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Use of a Climate Change Scenario Analysis Tool to Anticipate Various Futures Associated with Extreme Urban Flooding

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ABSTRACT

This paper reviews the connection and impacts of flooding related to climate change in Southern Ontario. The cased study used was the City of Hamilton and the $20 billion portfolios of assets managed by the City of Hamilton's Public Works Department. The process involved the development of a Scenario Analysis tool, which is well-suited to assess climate resiliency in the face of considerable uncertainty. After analyzing drivers of climate, two axes of uncertainty were selected and generated four potential outcomes. The findings contribute to municipal strategic and capital planning processes with the purpose of increasing community resilience and adaptation to frequent flooding events. The outcomes reveal significant program and policy implications, not just for the focus of our case study, Hamilton, Ontario, Canada, but for other mid-sized coastal cities confronting and contemplating the effects of flooding associated with a changing climate.

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Introduction

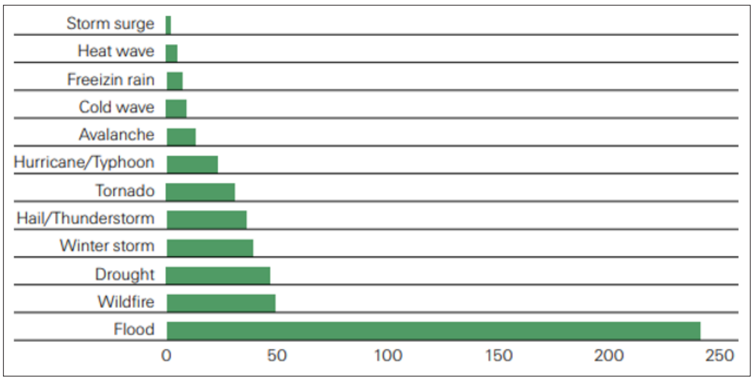
Climate change and flooding events in South Ontario

Climate change is altering climate patterns and adding pressure to climate systems around the world [1-3]. The climate regions dominated by snowfall in winter and glacial melting in spring are particularly vulnerable to the recent warming [1,2]. South Ontario, Canada is experiencing changes in both temperature and precipitation patterns [1]. Champagne et al. predict an increase in temperature and precipitation in most South Ontario regions [1]. Most of South Ontario is experiencing a 0.3-0.5 degree Celsius increase of annual mean temperature and a 3-9 mm increase in annual mean precipitation between 1957 and 2013. An increase of approximately 40% in winter streamflow was observed in 2019, as a result of the reduction of snow cover and precipitation increase. Wang et al. suggest that intensive rainfall events would increase by approximately 17 %, 22 % and 50 % by 2030, 2050 and 2080 respectively [4]. Buttle et al. also point out that the climate extremes observed in South Ontario pose the threat of flooding risks, as earlier spring thaws cause ice-melt-generated floods, especially in lower sections of local rivers [2]. During periods of increased water level, erosion and flooding of shoreline properties along the Great Lakes is a further threat [2,5].

Southern Ontario includes vast urban areas, industrial and agricultural lands [6]. The majority of these lands are located proximal to the Great Lakes and are particularly vulnerable to flooding events. Flood modelling, risk assessment/ mapping approaches and local adaptive infrastructures are the primary methods/ tools of calculating the risk of flooding [7-11]. Gaur et al. have researched flooding related impacts due to climate change on over 100 most populated cities in Canada and have concluded that the risk of flooding in Toronto, Ontario can be expected to increase from 100 years return period to 15 years return period, by the end of the 21st century [7]. From an economic perspective, Costas and Nirupama reported over 850 million worth of losses in Toronto properties during the latest 2013 Toronto flooding [11].

Hamlet et al. have conducted detailed risk assessments on four states in the Western US while DeGaetano et al. calculated the flooding risks in different territories among those states [8,10]. Other severe interruptions according to Costas and Nirupama include power outages, flight cancellations, and local transportation closures [11]. Aziz & Van Cappellen and Kubiszewski et al., further indicated that there is an uncollected economic value from flooding regulation [12,13]. As flood regulation alone contributes to 41% of the total potential value associated with ecosystem services, there would be $8 billion of value generated with proper flooding control and regulations. Therefore, there is an emerging need to find resilience tools/ methods to predict and regulate potential future flooding events in South Ontario to plan and construct infrastructure that can handle more frequent flooding events given the socio-economic value that derives from flooding regulation.

Floods are considered the most expensive natural disaster. The Canadian Disaster Database records 241 flooding events from 1900 to 2016 [14]. Figure 1 shows that flooding is almost five times as greater than the second-most frequent disaster (wildfires). Almost a quarter of these events (62) occurred in Ontario. Flooding in Canada is most likely to occur during the spring snowmelt period [15].



Direct, indirect, and intangible losses (Table 1) are the types of losses that floods cause (Disaster loss assessment guidelines, n.d.). It is easy to confuse the terms "impact," "damage," and "cost" in the literature. A more precise definition has been carried out to make the three distinct. Flood impacts are any negative effects a flood might have on a system; Damage is a monetary assessment of the loss. A "system" refers to a collection of components that interact and depend on one another -- such as stormwater management systems. The term "loss" can also refer to damage that result in the reduction or disappearance of some part of the system [16].

Table 1: Estimation of direct, indirect and intangible losses

Loss sector	Estimation Principle
Residential buildings - structures and contents	Depreciated economic value
Commercial and industrial buildings - structures and contents	Depreciated economic value
Public buildings - structures and contents	Depreciated economic value
Infrastructure	Depreciated economic value
Crops	Harvest value minus input costs avoided (value-added or profit)
Business disruption	Loss of value-added not taken up elsewhere in the area within a specified timeframe
Transport network disruption	Increased vehicle operating costs. Value of time for delayed people and freight (BTE 2001) Value of freight if spoilt by delays Cost of disruption elsewhere in the network
Disruption of public services	Cost of provision (BTE 2001)
Agriculture reduced agricultural yield (only applicable if crop not lost and yield significantly affected by the disaster)	Loss of profit on to a lost proportion of the crop
Disaster response and relief	Marginal costs incurred by relevant agencies. Opportunity costs of volunteer labour
Death	Human capital approach
Serious injury	Human capital approach
Health effects, stress and anxiety	Refer to Handmer, Lustig and Smith (1986), set out in BTE (2001) for 'lost time' method
Cultural and heritage sites and artifacts	Replacement or restoration costs where feasible

Flood disaster economics focuses on the relationship between flood disasters and the economy. An essential part of flood economics research is the study of flood economic activity (Table 2).

The three major flooding events in 2019 caused over 15000 residences either flooded or isolated, 13500 disaster victims and over 75 municipalities affected in Quebec, New Brunswick and Ontario. The Insurance Bureau of Canada stated that it is estimated that over one million of total private residences in Canada are at high risk of flooding, and some of these residences are at very high risk of repeated flooding in the next 20 years [17].

Since 2016, federal disaster assistance has totaled an average of $430 million a year, with more than three-quarters spent on flood recovery. According to the Insurance Bureau of Canada, for every dollar in damage covered by insurance, Canadian taxpayers pay an additional $3 to repair and rebuild public infrastructure [17].

Table 2: Economic losses due to flood disasters in ON, descending order [14].

Place	Event Start Date	Fatalities	Injured / Infected	Evacuated	Normalized Total Cost (2016)
Toronto ON	July 8, 2013	0	0	0	$982,866,450
Thunder Bay ON	May 28, 2012	0	0	0	$254,889,298
Eastern Ontario and Quebec	March 28, 1998	0	0	3757	$39,014,593
Ottawa ON	August 8, 1996	0	0	0	$30,775,559
Southern ON	Januar y 16, 1994	0	0	0	$21,423,473
Harrow, Kent, Essex, Leamington counties ON	July 19, 1989	0	0	0	$23,700,786
Kashechewa n and Fort Albany ON	March 24, 2012	0	0	269	$7,068,858

Figure 2 shows the increase in flooding frequency from 1970 to present. Ontario experienced the most flood disasters than any other province in Canada, experiencing 47 flood disasters from 1970 to 2019.

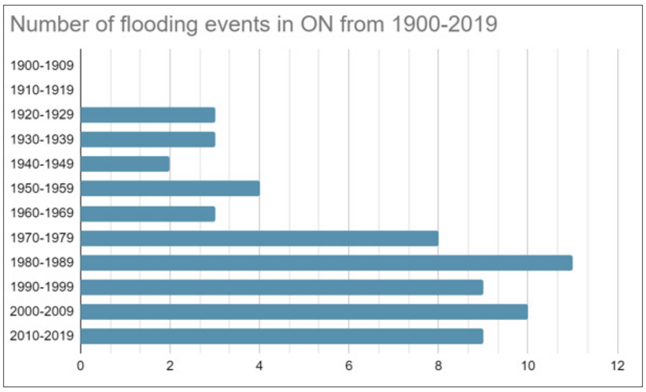


Figure 2: Number of flooding events in ON from 1900-2019 [14].

Turning to Hamilton, Ontario, the case study for this research, the City of Hamilton experienced a rainstorm event on July 26, 2009, with a cumulative rainfall of 111.7mm in 72 hours. The resultant water runoff on saturated ground exceeded the capacity that the municipal sewer system could manage. Consequently, severe flooding occurred and caused damage to over 2,000 households in different parts of the city [18]. The traditional flooding control and mitigation strategies in the City of Hamilton tended to be focused on alerting, evacuation and temporary suspension of services [19]. However, the adaptation of strategic planning and capital planning on future flooding events was missing. Consequently, a case study of Hamilton could illuminate possible future flooding events to analyze programs and policies that could lead to a preferred future and minimize the undesired future negative impact of flooding.

Hamilton Water began the Flooding & Drainage Master Servicing Study to develop a long-term strategy for managing stormwater in the combined sewer service area to reduce urban flooding. Solutions were recommended to reduce basement & surface flooding risks up to the 100-year storm event. The preferred solution consisted of sewer separation (coupled with Low Impact Development) below the escarpment and storage within the combined sewer area on the mountain. Table 3 shows a cost breakdown of the entire program:

Table 3: Cost breakdown

Installation of New Separated Storm Trunk & Local Sewers + Maintenance Holes (includes 40% for Contingency + Engineering Fees)	$	586,000,000
Installation or reconfiguration of Internal Flow Devices (including installation of inlet control devices at all catch basins)	$	30,000,000
Construction of In-Line or Off-line Storage Facilities	$	137,000,000
Construction of LID Measures	$	58,000,000
TOTAL COST =	$	811,000,000

Figure 3 illustrates the $0.127B needed for the 2018-2027 capital program (stormwater).

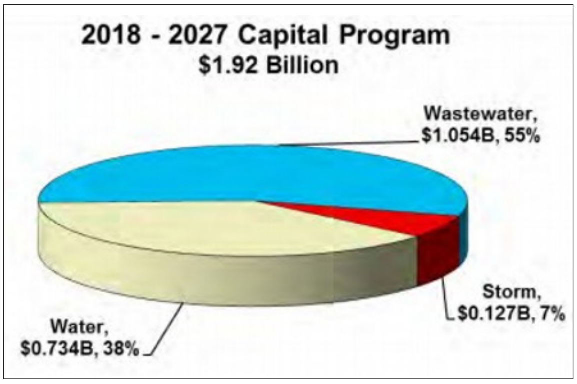


Figure 3: 2018-2027 Capital Program (2018 Recommended Water, Wastewater and Stormwater Budget (FCS17081))

The economic losses caused by floods in Ontario are largely influenced by the area's flood resistance capacity and the scale of the floods. As a result of the floods in Hamilton, the municipality has experienced substantial costs in terms of funds and human resources. It is reasonable to speculate that once the infrastructure is built, the annual investment will gradually stabilize and enhance the region's flood-resistance capacity. The flooding problem and economic development are inseparable.

Methodology

By understanding the impact of climate change on floods and extrapolate future changes, local governments can better formulate policies and programs to anticipate and address community threats. The threat of climate change is clearly an interdisciplinary issue that involved science, engineer, technology, social systems, economics, environment, and public policy [20]. Scenario analysis can be customized and applied in different areas because it provides a way to measure the multiple determinants that contribute to the change, in this case - flooding [21].

In this research, scenario analysis was deployed to uncover possible futures and forge a path to get to the preferred future where the city of Hamilton will be more resilient to flooding events. The case study focused on the City of Hamilton and the $20 billion portfolios of assets managed by the City of Hamilton's Public Works Department. While the findings can contribute to Hamilton's strategic and capital planning processes, it will also help the city to increase its resilience and adaptation to more frequent flooding events.

In the 1960s, scenario analysis was used to analyze possible changes in the future, and is now widely used in numerous fields. The process of environmental scenario analysis has been used to examine many different scales and types of problems ranging from global sustainability to very specific environmental issues, wherein this project, it is used examine the problem of flooding caused by climate change [22]. The with input from the City of Hamilton's Public Work Department.

The analysis began by examining and analyzing capital loss, human injury, and infrastructure and facility damages in Hamilton. That lead to the identification of major drivers which affect the resilience of the City, including financial capacity, social vulnerability, economy, precipitation, infrastructure, and permeability. Subsequently, a workshop was held with Hamilton Public Works representatives to provide feedback on those drivers, and further adjustments were made. This was followed with further discussion with Public Work officials, the purpose being to determine two critical forces belong to then select the final two "axes of uncertainty": social vulnerability and the built environment (a combined driver of both permeability and infrastructure).

With the final two axes determined (Figure 4). four quadrants representing distinct future outcomes were characterize by developing a detailed analysis of the four possible futures. This will enable strategies to be developed to improve the City's resiliency to future flooding events.

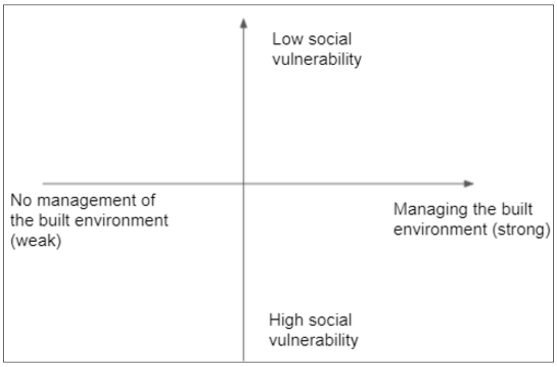


Figure 4: Quadrants showing different scenarios based on two selected drivers

Results: Driver Descriptions

Permeability of land, water catchment system and forestry strategy of Hamilton

Permeability affects how well the surface absorbs water. Water catchment systems and forestry strategies would also affect permeability. Different textures and soil types will affect the rate of water transmission. For example, sand has much better water permeability than clay (Food and Agriculture Organization of the United Nations, n.d.).

The land used for residential, commercial, industrial, and institutional purposes influences the permeability of the land. Urban land use usually results in hard surfaces making it less pervious, which inhibits water infiltration. .

Figure 5 is a land-use map of the city of Hamilton in 2016 [23]. The area of urban use of Hamilton is about one-third of the total area of the city of Hamilton, meaning except for agricultural, vacant and open space purposes land, the city has poor permeability

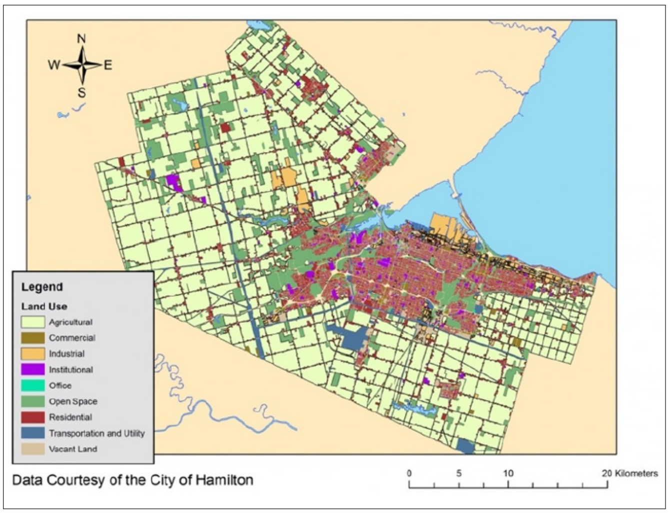


Figure 5: 2016 land use [23].

The city is expecting 110,300 more households in Hamilton by 2051. Additionally, according to the updated version of the Growth-Related Integrated Development Strategy (GRIDS), which is also known as GRIDS2, Hamilton is expecting approximately 1340 to 1640 hectares (3311 to 4052 acres) of land to accommodate the growing population to the year 2051 [24].

Hamilton's Urban Forest Strategy (UFS) is designed to protect the long-term health of Hamilton's urban forest [24]. The urban forest in the Hamilton area includes all publicly and privately- owned trees and supporting vegetation [25].

The forests in Hamilton helped remove about 393 metric tons of pollution per year, including ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particles less than 2.5 microns, which values at $1.59 million per year. It helps manage about 815,000 cubic meters of stormwater runoff per year, which values at $1.896 million per year. It is also valued at $1.54 million per year in sequestering carbon dioxide [26]. The urban forest can improve water infiltration, store water and reduce stormwater runoff.

The larger area of urban forest means a larger area of the previous surface of the land. The urban forest can help store water and avoid soil erosion. The current Hamilton's tree canopy coverage is about 21.2% [26]. The target is to increase the canopy coverage to 35% [27].

In the next 40 years, one could project more residential areas to accommodate the growing population, which means could lead to a more impervious future, which would increase the risk of urban flooding. However, according to GRIDS 2, the future urban boundary expansion of Hamilton is limited by the Green Belt Plan, of which approximately 2200 hectares of land could be used as a Community Area [27]. The influence of urbanization on permeability could be restricted if the expansion boundary of the city continues to be limited.

Infrastructure
To explore the relationship between infrastructure development and flooding in the City of Hamilton, this driver considers actions undertaken in the past 20 years, the current circumstances, and future prediction of the infrastructure development of the city. The City of Hamilton started to make sustainability plans for infrastructure development in the late 1990s. However, existing infrastructure networks are insufficient to manage surges of stormwater. The intense flooding events that occurred in the past 20 years continue to result in substantial insurance costs. Due to climate change, the frequency of intense storms that occurred in Hamilton has increased over the years, which has led to a heavy burden on the existing infrastructure system. As a result, the City of Hamilton now faces the challenge of renewing and maintaining the existing infrastructure system to adapt to future situations under the uncertainties caused by population growth, flooding pattern changes, and climate change.

Flooding in the waterfront area that is located beside the lake of Ontario (e.g. the Waterfront Trail), on the roadways, and in the basement of commercial or residential buildings created huge costs for the city of Hamilton. One of the severe storms that occurred on July 26, 2009), in Hamilton caused damage to 7000 basements and thousands of power supply pathways. The insurance loss during the event was estimated in between $200 and $300 million [28].

More than $720,000 was spent to repair the damage of the Waterfront Trail which was caused by flooding in 2017 and 2018 [29]. Nevertheless, large-scale flooding still forced the Waterfront Trail in Hamilton, the Breezeway Trail near the Burlington Bridge, and the stairs to the Bayfront Trail to close in 2019 [30].

According to the "2005 Life-Cycle State of the Infrastructure Report on Public Works Assets" (SOTI), the integrity of water infrastructure in Hamilton is a risk [31]. Most of the assets are underfunded, except water and wastewater networks. The stormwater network poses the greatest challenge regarding flood mitigation into the future. The SOTI report also stated that the existing infrastructure assets would deteriorate rapidly [31].

In response, Hamilton has proposed a processcalled "Building a Strong Foundation" (BASF) in 2003 to provide guidance for ongoing municipal infrastructure planning activities [32]. This process can also be considered a guide to the Growth Related Integrated Development Strategy (GRIDS) established in 2006. GRIDS aims to serve Hamilton concerning infrastructure, economy, and other aspects [27]. A new update of the GRIDS, known as GRIDS 2, amended the plan to account for population and job growth until 2051 [27].

If this driver is considered to have a high impact on local flooding and high uncertainty with respect to climate change, the future could be expected to head in one of two directions. At the positive end, the majority of the strategies outlined above are implemented as planned, and the funds for infrastructure upgrades and maintenance can be fulfilled. Infrastructure could then better withstand storms and damage. On the other hand, it is possible the strategies cannot be implemented as planned because of financial challenges or insufficient study and design. In this case, dramatic changes may be needed to update the plans, and the budget accordingly to avoid losses to life and property.

Financial Capacity and Social Vulnerability
Evaluating financial capacity and social vulnerability is essential in identifying specific communities that have a higher chance of needing support before, during and after certain disasters [33,34]. This driver is based on several indicators including household income, housing spending from a financial capacity perspective, and life expectancy, age, gender and race (ethnicity) from a social vulnerability perspective respectively, to further examine how social vulnerability and financial capacity impact the resilience of residents to flooding events.

Figure 6 shows the frequency of emergency flood service requests from the different wards. The areas with severe flooding impacts, from most severe to average severe, are 4,9 (southwest area only), 11(middle east area only), 5, and 1 (east area only). Subsequently the research examined the financial and social factors in those targeted ward areas. Ward 4, also known as the East Hamilton, sits below the Niagara Escarpment where approximately 1/3 of its area is comprised of industrial and commercial land. It also located within the Hamilton Conservation Authority watershed. In 2018, ward 4 increased in both area (+23%) and population (+12%). Ward 9, known as Upper Stoney Creek, sits above the escarpment. Urban and rural portions compose approximately 19% and 81% in land area respectively. In 2018, ward 9 increased in the area (+280%) but decreased in the population (-5%). Ward 11 experienced a decrease in both area (-28%) and population (-44%), where ward 5 decreased in area (-5%) but increased in population (+11%).

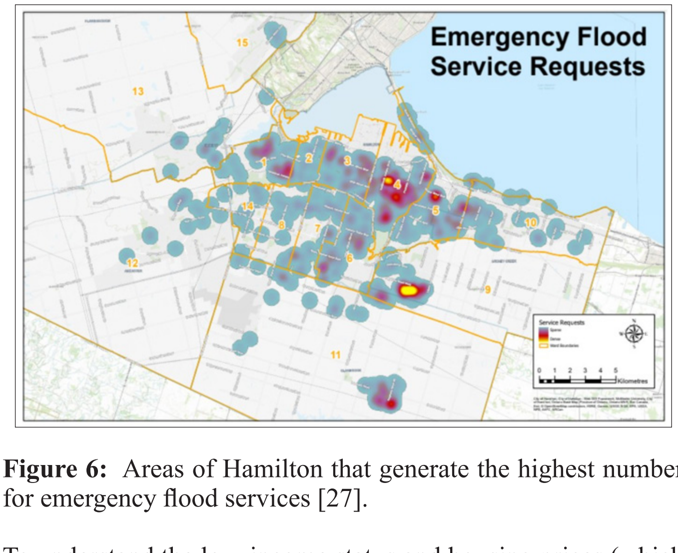


Figure 6: Areas of Hamilton that generate the highest number for emergency flood services [27].

To understand the low-income status and housing prices (which affect social vulnerability), census data on the distribution of such factors were obtained from the city of Hamilton Ward Profiles posted online. Property values were obtained from figures posted by realtors and local newpapers, as illustrated in Figure 7.

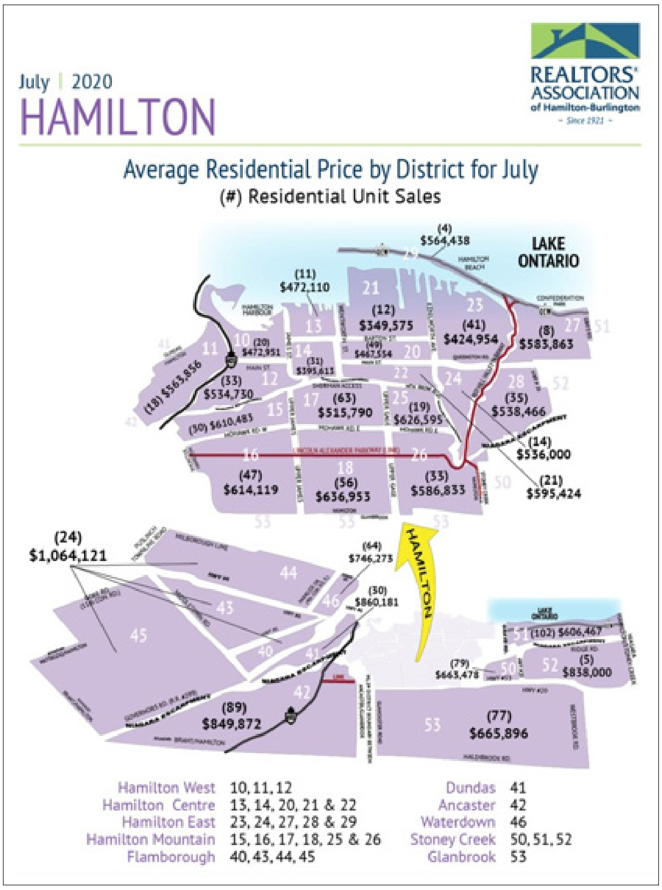


Figure 7: Hamilton property value [35].

The ward-by-ward comparison shows that the average total household income in ward 4 (East Hamilton) is the lowest, compared to other ward areas, which is $21,647 lower than Hamilton's average. Ward 5 and ward 1 also show similar situations, where the average income is $21,020 and $12,013 below Hamilton's average income, respectively. However, ward 9 and ward 11 have higher than average household incomes, which is negatively correlated to the flooding emergency calls.

Hamilton ward profiles show the housing price data on each of the targeted wards [36]. For ward 4, the community with the highest emergency flooding reports, the housing price in 2020 is $424,954 on average and the second-lowest among all the communities. For ward 9, the housing price in 2020 is $538, 466 on average, which is also about the average property value in Hamilton. Ward 11 has an average property value of $586,388, while Ward 5, and ward 1 are $583,863 and $563,856.

Communities with higher flooding risk have higher housing affordability, meaning lower housing price. However, these communities tend have lower than average income and could be more vulnerable to flooding. Those with lower financial capacity facing flood risk challenges, and are socially vulnerable.

Social vulnerability refers to the potential adverse effects on communities caused by external stresses on human health, including natural disasters and human-caused disasters. Social vulnerability is considered one of the most critical aspects of resilience measurement Gerlitz et al. [34,37]. The vulnerability to environmental hazards, in this case, floods, is measured by the adverse effects on households of floods. The degree of effects may vary associated with the change in the socio-demographic situation, over time, and among different social groups. Therefore vulnerability also varies over time and space Gerlitz et al. also further indicated a strong relationship between poverty and vulnerability from their survey result on previous vulnerability assessment [37]. In this context, focusing on measuring the vulnerability of different communities regarding life expectancy, gender, race (ethnicity), immigrants, and visible minorities could generate a holistic understanding of how different communities vary in their resilience towards flooding events. From that analysis, one could identify those communities with the least resiliency in order to develop corresponding plans and solutions for improving their resilience and reducing their vulnerability.

Social vulnerability is commonly measured using the social vulnerability index (SoVI) [34]. By giving a SoVI number of 0-1 on each community, we could visualize the social vulnerability considering Life expectancy (under health status), housing, Unemployment (under labourforce), gender (under population), and immigrants.

In 2006, the average unemployment in Hamilton was 6.5%. Ward 4, 5 and 1 had higher than average unemployment rates, while ward 9 and 11 had lower than average unemployment rates. By 2016, the unemployment rate in all the wards increased. In the next 20 years, unemployment could potentially keep increasing, based on the trend during the last 15 years. The unemployment rate could potentially increase to 9% by 2030 according to the previous trend.

Education experienced a significant improvement from 2006 to 2016 in Hamilton. People who have no certificate, diploma or degree aged 25-64 decreased from 25.1% to 12.2%. During the next 20 years, one could predict that higher education rates could increase due to employers' higher expectations and competition within the applicants. Another factor that could contribute to the increase in education is the higher housing price and unemployment rate, which could incentivize the search for higher education certificates to increase competitiveness in the job market.

From a financial capacity perspective, the rate of income increase is significantly lower than the rate of housing increase, leading to a decrease in relative purchasing/renting power of housing in Hamilton residents. From a social vulnerability standpoint, the city of Hamilton is facing a rising unemployment rate. Education has increased significantly and is projected to increase in the future.

Precipitation

Changes in precipitation, along with changes in temperature, can contribute to many impacts, including more frequent and severe floods and droughts. Flooding can result from:

- more frequent and intense rainfalls, such as downpours from thunderstorms
- more instances of rain falling on snow
- new storm patterns

In the past half century, precipitation across Canada has increased by approximately 13%, on average. Figure 16 shows the projected precipitation changes for Ontario under each of the three different RCP scenarios (RCP2.6, RCP4.5, and RCP8.5), where 2.6 is the lowest GHG scenario, and 8.5 is the highest, which is shown in Figure 8. Changes vary depending on different greenhouse gas concentration assumptions in each scenario, which are shown in Tables 9 - 11. If current emissions trends continue, the higher emissions scenarios will likely apply [23].

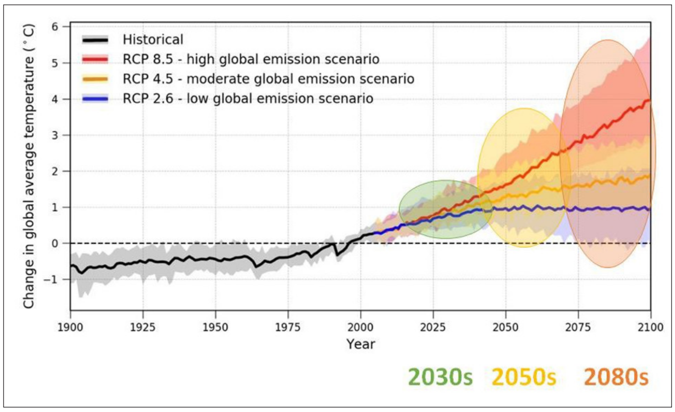


Figure 8: RCP Scenarios and Uncertainty Across the Time Horizons [24].

Hamilton's precipitation is expected to rise in line with the provincial changes reflected in the above data, with some decreases in precipitation in the summer months. The Canadian Climate Change Data and Scenarios (CCDS) tool provides information from a weather station located within the City of Hamilton (Hamilton A). Using a baseline of 1971-2000, the data shows projected precipitation change (not total precipitation) from A2 (high) and B1 (low) scenarios.

These projections are based on increases from the precipitation baseline, which is the average amount of precipitation from 1971-2000. Hamilton's average annual precipitation during this period was 912.2 mm. The projections to 2020, 2050, and 2080 reflect the projected amount of precipitation, in millimetres, from the annual and seasonal baselines [23]. In a high emission scenario (table 10-11), Hamilton can expect to experience an average annual precipitation increase of 24.9 mm in the 2020s, 66.7 mm in the 2050s, and 99.9 mm in the 2080s.

Projections are based on increases from the precipitation intensity rate baseline, which is the average amount of precipitation from 1962-2007. The projections to 2020, 2050, and 2080 reflect the projected amount of precipitation, in millimetres, from the annual and seasonal baselines [23]. Hamilton is being affected by climate change and increases in precipitation will largely be determined by trends in GHG emissions.

Discussion: Four quadrants storytelling

In Hamilton, the analysis started with the examination and analysis of capital loss, human injury, and damage to infrastructure and facilities. As a result, major influencers of resilience have been identified, including finance, social vulnerability, economy, precipitation, infrastructures, and permeability. The Hamilton Public Works representatives then participated in a workshop to provide feedback on these drivers, and further adjustments were made. Following this, Public Work officials conducted further discussion with McMaster University, in order to identify two critical factors, selecting the two final "axes of uncertainty": social vulnerability and the built environment (a driver of both permeability and infrastructure). The final two axes corresponded to four quadrants representing four distinct future outcomes (Figure 9). Thus, strategies can be developed to increase the City's resilience to future flooding.

Figure 9: Four scenarios

The Preferred Future Scenario (Quadrant 1)

In the S1 scenario, the storyline describes a positive future for Hamilton. The underlying theme is that the city will be much more permeable and less vulnerable compared to the current situation. With low social vulnerability, the resilience of residents and households living in the study area is high. The taxes and services, like the investment in education and healthcare costs, in the city are affordable to people living in Hamilton. The income and expenditure of each household can reach a balance, or the income has a higher increment than the expenditure. When a high-intensity storm attacks the city, the residents have funds for house repair, or the insurance provided in this city can cover the entire cost. A high level of built environment management means improvements to the municipal infrastructure and high permeability in the study area. Since the current condition of the infrastructure in Hamilton is not sufficient to manage storms, "high quality" in this scenario should be interpreted as efficient design, development and implementation of upgrades with investment having high returns. From a forest strategy perspective, increasing Hamilton's tree canopy coverage to 35% will generate approximately over $1.04 million in sequestering carbon dioxide, helping mitigate 529,750 cubic meters of stormwater runoff, which values at 1.21 millions per year.

The positive end is pointing to the future where the funding of all municipal infrastructure development projects goes well, and all of the new-built systems or repaired existing systems are strong enough to withstand the high-intensity storms that may happen in 20 years. All infrastructures that include road networks, public transit systems, and wastewater management systems can also face a 100-year flooding event or worse. The improvement in infrastructure will lead to approximately $200 to $300 million saving on insurance loss and over $720,000 on waterfront trail maintenance. Simultaneously, the high permeability of the local land helps with groundwater recovery and runoff reduction, which reduces the pressure of the infrastructure systems. The improvement of the local water circulation system also enhances the city's sustainable development under the climate change uncertainties.

Happiness in the Collapsing City Scenario (Quadrant 2)

The happiness in the collapsing city scenario at the right bottom corner of the coordinates has low social vulnerability and a poor built environment. As mentioned in the first scenario, low social vulnerability shows a well-developed living standard with a high employment rate, increased income, low tax, appropriate healthcare insurance, and high-quality education. Residents living in Hamilton have excellent resilience, reflecting on a sufficient budget of repairing costs after severe storms.

However, the challenge of this scenario is the dilapidated built environment, which means the municipal infrastructure could collapse during severe storms. All roads, transportation, and construction could be flooded or destroyed by the runoff, and residents need to be prepared to evacuate at any time. This possibility can arise for several reasons. The government has reduced social vulnerability by investing to improve people's livelihoods, but not investing to to improve urban infrastructure, such as sewerage systems. Plans may exist, but they are not fully implemented. There may be policies in place but not implemented. In other words, in this future citizens and staff have little control over the impact of flooding on their surroundings.

Out of control scenario (Quadrant 3)

In the out-of-control (S4) scenario, the City of Hamilton has high social vulnerability against flooding events and no overt management of the built environment. Precipitation intensity has increased in the past 20 years, assuming that the city is facing the RCP4.5 scenario, which is the moderate global emission scenario. The precipitation in winter and spring has now increased by nearly 10% compared to 20 years ago. The city has failed to have overt management of the built environment. There are many reasons for the current situation, which all lead to the same result - increasing frequency of flooding and more damage to society. Due to economic or policy reasons, the sewerage system has not been effectively upgraded and maintained. The current sewerage system cannot meet the existing demand due to urbanization, economic development, population growth, and other factors. The residential and commercial land use has increased across the region; the condition of the water system worsens; forested areas are removed. All of these cause the permeability of the region to decrease and the risk of flooding disasters to increase. From a forest strategy perspective, such a scenario will lead to approximately $1.04 million loss in sequestering carbon dioxide, missing the chance of mitigating 529,750 cubic meters of stormwater runoff, which values at 1.21 million per year. The lack of sufficient infrastructure upgrade and maintenance lead to approximately $200 to $300 million loss on insurance, and at least $720,000 on waterfront trail damage.

Under such a devastating situation, social vulnerability indicators, including income, housing, health, unemployment, immigration and education, could face significant shifts in the next 20 years. The cause of residents being exposed to significant risks under social vulnerability could potentially be the more severe weather (flooding) events, economic recession, lack of a holistic regulatory framework, and lack of action by decision-makers. To be more specific, expect a dramatic decrease in income, education, life expectancy and immigration. Infrastructure, including road networks, public transit systems, and wastewater management systems, cannot handle severe flooding events. The purchasing power of people could face a significant decrease since a great proportion of people are losing their jobs. Expect a higher proportion of people who are unemployed or underemployed. Minority groups, including women, lesbian, gay, bisexual, transgender, queer (or sometimes questioning), and two-spirited (LGBTQ2+), indigenous people, and immigrants could potentially experience more severe stress, with social equity and inclusion problem exacerbated under such circumstances. Residents would face significant challenges associated with flooding risks. They would be extremely vulnerable due to economic constraints, lack of financial resources, government support, and infrastructure that protects people from severe flooding events.

The Vacillating Scenario (Quadrant 4)

In this scenario, the built environment has developed to a high level, and the social vulnerability is also high. The high built environment refers to the high permeability of local land and well-organized municipal infrastructures. The public infrastructures in Hamilton are well maintained and constructed in the next 20 years. Under such circumstances, technology has developed to a certain level, and human society can better withstand the forces of nature. The enhanced permeability of the entire city, the upgraded sewage system and the stormwater management system is resilient to intense storms. However, in this future, the high social vulnerability indicates that the citizens of Hamilton continue to face risks other than flooding. A decrease in income, education level, employment rate, life expectancy and immigration rate are expected. People need to pay heavy taxes to support the built environment and infrastructure upgrades. Individual's purchasing power drops and people start to lose their jobs. Should damage occurred during an intense storm socially vulnerable residents cannot cover the repair costs, and some residents in the city with a low or no budget for this kind of situation will be heavily effeccted. This condition may also lead to a serious social hierarchy. Rich people will be able to receive health care and education with high quality, and low income residents having no protection. There is a possibility that the future of the city turns from the 'vacillating scenario' into the 'out-of-control scenario.'

Conclusion and Next Steps

Social vulnerability and the built environment (infrastructure and permeability) are critically important factors in determining Hamilton's flood resilience. The following are some recommendations:

- The human-made water catchment system should be widely used to increase the permeability level of Hamilton.
- The urban canopy cover rate could increase to a higher percentage to mitigate the risk of flooding, and generate revenue as carbon sequestration and stormwater sink.
- Upgrading key stormwater infrastructure, especially in areas with combined sewage systems, and proposed high social vulnerability areas.
- Approving new infrastructure projects based on updated flooding mapping program and ensuring it recognizes new technology and approaches for flood hazards
- Developing programs and applying new stormwater infrastructure technologies to help and support the high social vulnerability communities to increase their resilience to future flooding.

From a municipal perspective, other drivers, such as the economy and climate change (participation), are unpredictable and difficult to effect. Such drivers were not discussed in relation to program or policy options. Future considerations would be to explore what program and policy decisions were hypothetically made to result in the trajectories to different futures. This could inform decision making today while planning to achieve the desired future [38-62].

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