
La Haute-Yamaska	Quebec	very high
Queens	Prince Edward Island	very high
Elgin	Ontario	very high
Prescott and Russell	Ontario	very high
Division No. 10	Alberta	very high
Grey	Ontario	very high
Cape Breton	Nova Scotia	very high
Fraser-Fort George	British Columbia	very high
Deux-Montagnes	Quebec	very high
Leeds and Grenville	Ontario	very high
Chatham-Kent	Ontario	very high
Renfrew	Ontario	very high
York	New Brunswick	very high
Drummond	Quebec	very high

Algoma	Ontario	very high
Stormont, Dundas and Glengarry	Ontario	very high
Haldimand-Norfolk	Ontario	very high
Oxford	Ontario	very high
Le Haut-Richelieu	Quebec	very high
L'Assomption	Quebec	very high
Division No. 19	Alberta	very high
La Vallee-du-Richelieu	Quebec	very high
Lambton	Ontario	very high
La Riviere-du-Nord	Quebec	very high
Hastings	Ontario	very high
Thompson-Nicola	British Columbia	very high
Levis	Quebec	very high
Peterborough	Ontario	very high
Brant	Ontario	very high
Thunder Bay	Ontario	very high
Francheville	Quebec	very high
Vaudreuil-Soulanges	Quebec	very high
Westmorland	New Brunswick	very high
Therese-De Blainville	Quebec	very high
Frontenac	Ontario	very high
Les Moulins	Quebec	very high
Sherbrooke	Quebec	very high
Greater Sudbury / Grand Sudbury	Ontario	very high
Le Saguenay-et-son-Fjord	Quebec	very high
Nanaimo	British Columbia	very high
Division No. 2	Alberta	very high
Roussillon	Quebec	very high

Central Okanagan	British Columbia	very high
Division No. 8	Alberta	very high
Wellington	Ontario	very high
Division No. 1	Newfoundland and Labrador	very high
Gatineau	Quebec	very high
Division No. 6	Saskatchewan	very high
Fraser Valley	British Columbia	very high
Division No. 11	Saskatchewan	very high
Capital	British Columbia	very high
Essex	Ontario	very high
Longueuil	Quebec	very high
Laval	Quebec	very high
Halifax	Nova Scotia	very high
Niagara	Ontario	very high
Middlesex	Ontario	very high
Simcoe	Ontario	very high
Hamilton	Ontario	very high
Quebec	Quebec	very high
Waterloo	Ontario	very high
Halton	Ontario	very high
Durham	Ontario	very high
Division No. 11	Manitoba	very high
Ottawa	Ontario	very high
York	Ontario	very high
Division No. 11	Alberta	very high
Peel	Ontario	very high
Division No. 6	Alberta	very high
Montreal	Quebec	very high
Greater Vancouver	British Columbia	very high
Toronto	Ontario	very high

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Appendix A: An Example of Population Exposure Assessment

In this section, a detailed example of how the population exposed was assessed is described. To begin, this process was performed using ArcGIS 10.7.1, specifically ArcMap. This process can be followed using any newer versions of ArcGIS, but it is recommended using version 10.6 or higher for the reason that previous versions have a different layout that could potentially be more complicated to follow along with. To download ArcGIS, users must get special permission from the educational institute they are with or contact ESRI support. For more details, visit https://www.esri.com/en-us/arcgis/products/index.

Step 1: For this example, we used the GHS (Global Human Settlement) dataset to figure out the population exposed to flooding for the year 2015. In this step, users must add all relevant data which includes: the provincial boundaries file (in shapefile format), the GHS dataset for 2015 (in TIF format), and the pre-processed flood map for 2015 (also in TIF format). The spatial resolution for the data and map used should be same (1 km in this study), to prevent future issues with the mismatch in grid resolutions in ArcMap. Adding all relevant data is done using the "Add Data" option in ArcMap, shown in the picture below (**Figure A1**). From here, GIS users choose these data files from their saved files. These files must be sorted in separate folders that can easily be identified and found using ArcMap. Another method to add data can be using the "Drag and Drop" option, where you can simply drag your spatial data from your folders to the application running in your browser. However, this feature may not always work due to the specific data you are dealing with. In our case when the GHS data is added, ArcMap will ask if you want to "build pyramids" on to the existing data, in which users should select the "no" option.

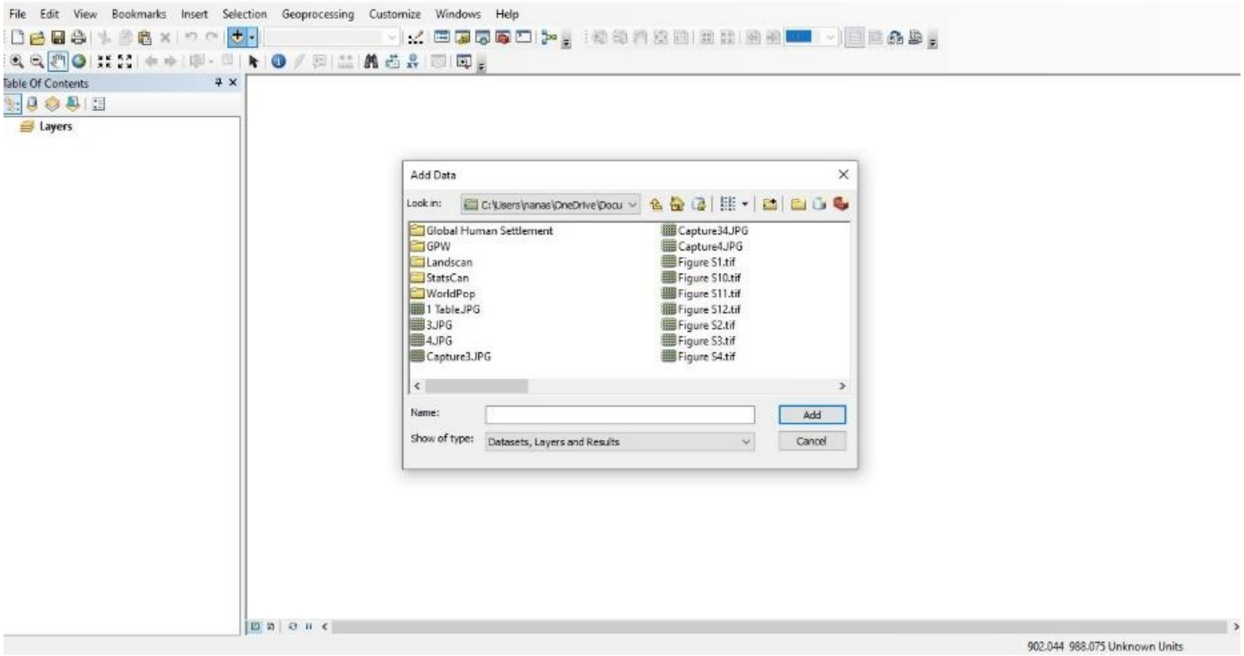


Figure A1: Screenshot of the "Add Data" Function in ArcMap

Step 2: This next step may not be necessary for all datasets. In this step, the GHS data is only available showing world-wide data, which must be clipped to match the Canada boundary map since we are only assessing the exposed population in Canada, and not other parts of the world. This can be achieved in various ways, but the easiest approach would be to use the "Extract by Mask" option found in Arc Toolbox found under "Spatial Analyst Tools" ---> "Extraction." In this step, the input raster would be the dataset in TIF format (GHS dataset) and the input raster or feature mask data would be the Canada boundary map in SHAPEFILE format. This option would then extract the data to exactly match the boundary map (shown in **Figure A2**), without messing up any projections. After the software is done processing the task, the new extracted dataset should show-up as "Extract_tif1" (users' screens should look like **Figure A3**) which can further be changed to another name, done by left clicking on the data once.

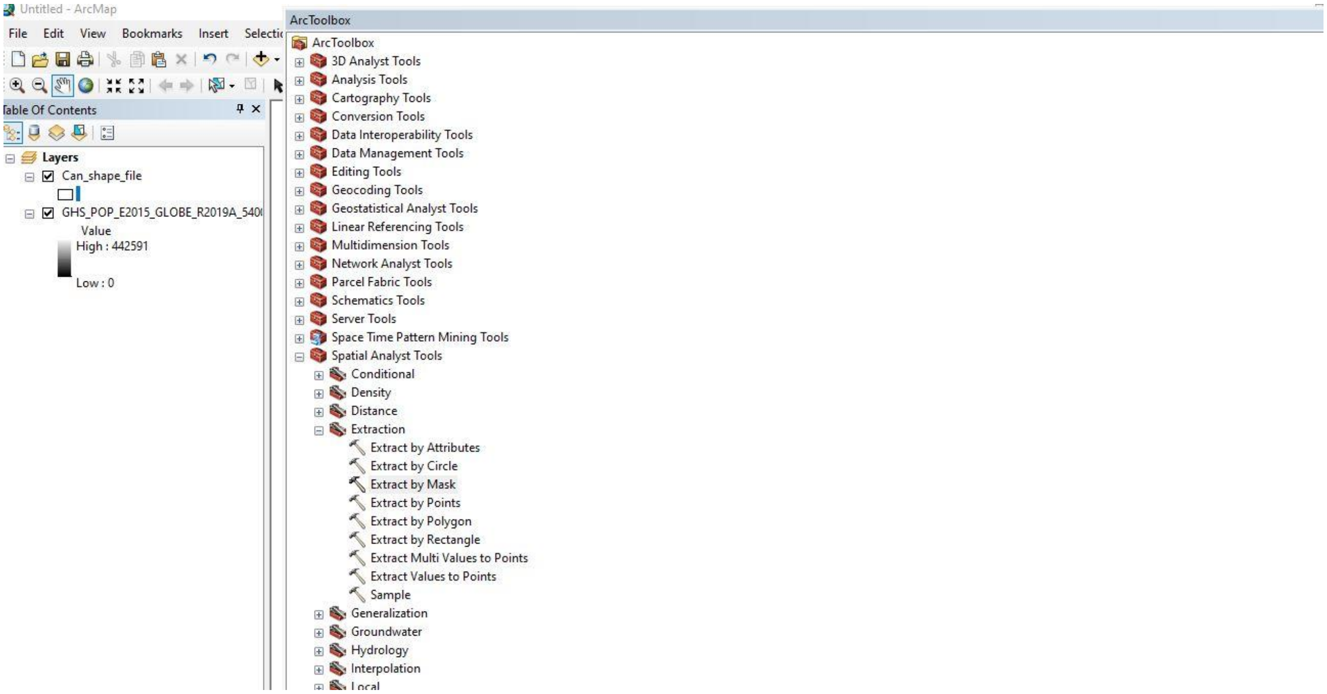


Figure A2: Screenshot of the "Extract by Mask" Tool in ArcMap

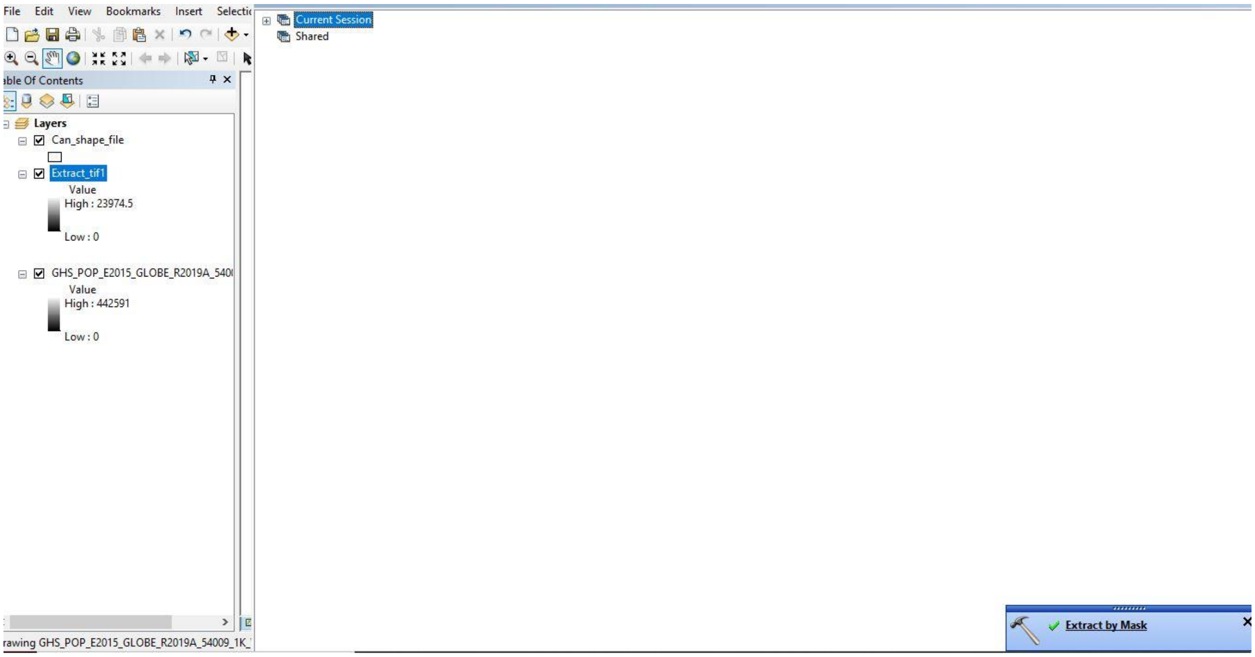


Figure A3: Screenshot of the Screen After the "Extract by Mask" Process is completed

<u>Step 3:</u> In this step, all the relevant data is overlaid on the flood map of 2015. This step is quite simple and only requires checking all layers found under the 'Table of Contents' on the far left of ArcMap which include: the Canada boundary map, the flood map for the 2015 year, and the population data for the same year. Users' screens should appear similar to **Figure A4**, even when zoomed in.

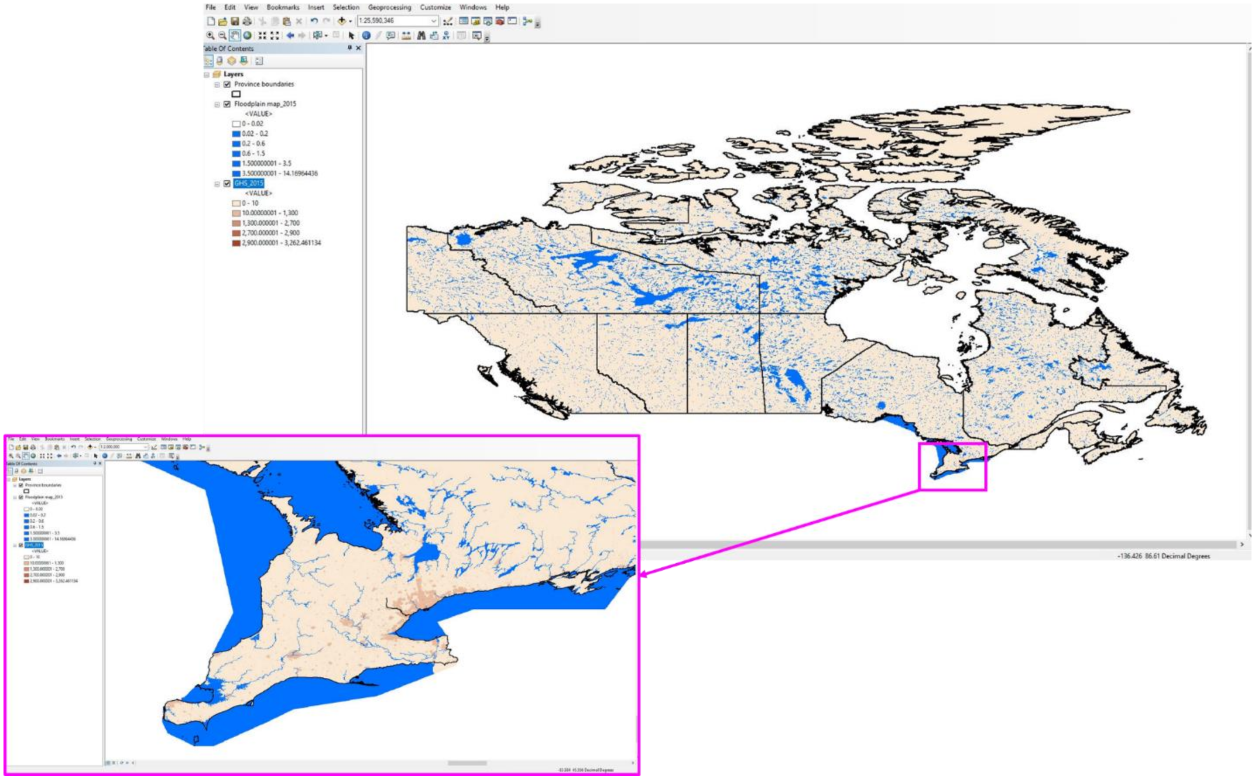
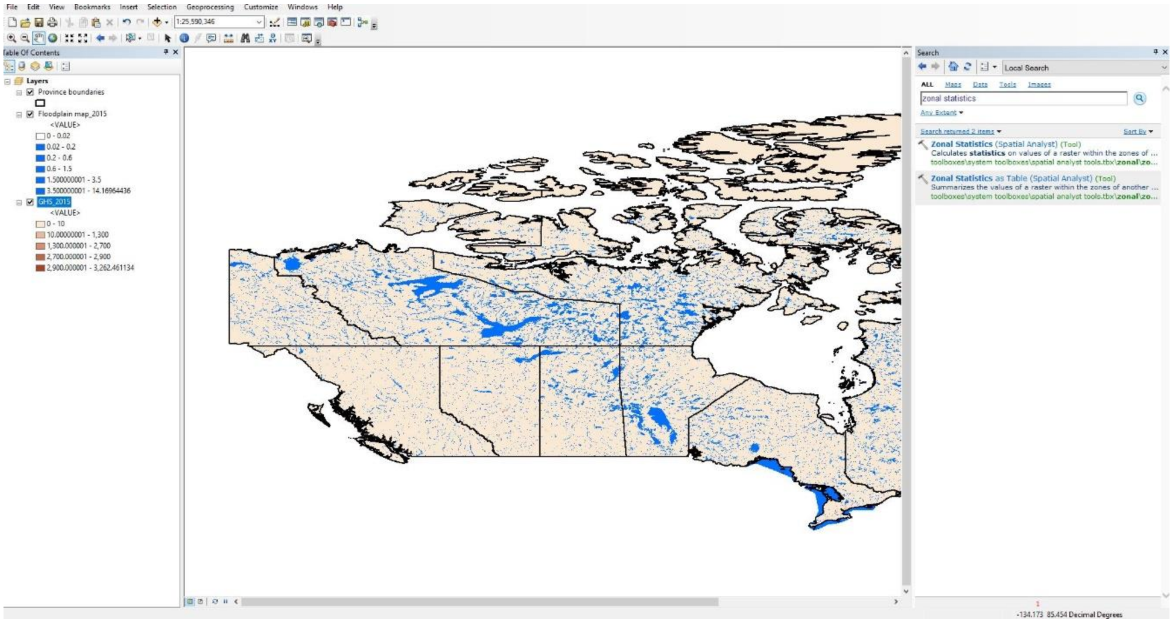


Figure A4: The GHS population map overlaid on the flood map for 2015

<u>Step 4:</u> Finally, for the last step when the data is overlaid, to find the exposed population to flooding, users must use the "Zonal Statistics" option found in Arc Toolbox (see **Figure A5**). "Zonal Statistics" would calculate how much of the population is affected by flooding in each specific location. The "Zonal Statistics as Table" option would fulfill the exact same process but would put the results in the form of a table, which may potentially be easier for users to compare the population exposed. See **Section 5.2** for the results we got after following this process.



Layers
- ☑ Province boundaries
- ☑ Floodplain map_2015
  - <VALUE>
  - 0 - 0.02
  - 0.02 - 0.2
  - 0.2 - 0.6
  - 0.6 - 1.5
  - 1.500000001 - 3.5
  - 3.500000001 - 14.16964436
- ☑ GHS_2015
  - <VALUE>
  - 0 - 10
  - 10.00000001 - 1,300
  - 1,300.000001 - 2,700
  - 2,700.000001 - 2,900
  - 2,900.000001 - 3,262.461134

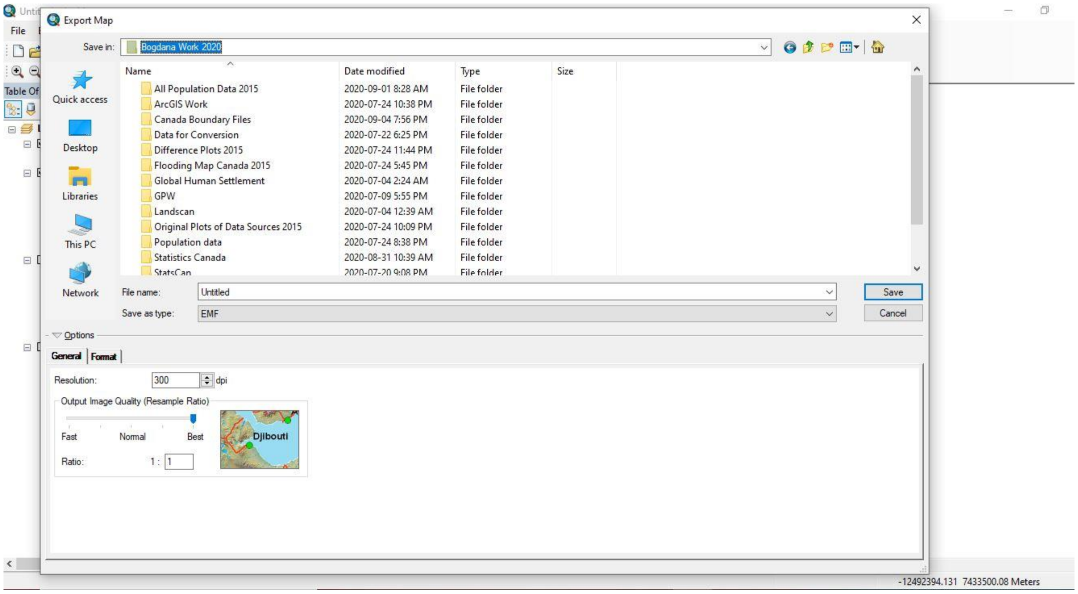
Search: zonal statistics

Zonal Statistics (Spatial Analyst) (Tool)
Calculates statistics on values of a raster within the zones of ...
toolboxes\system toolboxes\spatial analyst tools.tbx\zonal\zo...

Zonal Statistics as Table (Spatial Analyst) (Tool)
Summarizes the values of a raster within the zones of another ...
toolboxes\system toolboxes\spatial analyst tools.tbx\zonal\zo...

Figure A5: Screenshot Using the "Zonal Statistics" Tool in ArcMap to Determine the Population Exposed to Floods

Step 5: After all the above steps are completed, users must save the map of the exposed population to flooding. This can be done using the "Export Map" option found under "File" in ArcMap. The format saved should be in either TIF or EMF for higher resolution (see **Figure A6**).



Save in: Bogdana Work 2020

Name	Date modified	Type	Size
All Population Data 2015	2020-09-01 8:28 AM	File folder	
ArcGIS Work	2020-07-24 10:38 PM	File folder	
Canada Boundary Files	2020-09-04 7:56 PM	File folder	
Data for Conversion	2020-07-22 6:25 PM	File folder	
Difference Plots 2015	2020-07-24 11:44 PM	File folder	
Flooding Map Canada 2015	2020-07-24 5:45 PM	File folder	
Global Human Settlement	2020-07-04 2:24 AM	File folder	
GPW	2020-07-09 5:55 PM	File folder	
Landscan	2020-07-04 12:39 AM	File folder	
Original Plots of Data Sources 2015	2020-07-24 10:09 PM	File folder	
Population data	2020-07-24 8:38 PM	File folder	
Statistics Canada	2020-08-31 10:39 AM	File folder	
StatsCan	2020-07-20 9:08 PM	File folder	

File name: Untitled

Save as type: EMF

Resolution: 300 dpi

Output Image Quality (Resample Ratio)

Ratio: 1 : 1

Figure A6: Screenshot of the "Export Map" Feature in ArcMap

Appendix B: Previous Reports in the Series

ISSN: (Print) 1913-3200; (online) 1913-3219

In addition to 89 previous reports (No.01 – No.089) prior to 2014 (available at https://www.eng.uwo.ca/research/iclr/fids/products.html)

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ResilSIMt. Water Resources Research Report no. 105, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 112 pages. ISBN: 978-0-7714-3115-7.

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