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Introduction to ResilSIM: A Decision Support Tool for Estimating Disaster Resilience to Hydro-Meteorological Events

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INTRODUCTION TO ResilSIM: A DECISION SUPPORT TOOL FOR ESTIMATING DISASTER RESILIENCE TO HYDRO-METEOROLOGICAL EVENTS

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March, 2016

Executive Summary

Natural disasters have become more frequent and damaging to urban systems in recent years. The observed trend is expected to continue in the future as the impacts of population growth, rapid urbanization and climate change persist, affecting both developing and developed countries around the world. To alleviate the damages associated with these impacts it is recommended to integrate disaster management schemes into planning, design and operational policies under all levels of government. This paper proposes the concept of ResilSIM: a decision support tool that estimates the resilience – a modern disaster management measure that is dynamic in time and space – of an urban centre to the impacts of hydro-meteorological (flooding) events. The objective of the tool is to assist decision makers (engineers, planners, government officials) in selecting the best options for integrating adaptive capacity into their communities in order to protect against the hazardous impacts of a flooding event. The tool relies on hydraulic principles to simulate flood depths and publicly accessible datasets to estimate community resilience. It is designed for application in two Canadian cities; namely, London and Toronto, Ontario and it must be programmed for application in each municipality separately. ResilSIM is a web-based tool with mobile access that estimates a resilience metric in real-time. It very rapidly evaluates a suite of alternative adaptation options (responses, emergency measures, etc.) by comparing the corresponding values of community resilience. The proposed model structure is explained in this report and it offers a foundation for other researchers to improve upon. Several suggestions for improvement are provided.

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1. Introduction

Natural disasters have become more frequent and damaging to physical and socioeconomic environments in recent decades. The World Bank reports that in the last 30 years approximately $4 trillion of economic damages have been attributed to natural disasters globally; this does not account for loss of life and cultural assets that are difficult to valuate (World Bank, 2015; IPCC, 2012). Economic damages have the most significant impact on developing nations relatively; however the losses are greatest in magnitude in larger, developed countries (US, Canada, Western Europe, China, Japan and others). As such, disaster mitigation is a common goal shared among all countries (IRDR, 2014).

From the 1980's to the last decade the annual economic losses caused by natural disasters have increased from $50 billion to $180 billion and of these losses, 75% are linked to extreme weather events. The trend suggests that losses will continue to increase in future years due to economic development, population growth, rapid urbanization and climate change. In order to mitigate the significant damages associated with natural disasters and extreme hydro-meteorological (flooding) events in particular, it is recommended to integrate disaster risk management schemes into various planning, design and operational policies (World Bank, 2015).

Traditional disaster risk management is defined as the combination of three elements: (i) the hazard - that is in the context of this work - the probability of occurrence of an extreme hydro-meteorological event; (ii) exposure - the location of people, property, infrastructure and industry relative to the hazard; and (iii) vulnerability - the susceptibility of people, property, infrastructure and industry to damage caused by the hazard (World Bank, 2015). In order to manage disaster risk, measures are taken to reduce the vulnerability of the system components exposed to the climatic hazards. More recently, however, there has been a shift from the traditional, vulnerability-driven approach to disaster resilience that is the foundation of the presented research (Simonovic and Peck 2013).

Resilience - in the context of disaster management - is defined as: "the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions," (IPCC, 2012). While disaster risk management focuses on the reduction of pre-hazard vulnerabilities, disaster resilience is achieved by introducing adaptation options that enable the community to adapt to the impacts of the hazard and enhance the ability of the physical, social, economic sectors to function in the event of a disaster. These adaptation options help the system components to cope with and recover from hazard impacts in order to return to a pre-disaster level of performance as rapidly as possible. Adaptation options can be grouped into four categories: (i) robustness that is the strength or the ability of the system to resist hazard-induced stresses (ex. flood protection measures); (ii) redundancy that is the ability of a system to provide uninterrupted services in the event of a disruption (ex. a twinned pipeline); (iii) resourcefulness that is the utilization of materials (monetary, technological, informational, and human resources) to establish, prioritize and achieve goals (ex. mobilization of disaster management funds); and (iv) rapidity that is the capacity to return the system to a pre-hazard level of functioning as quickly as possible (Bruneau et al., 2003). Evidently, resilience is a proactive means of disaster management making it more desirable for implementation (Simonovic and Peck, 2013). Using a simulation approach to resilience, a suite of adaptation options can be implemented, modified and compared in a dynamic fashion; for example, in response to an extreme precipitation event several adaptation options can be considered. The proposed ResilSIM tool is capable of testing the impacts of all adaptation options on the value of community resilience very rapidly and therefore, it assists in the decision making process by selecting the adaptation option that will improve resilience the most.

The rising number of natural disasters that have occurred in recent years may be attributed to three key factors including: (i) climate change; (ii) population growth; and (iii) land use change, especially mass urbanization. Climate change increases the frequency and intensifies the magnitude of the hazards. Strong scientific evidence suggests that the climate is changing due to natural and anthropogenic forcing. The average global temperature is projected to rise as much as 4.8 degrees Celsius by the 2081-2100 time period (IPCC, 2013). This increasing trend in temperature will disrupt the balance of the global climate system, causing unprecedented extreme hydro-meteorological events that will overwhelm critical infrastructure. Population growth and urbanization increase the number of people and infrastructure in urban centres, thereby increasing their exposure and vulnerability to natural hazards. Many cities, especially in developing countries, are located in regions that are susceptible to natural hazards such as floods; for example, they are often located adjacent to large bodies of water. Large cities have also undergone significant development, increasing the proportion of impervious surfaces that hinder the infiltration of surface water and convey runoff to river systems more quickly. As a result water levels of the receiving streams, creeks and rivers rise rapidly, leading to an increased number of flooding events. It is not only the exposure of people but also the exposure of municipal infrastructure to the hazard that impacts the function of the urban system. Critical infrastructure provides people with essential services such as water, sanitation, transportation, shelter, power and flood protection. Failure of the structures that provide these services can jeopardize the health and safety of the public and have severe economic implications. As such, it is crucial to adapt the urban system to be more resilient to future changing conditions (INFC, 2006).

It is apparent that the need for the integration of disaster resilience management into planning, design and operational policies is strong. Sufficient literature is available on the conceptualization of disaster resilience (Bruneau *et al*., 2003; Chang and Shinozuka, 2004; Cutter *et al*., 2008). More recently, however, researchers have found merit in defining resilience quantitatively. All work done on the quantification of resilience to date, however, has used a static resilience measure; that is a single measure calculated over the duration of the disaster (Bruneau *et al*., 2003). Simonovic and Peck (2013) are the first to quantify resilience dynamically in time and space; they calculate the metric using simulation linked to a geographic information system (GIS) for temporal and spatial analysis. A dynamic resilience metric allows for prioritization of regions and systems that require adaptation upgrades. It also allows for the comparison of adaptation options that improve community resilience and the functioning of critical facilities in the event of a disaster. The objective of this report is to propose the concept of ResilSIM: a web-based decision support tool (with mobile access) used to estimate the dynamic resilience of an urban center to hydro-meteorological events that is based on the metric developed by Simonovic and Peck (2013). The tool uses fundamental hydraulic principles to simulate hydro-meteorological events under climate change scenarios in conjunction with publicly accessible spatial datasets to estimate the resilience metric. The users will be able to virtually employ different adaptation measures and assess how they improve or degrade urban resilience, thereby assisting decision makers in selecting and prioritizing community upgrades and protection measures. Data requirements are determined based on publicly accessible data of the municipality that the tool is designed for. ResilSIM must be programmed separately for each municipality it is applied to due to differences in the typical hazard types, publicly available datasets required for the computation of resilience and the potential for and allowance of the implementation of various adaptation options. This report demonstrates how ResilSIM can be designed for application in two major urban centres: London and Toronto, Ontario, Canada. A generic methodology is proposed for the foundation of the tool's structure in addition to recommendations for further improvement.

The remainder of the report is organized as follows: the study areas are described and the data requirements are listed in sections 2 and 3; the methods for the generation of flood inundation depths and the computation of resilience are presented in section 4; and finally recommendations for future work are provided in section 5.

2. Study Area

This report demonstrates how the ResilSIM tool can be applied in two municipalities namely, London and Toronto, Ontario. Both cities are located in the Great Lakes-St Lawrence lowlands climate region of Canada. The regional climate is characterized by prevailing winds from the West, humid air from the Gulf of Mexico and cold, dry air from the North in addition to the presence of the Great Lakes and their interactions with the lower atmosphere (USEPA, 2012). Lake effect precipitation is common during the fall and winter seasons (Lapen and Hayhoe, 2003; Sousounis, 2001), and convective rainfall and thunderstorms are typical of the summer season (Ashmore and Church, 2001).

Although both cities experience similar climates, they are subject to different types of flooding. London is most susceptible to riverine flooding, while Toronto is prone to a combination of riverine and urban flooding. The latter is caused by high intensity precipitation events that overwhelm the capacity of the municipal drainage system, resulting in the pooling of floodwater on the impervious surface. An explanation of the flood generation processes is provided for each city.

Flooding in London, Ontario

The municipality of London Ontario is particularly susceptible to riverine flooding of the city's main artery - the Thames River. London resides in the Upper Thames River watershed that is managed by the Upper Thames River Conservation Authority. The majority of the watershed's landscape is rural except for the large urban centres of Stratford, Woodstock, Ingersoll, St. Mary's, Mitchell and London. Surface water runoff is diverted into streams and creeks that drain into the Thames River. The Thames River is composed of two branches; the north branch flows southward through Mitchell, St. Mary's and London, and the east branch flows westward through Woodstock, Ingersoll and into London (see **Figure 1**). The branches converge at the Forks located in downtown London where the river continues to flow westward, exiting the city in the Byron suburb (Prodanovic and Simonovic, 2007).

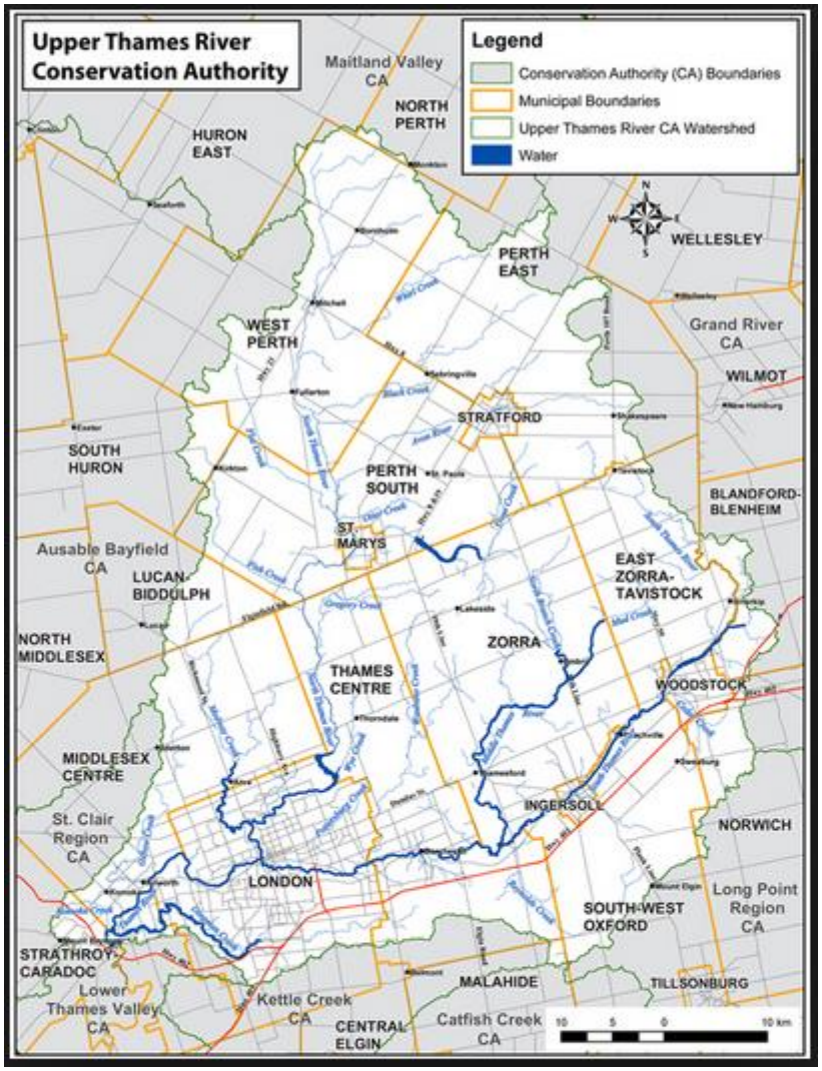

Figure 1: Map of the Upper Thames River Watershed (http://thamesriver.on.ca/, last accessed 2016 January).

The transformation of surrounding lands from dense, deciduous forest to urban and agricultural development contributes to increased riverine flooding. Urban and agricultural development has led to the introduction of impervious land surfaces and sewer systems that increase the rate of runoff to the river resulting in uncontrolled, rapidly rising water levels (Thames Topics, 1999; Irwin *et al*., 2012). Evidently, the Thames River is susceptible to flooding due to the characteristics of its surrounding environment. The most severe flooding event on record occurred in April 1937 when 130 mm of rainfall fell on the watershed over a six day period. During this time water levels were already high due to the spring snowmelt. The flood led to one death and 1,100 damaged homes and businesses; hundreds of people were left homeless. Fortunately, since then there have not been any floods nearly as devastating which may be attributed to the creation of the Ontario Conservation Authority Act of 1946. The act awarded authority to various groups – known as conservation authorities – that are located within major watershed boundaries to undertake natural resource management of their respective areas. The Upper Thames River Conservation Authority has acted to protect the people and properties from flooding within the watershed through the construction of three large dams; namely (i) Fanshawe (1953); (ii) Wildwood (1965); and (iii) Pittock (1967), (Thames Topics, 1999). Although the dams have significantly reduced the magnitude of flooding throughout the city, there are still certain low-lying areas along the river that are subject to annual flooding (the north branch and the river forks). As climate change persists it is expected that regional flooding will increase in depth and areal extent. **Figure 2** depicts the extent of the projected flood inundation of the Thames River (and Dingman Creek to the south) under future climate change scenarios and a 250 year return period (Sredojevic and Simonovic, 2009). As such, the City of London will benefit from the implementation of adaptation options to proactively reduce the impacts of future projected flooding of the Thames River.

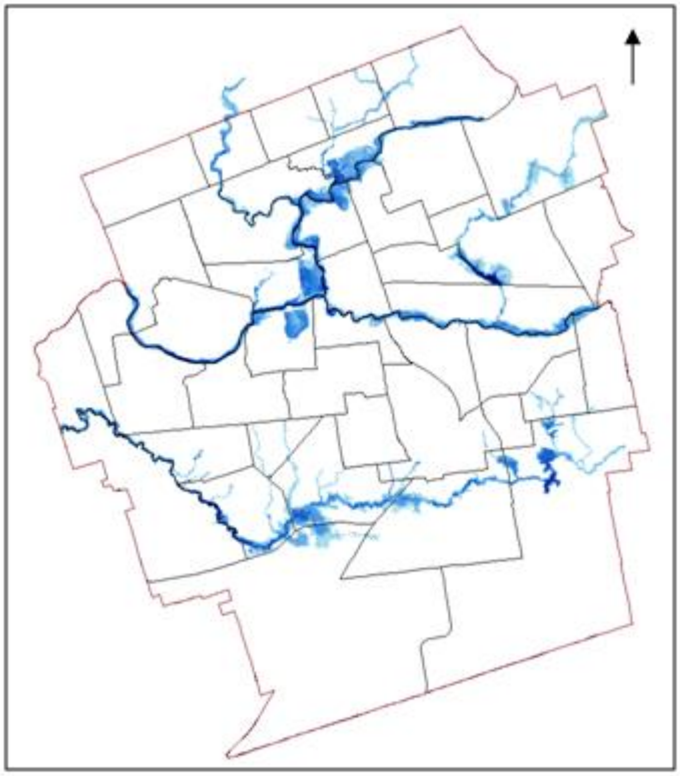

Figure 2: Map of the extent of projected flood inundation of the Thames River (north) and Dingman Creek (south) within the municipal boundary of the City of London.

Flooding in Toronto, Ontario

Toronto is the largest city in Canada with approximately 2.5 million people residing in the core and 5.5 million people in the Greater Toronto Area (GTA). Due to its large population and proximity to Lake Ontario – that is part of the world's largest fresh water system; the Great Lakes – Toronto is also considered to be the most physically, socially and economically vulnerable city to climatic extremes in Canada. Toronto is susceptible to both riverine and urban flooding events. It is located within the Rouge River, Don River and Humber River watersheds (east to west); see **Figure 3**. The Don River and Humber River are major waterways that drain into Lake Ontario. Significant urbanization in the GTA has lead to accelerated runoff to the creeks and streams that feed these river systems. As a result, water levels quickly rise, causing flooding and erosion of the adjacent banks. The Don River Valley is particularly prone to flooding. The Don River itself is 15 m wide while the low-lying valley spans 200 m in width. The valley – referred to as the Don Valley – has undergone substantial development and therefore it is highly vulnerable to the impacts of riverine flooding (Armenakis and Nirupama, 2014).

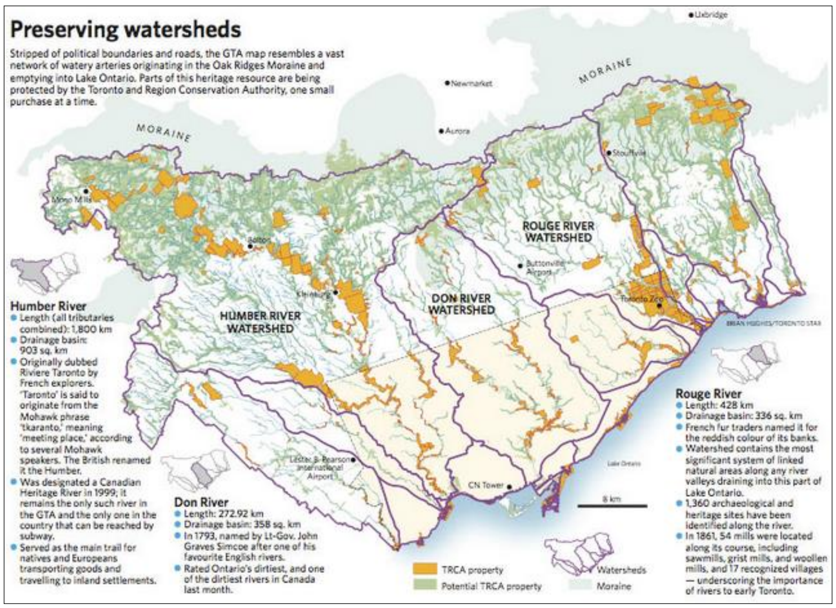

Figure 3: Map of the Toronto Region Conservation Authority that is comprised of several watersheds including the Humber River, Don River and Rouge River watersheds (http://spacing.ca/toronto/2008/01/13/mapping-our-urbanism-watersheds/, last accessed 2016 January).

Urban flooding is another major problem facing the city. These flooding events are typically caused by slow moving storms or multiple thunderstorms that pass over the area. The rainfall generates a significant amount of surface water runoff that exceeds the capacity of the drainage infrastructure. On August 19, 2005, for example, Toronto experienced a major urban flooding event. The flood was generated from a series of severe thunderstorms that originated south of the city. The storms caused torrential rainfall – 130 mm of rain was recorded at the Downsview

Environment Canada rain gauge – and golf ball-sized hail (https://www.ec.gc.ca/meteo-weather/, last accessed 2016 January). There was even a tornado warning, that is rare for Toronto. The storm resulted in over $500 million in insured damages. Failure of a culvert located under Finch Avenue caused damage to the road (that was completely washed out) as well as the overhead utilities located within the right-of-way (INFC, 2006). The interdependency of municipal infrastructure can dramatically increase the cost of repair. If action is not taken to upgrade or replace vulnerable infrastructure similar events may become more common in the future. Due to the severity and the enormous consequences of the August 19, 2005 storm and urban flooding event, the day was given the name "Freaky Friday".

Toronto's most economically damaging urban flooding event occurred on July 8, 2013. The event was generated by two thunderstorms that merged over the downtown and airport areas. More than 90 mm of rainfall accumulated in certain parts of the GTA and the Pearson Airport over a 2 hour period, overwhelming the capacity of the drainage infrastructure. The storm resulted in $1.2 billion in insured damages that is primarily attributed to property damages such as basement flooding. Approximately 300,000 residents of the GTA were left without power, many flights were cancelled and public transportation systems were unable to operate including the main train station, Union Station (Armenakis and Nirupama, 2014).

Many tributaries that feed the river systems of the Toronto area have been covered to allow for development. These streams and creeks now flow underground through the municipal storm sewers. The aging drainage infrastructure has been designed to convey a certain capacity of stormwater runoff to the lake. As precipitation events become more intense and frequent in nature – due to the effects of climate change – the current infrastructure is less capable of handling the surface runoff generated from severe storms. As a result, urban flooding events are likely to become a more common occurrence unless various adaptation and disaster-resilience measures are implemented. The proposed ResilSIM structure estimates the community resilience metric for urban flooding in Toronto; although it may also be extended to estimate resilience associated with riverine flooding events in future model generations.

3. Data

This section lists the spatial datasets required for model development. The resilience metric combines several performance measures that represent the physical, social and economic impacts to an urban system. The data used to compute the physical performance measure are obtained from a few sources including the City of London, the Municipal Property Assessment Corporation (https://www.mpac.ca/about/corporate_overview/default.asp, last accessed 2016 January), the City of Toronto (http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=1a66e03bb8d1e310VgnVCM10000071d60f89RCRD, last accessed 2016 March) and CanVec+ (http://geogratis.gc.ca/, last accessed 2016 January), while the data required to compute the social and economic performance measures are Census profiles acquired from Statistics Canada. These datasets were chosen because they are frequently available from municipalities in the Province of Ontario; CanVec+ and Canadian Census profiles are available across the country. **Table 1** provides a summary of the required and publically available datasets.

Table 1: Summary of data used in the development of ResilSIM.

SYSTEM	DATASET	FORMAT	SOURCE
Physical	BUILDINGS (land use)		
	Commercial	shape-file	MPAC, City of London
	Industrial	shape-file	MPAC, City of London
	Residential	shape-file	MPAC, City of London
	CRITICAL FACILITIES (description)	shape-file	
	Ambulance Station	shape-file	MPAC, City of London, City Toronto
	Fire Hall	shape-file	MPAC, City of London, City of Toronto
	Hospital, private or public	shape-file	MPAC, City of London
	Police Station	shape-file	MPAC, City of London, City of Toronto
	School (elementary or secondary, including private)	shape-file	MPAC, City of London, City of Toronto
	ENGINEERING INFRASTRUCTURE		
	Domestic waste facilities	shape-file	CanVec+
	Gas and oil facilities	shape-file	CanVec+
	Industrial solid waste facilities	shape-file	CanVec+
	Pipeline	shape-file	CanVec+
	Pipeline (sewage/liquid waste)	shape-file	CanVec+

	Power transmission line	shape-file	CanVec+
	Railway	shape-file	CanVec+
	Road segments	shape-file	CanVec+
	Transmission stations/lines	shape-file	CanVec+
Economic			
	Unemployed persons	shape, csv-file	StatsCan
	Families w/ annual income < $50,000	shape, csv-file	StatsCan
Social			
	Age (<6; > 65)	shape, csv-file	StatsCan
	Single (divorced/widowed)	shape, csv-file	StatsCan
	Single Parent	shape, csv-file	StatsCan
	Migrants	shape, csv-file	StatsCan
	Allophones	shape, csv-file	StatsCan
	Immigrants	shape, csv-file	StatsCan
	Visible Minorities	shape, csv-file	StatsCan
	Persons w/o highschool education	shape, csv-file	StatsCan

The Municipal Property Assessment Corporation (MPAC) is a not-for-profit organization funded by Ontario municipalities. Its objective is to assess and classify all properties in compliance with the Ontario government's Assessment Act. The City of London has derived building “envelopes” (outlines) from topographic information and assigned land use classifications and descriptions supplied by MPAC to all of the properties within their jurisdiction. This type of dataset is very useful to the ResilSIM application; however, it is not made available by all Ontario municipalities such as the City of Toronto. A list of the subset of MPAC land use categories and descriptions is provided in **Appendix A**. In the physical system of the ResilSIM tool, the buildings that are assigned to all commercial, industrial and residential land use categories are retained for analysis. The critical facilities with the following descriptions are also retained and used in model development: ambulance stations, fire halls, hospitals, police stations and schools. For the City of Toronto building envelopes for critical facilities are obtained from the Open Data source that is available online.

The engineering infrastructure data that are employed in the physical component of the model are obtained from the CanVec+ catalog that is produced and maintained by Natural Resources Canada (NRCan). CanVec+ is a digital cartographic reference product that is comprised of a variety of topographic entities in a vector format. With CanVec+, NRCan aims to provide uniform topographic data across Canada that is updated frequently to offer the best available resources at the highest resolutions. The entities are available for download from: ftp://ftp2.cits.rncan.gc.ca/pub/canvec+ (last accessed 2016 January). A list of filename acronyms and corresponding entities are available in **Appendix B**.

The data used for the calculation of the social and economic performance measures are Census profiles acquired from Statistics Canada. The Canadian Census program provides a statistical representation of the country's socio-economic environment every five years; the last year being 2011. Canadian Census boundaries are available as shape-files for a variety of geographic levels; the smallest of which are the dissemination areas. In the presented research it is recommended to compute resilience for dissemination areas in order to provide the highest level of information detail. The Census profile datasets are stored in comma separated value files (csv-files) that are accessible from: https://www12.statcan.gc.ca/ (last accessed 2016 January). The Census profile data are assigned to their respective dissemination areas by matching identification codes. This function is performed in an ArcGIS environment (https://www.arcgis.com/features/, last accessed 2016 January). Although it is recommended to compute resilience for each dissemination area, other larger Census boundaries (such as Census Tracts) may be used to define the study area in which several resilience metrics are estimated.

4. Method

The procedure for estimating the disaster resilience metric can be described in two broad steps: (i) the identification of hazard impacts (in our case generation of flood inundation maps); and (ii) the computation of the resilience metric. The general procedures are outlined herein.

4.1 Generation of Flood Inundation Maps

The methods for generating flood inundation maps for the municipalities of London and Toronto are described below.

4.1.1 Flood Inundation Maps - City of London

Flood inundation maps are available for the City of London. Sredojevic and Simonovic (2009) generated the maps for a range of climate change scenarios using accepted hydraulic practice. A suite of global climate models (GCMs) are used to downscale future, projected precipitation records to be used as input for a hydrologic model. The hydrologic model is run to produce flow rates that are subsequently used as input to the hydraulic model to generate water elevation (flood depth) values (Eum et al, 2011). Two flood inundation maps are generated to represent lower and upper bound of climate change scenarios. The lower bound scenario uses a conservative estimate of precipitation statistics in the modeling procedure, while the upper bound scenario uses the most extreme estimates of future precipitation, resulting in greater flood depths. These maps are used directly in the ResilSIM tool in order to estimate urban resilience for a range of plausible flooding events.

4.1.2 Flood Inundation Maps - City of Toronto

Since flood inundation maps are not accessible for the City of Toronto it is recommended to employ the following method for map generation:

1. Estimate the average rainfall intensity for the City of Toronto corresponding to the return period of the storm ($\bar{\iota}_s$) and the capacity of the drainage infrastructure ($\bar{\iota}_i$); [Eq. 1]:

$$\bar{\iota} = a{T_c}^b \qquad (1)$$

   where, $\bar{\iota}$ is the average rainfall intensity; a and b are curve fitting parameters of an intensity-duration-frequency curve for the Toronto region; and T_c is the time of concentration. The City of Toronto recommends a time of concentration of 10 minutes for post-development landscapes (City of Toronto, 2006). This value is validated by an Average Runoff to Time of Concentration chart (City of London, 2015). All parameters required for the computation of average rainfall intensity are available in **Appendix C**.

2. Employ the Rational Method to compute the peak flow rate $Q_{p,s}$ corresponding to the return period of the storm [Eq. 2]:

$$Q_{p,s} = C\bar{\iota}_s A \qquad (2)$$

where $Q_{p,s}$ is the peak flow rate corresponding to the return period of the storm event; C is the runoff coefficient that is approximately 0.9 for post-development sites (City of Toronto, 2006); and A is the watershed area for which the flow rate is calculated.

3. Again, employ the Rational Method to compute the peak flow rate $Q_{p,i}$ for the return period corresponding to the drainage infrastructure capacity using [Eq. 3]:

$$Q_{p,i} = C\bar{\imath}_i A \quad (3)$$

where $Q_{p,i}$ is the peak flow rate corresponding to the return period for which the drainage infrastructure is designed to accommodate.

Construct a Modified Rational Hydrograph for the peak flow rate of the storm event $Q_{p,s}$ where t_d is the storm duration (see **Figure 4**).

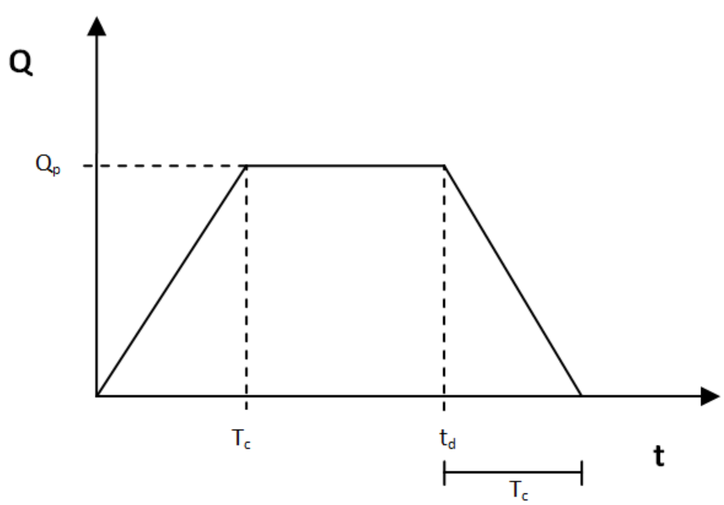

Figure 4: Modified Rational Hydrograph depicting the flow rate generated by the storm event.

4. Accounting for the capacity of the drainage infrastructure, estimate the effective flow rate and flood inundation depth that is computed as the area of the shaded region in the **Figure 5**.

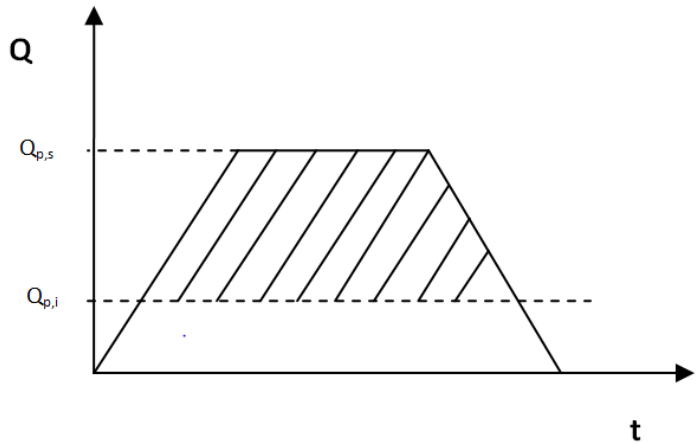

Figure 5: Modified Rational Hydrograph showing how to compute the effective flood depth as the shaded area under the curve.

4.2 Computation of the Disaster Resilience Metric

The ResilSIM tool integrates physical, social and economic impacts of a hydro-meteorological event to an urban system into a single measure known as resilience, *R*. The procedure for its computation calls for flood inundation maps to be overlaid with the spatial datasets (summarized in **Table 1**) in ArcGIS. The values of flood inundation corresponding to each spatial entity drive the calculation. The procedure and equations used to compute the metric are adapted from Peck *et al.*, (2011), Peck and Simonovic (2013) and Simonovic and Peck (2013).

5. Once the extent of flood inundation is simulated, system performance with respect to the impacts of the physical, social and economic units of resilience is determined. The methods for calculating system performance are unique to each type of impact.

a. Physical system performance measure:

The physical component of the urban system is comprised of buildings, critical facilities and critical engineering infrastructure for the purpose of this research. Buildings are further grouped into commercial, industrial and residential categories. Critical facilities (ex. ambulance stations, fire stations, hospitals, police stations and schools) and critical engineering infrastructure (ex. roads, bridges, railways, energy and communications towers, water supply and treatment facilities) provide essential services and should be given the highest level of protection in the event of a disaster (FEMA, 2015).

To measure physical system performance a suite of different impacts are used:

- 1 – Length of road inundated by the flood (km);
- Number of structures inundated by the flood (no.):
    - 2 – Critical facilities;
    - 3 – Commercial buildings;
    - 4 – Industrial buildings;
    - 5 – Residential buildings;
    - 6 – Engineering infrastructure;
- Economic damages incurred ($):
    - 7 – Critical facilities;
    - 8 – Commercial buildings;
    - 9 – Industrial buildings;
    - 10 – Residential buildings;

- 11 – Engineering infrastructure (unable to compute without stage-damage curves);

Calculation of physical system performance with respect to the length of road inundated by the flood is simply the summation of the length of road segments that overlap with the flood maps and the number of structures inundated by the flood is the summation of structures that overlap with the flood maps in a geographic information system (GIS) environment. To measure physical system performance with respect to the economic damages incurred by the various structures the following equation is used:

$$P_1^i(t,s) = \sum_{i=1}^{2}(D_{ike} \times IM_{ike}) \tag{5}$$

Here, P_1^i is the physical performance measure that is computed at a particular time (*t*) and location (*s*) where each location represents a dissemination area; it is measured in units of dollars. The monetary damage incurred as a result of the hazard is represented by *D*, while the impact multiplier that is the proportion of damage endured by the physical element is represented by *IM*. Furthermore, *e* signifies the infrastructure element; *k* denotes the infrastructure type (each type corresponds to a unique stage-damage curve as explained below); and finally, *i* stands for the impact category that is either: 1 – loss of function/structure or 2 – loss of equipment.

The impact multiplier (*IM*) signifies the degree of impact to the infrastructure as a consequence of the hazard. There are three impact categories: (i) loss of function/structure (IM_{1ke}) and (ii) loss of equipment (IM_{2ke}). All categories of impact multipliers are measured as the percentage of the economic damage incurred by the infrastructure element. The expanded version of [Eq. 5] shows how each impact multiplier is applied to the value of the total economic damage incurred by the structure; [Eq. 6]:

$$P_1^i(t,s) = D_{1ke} \times IM_{1ke} + D_{2ke} \times IM_{2ke} \tag{6}$$

The loss of function/structure impact multiplier (IM_{1ke}) measures the percent loss of the intended function of the infrastructure element; its value ranges from 0 to 1 where a value of 1 is indicative of a complete loss of function. All infrastructure elements including buildings, critical facilities and other engineering structures experience a total loss of function once inundated by floodwater and therefore, are assigned a value of $IM_{1ke} = 1$. Buildings and critical facilities may undergo partial loss of function. This occurs when their access routes are obstructed by the flood; for example, a fire station may have four access routes and if 3 out of the 4 routes are inundated, the station has lost 75% of its typical functioning level and therefore, the corresponding impact multiplier is assigned a value of $IM_{1ke} = 0.75$. The equation used to compute the partial loss of function of buildings and critical facilities due to the obstruction of access routes is provided in [Eq. 7]:

$$IM_{1ke} = 1 - \left[\frac{n-r}{n}\right] \tag{7}$$

where n is equal to the total number of access routes and r is equal to the number of access routes that have been inundated by the flood.

The loss of equipment impact multiplier (IM_{2ke}) estimates the percentage of equipment lost where equipment is defined as the contents or non-structural components of the element. Evidently, most engineering structures (roads, bridges, culverts, power and communications towers, etc.) do not contain equipment and therefore, this measure cannot be applied to these infrastructure types. For buildings and critical facilities, however, it is estimated that in the case that the structure is inundated, the consequential loss of equipment will be equal to 30% of what the total structural damage may be (Peck *et al*., 2011).

Both impact multipliers correspond to a damage parameter that is the total economic damage that the structure has incurred as a result of the flood (D). Stage-damage curves are used to estimate the monetary damage caused to a structure, or physical entity, for a particular flood depth. A unique curve exists for each infrastructure type (k). The Ontario Ministry of Natural Resources has developed stage-damage curves to represent buildings classified as residential and commercial/industrial/institutional within the province. The respective curves are used to determine the damage parameter for all buildings and critical facilities that are classified as institutional; refer to **Appendix D**. At this time, stage-damage curves are not available for certain physical entities (engineering infrastructure including energy and communications infrastructure) in London or Toronto. As such, they are not included in the current ResilSIM models. It is strongly recommended to develop stage-damage curves for these infrastructure types to be included in future generations of the tool.

Stage-damage curves are unique to certain regions and therefore, they are not easily transferrable between study areas. For development of a resilience simulation tool outside of Ontario it is recommended to create stage-damage curves using the generic depth-damage functions created by the U.S. Army Corp of Engineers. Depth-damage functions provide the economic damages incurred by the structure as the percent-loss of its total value. The percentages derived from these functions are multiplied to the value of the structure in order to determine the total economic damages.

System performance measures may be static or dynamic. Dynamic performance measures are driven by the Modified Rational Hydrograph presented in Step 5: It is apparent that the magnitudes of effective flow rate and the corresponding flood depth change over the duration of the storm event. Since all physical impacts including the length of road inundated by the flood, the number of structures inundated by the flood, and the economic damages sustained by the infrastructure are directly affected by the flood extent and flood depth, the values of the system performance measures also fluctuate over the course of the hazard; refer to **Figure 6** for a sample dynamic system performance curve for impact *i*. The shaded area above the curve represents the total loss of system performance. Parameters t_0 and t_1 represent the time at the beginning and end of the disruption (disaster or hydro-meteorological event), respectively. Evidently, system performance drops once the disruption beings (t_0) and recovers overtime. Note that the units of system performance are unique to each impact and the normalized area under the curve represents the resilience with respect to impact *i*.

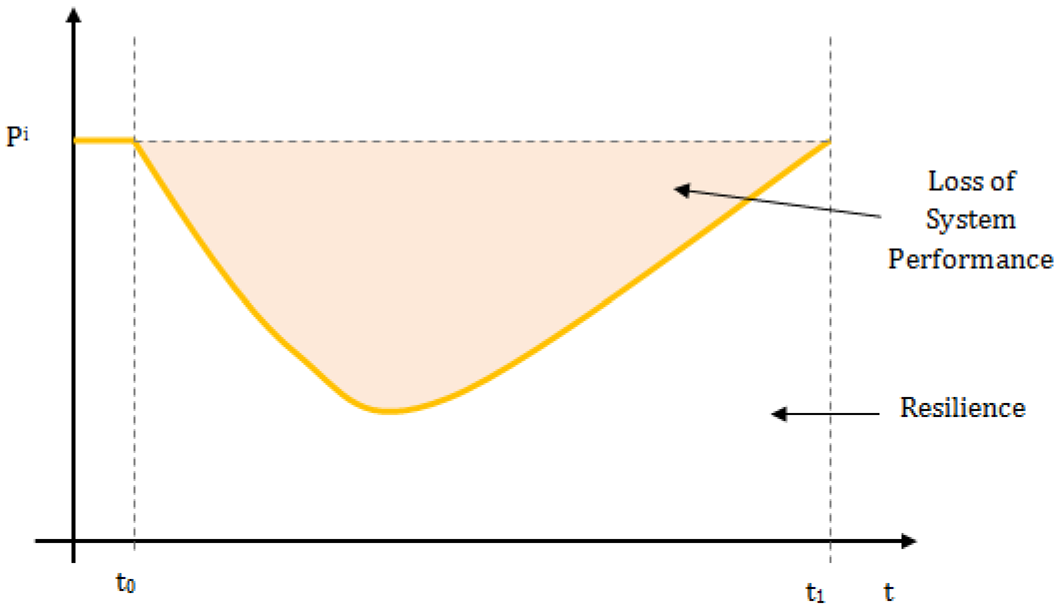

Figure 6: Sample of a dynamic measure of system performance.

Alternatively, system performance may be computed as a static measure. For the City of London, flood depths are provided on a single inundation map for one time slice that is assumed to represent the time at which peak flooding conditions have occurred. **Figure 7** provides a sample static system performance curve. Comparing the performance curves of **Figure 6** and **Figure 7** it is evident that the static system performance measure significantly overestimates loss of system performance and therefore, it underestimates community resilience that is represented by the area under the curve. To alleviate this problem it may be more reasonable for system performance to decrease at a constant, linear rate from a normal level of performance to a peak loss in performance – that may occur at the peak of the flooding event – then increase at another constant rate to the post-hazard performance level; see **Figure 8**. For future generations of the ResilSIM tool, however, inundation maps should be included for several time slices of the flood duration in order to dynamically measure system performance, thereby improving the resilience estimation.

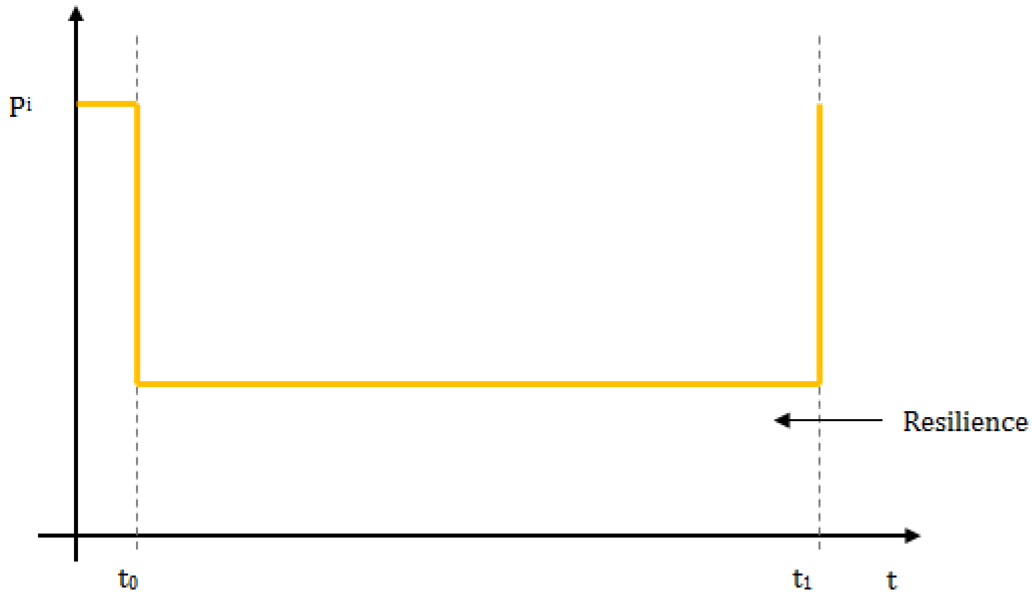

Figure 7: Sample of a static performance measure - option 1.

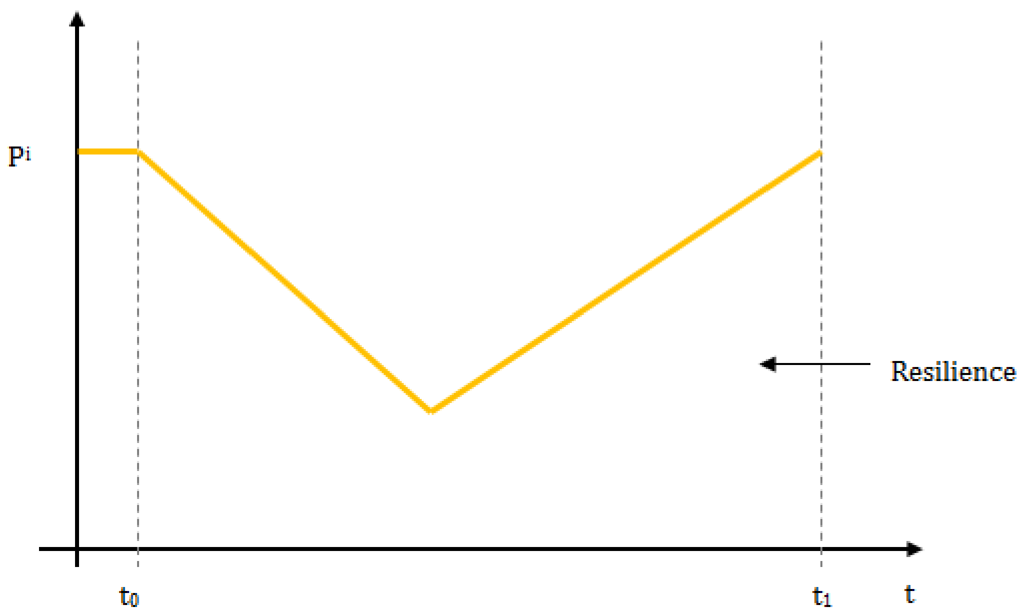

Figure 8: Sample of static performance measure - option 2.

b. <u>Social and economic</u> system performance measure:

Social and economic measures of system performance are calculated as the number of people belonging to a suite Canadian Census Profiles groups that are considered to be vulnerable or susceptible to harm as a result of the hazard (Armenakis and Nirupama, 2013). The social impacts of system performance are measured as follows:

- 1 – Number of persons younger than 6 or older than 65 (A);
- 2 – Number of people who are divorced or widowed (DW);
- 3 – Number of single parents (SP);
- 4 – Number of migrants (MG);
- 5 – Number of allophones – a resident whose first language is neither English nor French (L);
- 6 – Number of immigrants (IM);
- 7 – Number of visible minorities (VM);
- 8 – Number of persons without a high school education (ED)

As an example, the loss of system performance with respect to the number of persons younger than 6 or older than 65 is presented in [Eq. 8]:

$$P_2^1(t,s) = A_s \times I \quad (8)$$

The equation calculates the number of people belonging to the vulnerable age Canadian Census Profile group – for dissemination area s – that are subject to flooding. P_2^1 is the social performance measure that is computed at a particular time (t) and location (s) where each location represents a single dissemination area; A_s is the number of persons belonging to the vulnerable age category in dissemination area s; and I is the percentage of the dissemination area that is flooded.

The economic impacts of system performance are measured as follows:

- 1 – Number of unemployed persons (UE);
- 2 – Number of families with annual income less than $50,000

As another example, the loss of system performance with respect to the number of unemployed persons is shown in [Eq. 9]:

$$P_3^1(t, s) = UE_s \times I \tag{9}$$

The equation calculates the number of people belonging to the unemployed persons Canadian Census Profile group – for dissemination area s – that are subject to flooding. P_3^1 is the economic performance measure that is computed at a particular time (t) and location (s) where each location represents a single dissemination area; UE_s is the number of people belonging to the unemployed persons category in dissemination area s; and I is the percentage of the dissemination area that is flooded.

6. Loss in system performance over time; that is, the area above the system performance curve with respect to a particular resilience unit from the initial time of disturbance to the time at the end of system recovery is calculated using [Eq. 10]:

$$\rho^i = \int_{t_0}^{t} \left[P_0^i - P^i(t,s)\right] dt \tag{10}$$

7. Compute the resilience of each system component - or resilience unit - that is represented by the area below the system performance curve in **Figure 6-8** using [Eq. 11]:

$$r^i(t,s) = 1 - \left(\frac{\rho^i(t,s)}{P_0^i \times (t - t_0)}\right) \tag{11}$$

8. Finally, the resilience of each system component - or resilience unit - is combined into the final, all-encompassing resilience metric in [Eq. 12]:

$$R(t,s) = \left\{\prod_{i=1}^{M} r^i(t,s)\right\}^{\frac{1}{M}} \tag{12}$$

Figures 9-11 show the relationship between resilience and time in the event of a disaster (flood). Resilience takes on a value between 0 and1; t_0 is the initial time of disruption; t_1 is the end of the disruption or the time at which the system begins to return to a normal level of performance; and t_r is the time at the end of the recovery period. The difference between the diagrams is attributed to the way in which system performance is measured. The resilience graph in **Figure 9** corresponds to the system performance curve in **Figure 6** that is measured for several time slices over the course of the disruption. **Figure 6** reveals that the total loss of system performance (the shaded area above the curve) increases at a higher rate, reaches a peak value, and continues to increase at a declining rate until the end of the disruption t_1. This is reflected in the resilience curve: Resilience decreases over the duration of the disaster; however it decreases at a higher rate at the beginning of the disruption and a lower rate toward the end of the disruption. Recovery - improvement of urban resilience - tends to occur after the disturbance has ceased (after the flood has retreated).

Static system performance curves of **Figure 7** and **Figure 8** corresponds to the resilience curves of **Figure 10** and **Figure 11.**

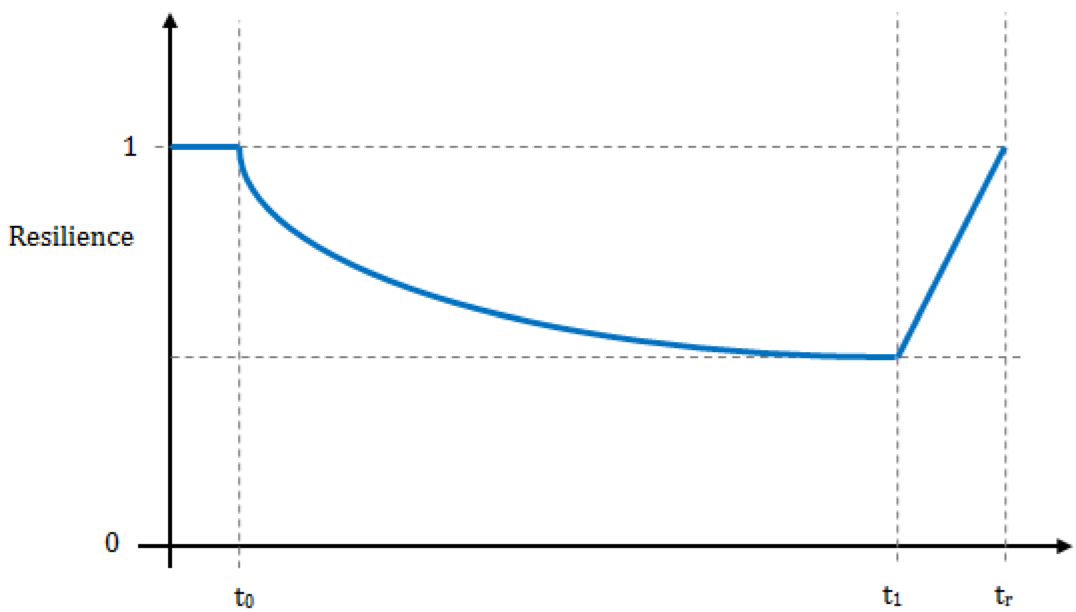

Figure 9: Resilience curve corresponding to a dynamic system performance curve.

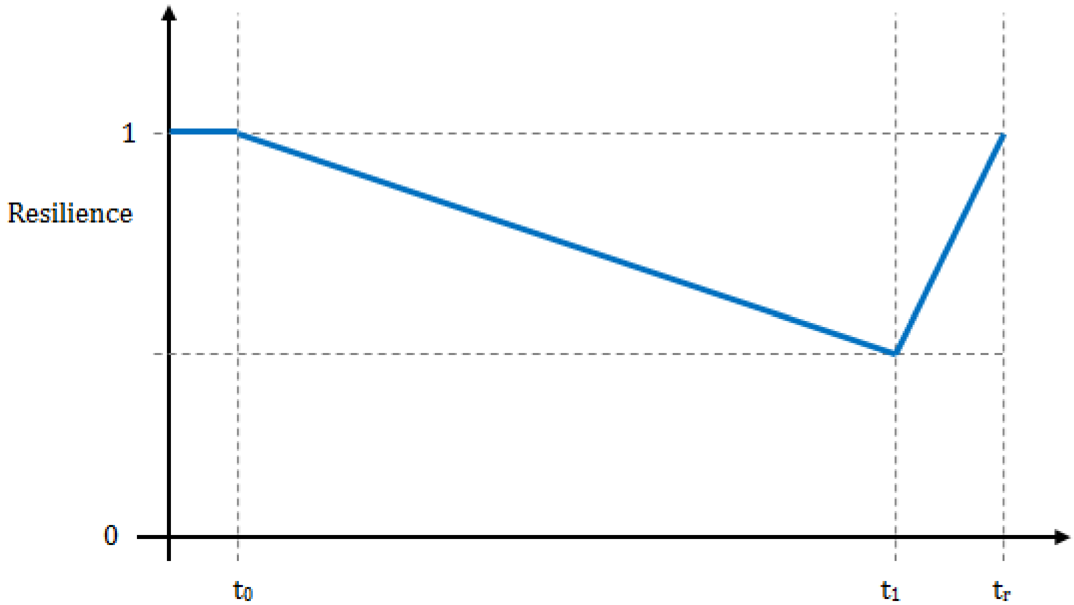

Figure 10: Resilience curve corresponding to a static system performance measure - option 1.

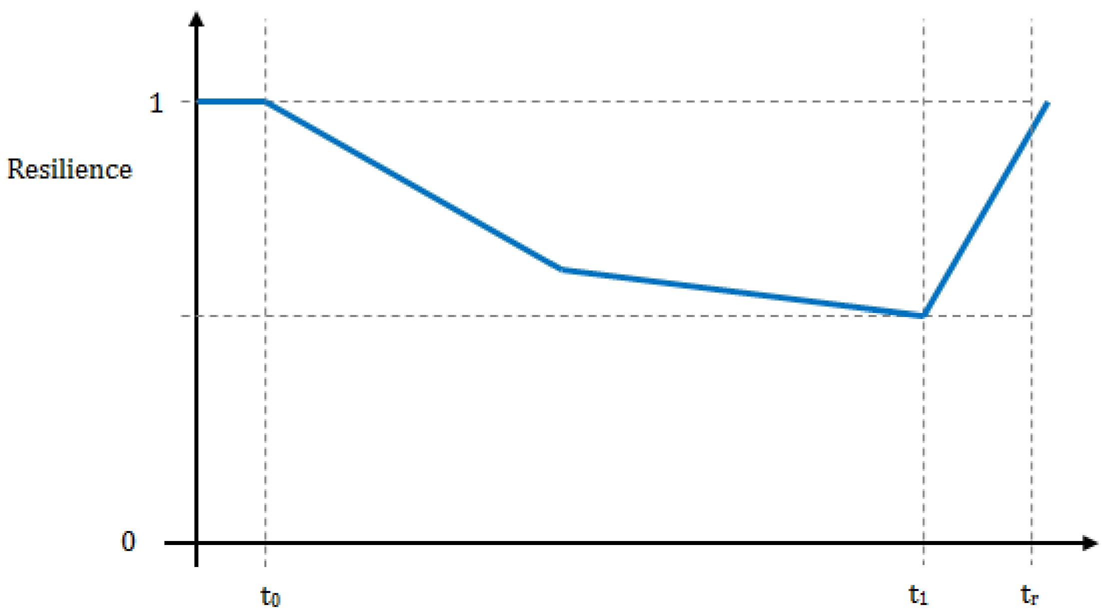

Figure 11: Resilience curve corresponding to a static performance measure - option 2.

Disaster resilience and risk are quite similar. The key difference between the two methods of disaster management is the incorporation of adaptive capacity into the resilience metric. In other words, risk is solely determined by the pre-hazard vulnerabilities of the physical, social and economic system components that are exposed to a hazard. Resilience is affected by the same pre-hazard vulnerabilities in addition to the system's ability to cope with and rapidly recover from the impacts of the hazard through the implementation of adaptation options.

9. Adaptive capacity is a measure of system performance with respect to the physical, social and economic impacts to the urban system after adaptation option(s) have been implemented; for example, the installation of lot level flood protection measures will reduce the magnitude of the initial loss in system performance. In addition, the allocation of materials such as disaster relief funds increases the rate of recovery of system performance. To introduce adaptive capacity into the analysis, apply the appropriate adaptation option and re-compute the resilience metric following steps 5 to 8. Employment of adaptation measures should mitigate the loss of system performance, thereby improving community resilience. The dashed line in **Figure 12** represents the system performance post implementation of adaptive capacity. When compared to **Figure 6**, the overall loss in system performance has been reduced.

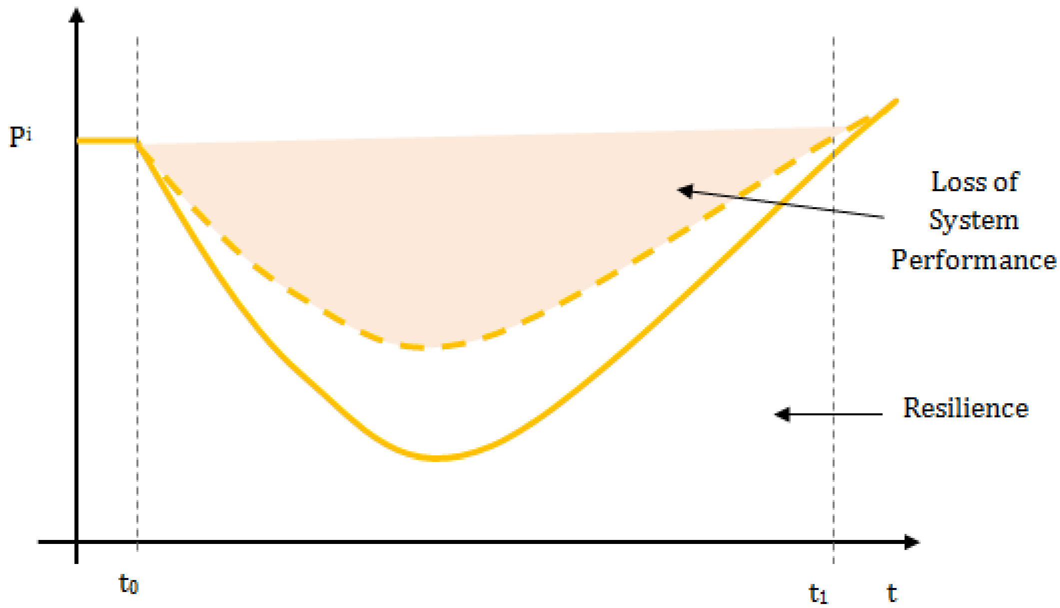

Figure 12: Demonstration of the change in system performance after adaptation measures have been implemented.

Overall, the introduction of adaptive capacity into the urban system reduces the loss of system performance over the duration of the hazard. As a result, community resilience is improved. ResilSIM provides a list of adaptation options that can be applied to improve the system performance with respect to the physical, social and economic units of resilience. The options are listed in **Table 2** and they are divided into two groups: (i) real-time adaptation measures that are implemented during the flooding event; and (ii) proactive adaptation measures that are implemented in advance of the flooding event.

Table 2: Adaptation options available on ResilSIM.

	Adaptation Option
Real-time	i. Implementation of **temporary dyking measures** (**ex. sand bags**) to maintain roads and access routes to buildings and critical facilities; ii. **Pumping out of flooded area** - divert floodwater to adjacent open areas such as parks; iii. **Allocation of resources** (monetary, technological, informational, and human resources) to clean up after the flooding event; iv. **Evacuation and relocation** of people belonging to vulnerable social and economic groups;
Proactive	v. Implementation of **lot-level flood protection measures** to prevent floodwater from entering buildings, thereby maintaining structural function; vi. **Maintenance of drainage infrastructure** (through the removal of debris) in order to optimize drainage capacity and reduce the effective flood depth; vii. **"Twinning" critical infrastructure** (water and power supplies) such that if one infrastructure piece fails in the event of a hazard, there is a **secondary source**.

Real-time adaptation options are implemented in response to a flood warning that has been issued by the regional conservation authority. In the province of Ontario, regional conservation authorities are responsible for operating flood forecasting models and providing flood alerts to municipalities located within their watershed. Flood forecasting tools use near real-time estimates of precipitation (from rain gauge or radar instruments) as input to hydrologic models to estimate surface water flows and subsequently, accumulated water elevations in drainage basins. Once municipalities are warned of an imminent flooding event, government officials from several groups including communications, fire, paramedic, police, public health and transportation services must be available to act in accordance with their local emergency response plan. Other municipal departments, namely those that are responsible for critical engineering infrastructure such as power, water supply, water treatment and solid waste management are often assigned responsibilities during the recovery phase of the flooding event that typically begins two days after the disaster has ceased (Toronto, 2014). The engineering departments are also most likely involved with the proactive adaptation options that are implemented in advance of the flood. The ResilSIM tool may be employed once a flood alert has been issued in order to select the real-time adaptation options that result in the highest value of resilience. The tool may also be used to create detailed emergency response plans that outline the best real-time adaptation options to be implemented for different regions of the city. Alternatively, ResilSIM can be used to select from the best proactive adaptation options.

An explanation of how each adaptation option affects the resilience calculation is provided below:

i. Temporary dyking measures (ex. earth berms and sand bags) are used to prevent water from flooding roads and access routes to buildings and critical facilities. This, in turn, improves building function that is accounted for using several different impacts of the physical performance measure (length of road inundated by the flood and the economic damages incurred by critical facilities as well as communications, industrial and residential buildings). This measure is more easily employed in municipalities that are subject to riverine flooding. Sand bags may also be employed as flood proofing measures that protect structures and when used in this context, are accounted for by the physical performance impacts that measure the magnitude of flood inundation of the buildings, critical facilities and engineering infrastructure.

ii. Pumping out floodwater from vulnerable regions and diverting it to open areas such as parks and stormwater management ponds is an adaptation option that reduces the magnitude of flood extent and inundation over a region. Since all impacts of the physical, social and economic performance measures are driven by the magnitude of flood inundation and flood extent, this adaptation option may have a significant effect on the overall value of resilience.

iii. The allocation of resources (monetary, technological, informational, and human resources) to clean up after the flooding event increases the rate of recovery of an urban system to a normal level of functioning. When more resources are assigned to a certain activity (ex. deployment of personnel, equipment and financial support required for the construction of temporary dykes), the rate of improvement to the relevant impacts of system performance are higher and consequently, the community is more resilient. The

ResilSIM tool applies different rates of recovery to the impacts of system performance depending on the proportion of resources that are made available to the region.

iv. Evacuation and relocation of vulnerable social and economic groups requires the establishment of reception centres such as schools and community halls that act as a safe and protected shelter for evacuees to be transported to and reside in during the flood. Police services are typically responsible for evacuation and for protecting the properties of those who are evacuated until the flood recedes; looting is common during this time. The "evacuation and relocation" adaptation measure directly affects all impacts of the social and economic performance measures.

v. Lot-level protection measures may be employed proactively to prevent floodwater from surrounding and entering buildings, thereby maintaining structural function and integrity (ex. the physical performance impacts that measure the magnitude of flood inundation of the buildings, critical facilities and engineering infrastructure). Lot-level protection measures include the installation of backwater valves and downspout disconnections (that may be done in conjunction with the installation of a rain barrel) that mitigate basement flooding due to sewer surcharge events; in addition to lot re-grading and the sealing of windows and foundation cracks to prevent basement flooding attributed to infiltration and overland flows.

vi. Maintenance of drainage infrastructure (through the removal of debris) may be conducted to optimize drainage capacity and reduce the effective flood depth. Municipalities may wish to implement annual programs where drainage infrastructures, particularly structures located in regions that are vulnerable to flooding, are maintained so they can operate at their full potential. This may be accomplished through the ResilSIM tool using fuzzy set theory; a fuzzy membership function is used to represent the level of infrastructure maintenance or alternatively, the proportion of designed infrastructure capacity that is available for conveying stormwater. By following the methodology proposed herein, this adaptation option can only be employed for cases of urban flooding.

vii. “Twinning of critical infrastructure (water and power supplies) means that there is a backup or secondary source in the event that one infrastructure piece fails as a result of the hazard. It is an example of building redundancy into the urban system. Using the ResilSIM tool, if one critical infrastructure entity is inundated by the flood and there is a secondary source that can provide the same services within the region, then there is no loss in system performance with respect to the critical infrastructure that is inundated.

5. Recommendations

This report presents the concept for ResilSIM: A web-based decision support tool used to estimate urban resilience in the event of a flood. The purpose of the tool is to assist decision makers (engineers, planners and government officials) in selecting the best options for integrating adaptive capacity into a community in order to protect against the hazardous impacts of a flooding event. The proposed first generation of the model is employed in two Canadian cities: (i) London, Ontario to estimate the resilience corresponding to riverine flooding events; and (ii) Toronto, Ontario to estimate the resilience corresponding to urban flooding events. The current structure of the tool is quite basic; however, it provides a foundation for other researchers to improve upon. Several suggestions for model improvement are provided below:

i. Improve the procedure for simulating urban flood depths in the City of Toronto. Replace the Modified Rational Hydrograph that is created in Step 3 of the methodology with a continuous hydrograph to provide a more detailed and accurate estimation of storm-generated surface water runoff. It is recommended to use the Instantaneous Chicago Method to generate a time series of rainfall intensity values and the Unit Hydrograph method to create the flow rate versus time relationship;
ii. Program ResilSIM to estimate community resilience for the City of Toronto with respect to both urban and riverine flooding. Hydraulic analyses must be performed to create inundation maps for the major rivers within the municipal boundaries; namely, the Don and Humber Rivers. Inundation maps should be generated for several time slices over the duration of the flooding event to allow for a dynamic calculation of system performance and community resilience;
iii. Improve the simulation of riverine flooding for the City of London. Generate flood inundation maps for several time slices over the duration of the flooding event to allow for a dynamic calculation of system performance and community resilience;
iv. Develop stage-damage curves to represent infrastructure types that have been omitted from the analysis; i.e. pipelines, energy and communications infrastructure.

High quality, easily accessible data is essential for successful operation of the ResilSIM tool. To further improve the tool's performance and ease of application more publicly accessible data is required. Datasets such as CanVec+ and the Canadian Census Profiles that are maintained by

Natural Resources Canada and Statistics Canada, respectively, are very useful as they provide complete, uniform datasets for the entire country. However, additional nationally maintained databases are needed including a publicly accessible spatial database of building envelopes that are grouped into standardized classifications.

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Appendix A – MPAC Land Use Classifications and Descriptions (City of London, 2015)

** All Land Use Classifications and Descriptions used in the development of ResilSIM are italicized*

MPAC Land Use Classifications

Agriculture
Apartment
Commercial - Automotive
Commercial - General Retail
Commercial - Office
Institutional - Educational, Cultural, Medical
Institutional - Public Administration
Major Industry
Minor Industry
Parking Areas
Parks and Open Recreation
Public Utilities, Transportation, Communication
Residential Conversions
Row Housing
Single Family
Single Family - Duplex
Single Family - Semi-Detached
Unknown

MPAC Land Use Descriptions

Airport authority
Ambulance station
Amusement park
Armoury
Assembly hall, community hall
Auto dealership
Auto dealership - Independent dealer or used vehicles
Automotive assembly plant
Automotive fuel station with or without service facilities
Banks and similar financial institutions including credit unions - typically multi-tenant
Banks and similar financial institutions including credit unions - typically single tenant
Banquet hall
Bed and breakfast establishment
Big box shopping/power centre greater than 100,000 s.f. with 2 or more main anchors
Billboard

Cemetery
Cemetery with non-Internment services
Cinema/movie house/drive-in
Clergy residence
Clubs - private, fraternal
Commercial sports complex
Commercial condominium
Commercial buildings
Communications towers with or without secondary communications structures
Community lifestyle
Community shopping centre
Concert hall/live theatre
Condominium development land - residential
Condominium parking space unit
Conservation authority land
Cooperative housing - non-equity
Crematorium
Day care
Department store
Distillery/brewery
Driving range/golf centre/mini-put - stand alone, not part of a regular golf course
Dump/transfer station/incineration plant/land fill
Duplex
Exhibition grounds/fair grounds
Farm property without any buildings/structures
Farm with residence - with commercial/industrial operation
Farm with residence - with or without secondary structures; no farm outbuildings
Farm with residence - with or without secondary structures; with farm outbuildings
Farm without residence - with commercial/industrial operation
Farm without residence - with secondary structures; with farm outbuildings
Fire hall
Freehold townhouse/row-house
Freestanding Beer Store or LCBO - not associated with power or shopping centre
Freestanding large retail store, national chain - generally greater than 30,000 s.f.
Freestanding supermarket
Freezer plant/cold storage
Full service hotel
Funeral home
Golf course
Government - agriculture research facility - predominately farm property
Grain handling - Lakehead terminal elevators
Grain/seed and feed operation
Gravel pit, quarry, sandpit

Group home as defined by the Municipal Act 2001
Heavy manufacturing (non-automotive)
Hospital, private or public
Hydro One Transformer Station
Industrial condominium
Industrial mall
Intensive farming operation - with residence
Intensive farming operation - without residence
Land designated and zoned
Land owned by a farmer and improved with a non-farm residence with a portion being farmed
Land owned by a non-farmer and improved with a non-farm residence with a portion being farmed
Large medical/dental building (generally multi-tenanted over 7,500 s.f.)
Large office building (generally multi-tenanted over 7,500 s.f.)
Large retail building centre, generally greater than 30,000 s.f.
Large scale greenhouse operation
Large scale poultry operation
Library and/or literary institution
Life lease - Return on invest (guaranteed return or market based return on investment)
Limited service hotel
Link home
MEU transformer station
Military base or camp (CFB)
Mobile home park
More than one structure used for residential purposes with at least one of the structures
Motel
Multi-residential vacant land
Multi-residential with 7 or more self-contained residential units, with small commercial
Multi-residential with 7 or more self-contained units (excluding row-housing)
Multi-type complex - defined as a large multi-use complex consisting of retail/office
Multiple occupancy educational institution residence located on or off campus
Municipal park (excludes Provincial parks, Federal parks, campgrounds)
Museum and/or art gallery
Neighbourhood shopping centre - with more than two stores attached, under one ownership
Neighbourhood shopping centre with offices above
Non-buildable land (walkways, buffer/berm, stormwater management pond, etc.)
Non-commercial sports complex
Nursing home
Office use converted from house
Old age/retirement home
Other industrial (all other types not specifically defined)
Other correctional facility
Other educational institutional residence (ex. Schools for the blind, deaf, special education)

Other institutional residence
Parking garage - excludes parking facilities that are used in conjunction with another property
Place of worship - without a clergy residence
Place of worship - with a clergy residence
Police station
Post-secondary education - university, community college, etc
Postal mechanical sorting facility
Private generating station (fossil fuels)
Provincial correctional facility
Provincial park
Public transportation - easements and rights
Railway buildings and lands described as accessible in the Assessment Act
Recreational sport club - non-commercial (excludes golf clubs and ski resorts)
Recycling facility
Regional shopping centre
Residence with a commercial unit
Residential condominium
Residential development land
Residential property with four self-contained units
Residential property with five self-contained units
Residential property with six self-contained units
Residential property with three self-contained units
Residence with a commercial/industrial use building
Restaurant - conventional
Restaurant - conventional/national chain
Restaurant - fast food
Restaurant - fast food/national chain
Retail - one storey, generally under 10,000 s.f.
Retail or office with residential units above or behind - greater than 10,000 s.f.
Retail or office with residential units above or behind - less than 10,000 s.f.
Retail use converted from house
Retail with more than one non-retail use
Retail with office(s) - less than 10,000 s.f., GBA with offices
Retail with office(s) - greater than 10,000 s.f., GBA with offices
Retail - one storey, generally over 10,000 s.f.
Rooming or boarding house
Row housing, with three to six units under single ownership
Row housing with seven or more units under single ownership
School (elementary or secondary including private)
Semi-detached residential
Semi-detached with both units under one ownership
Sewage treatment/waste pumping/waste disposal
Single family detached (not on water)

Single family detached on water
Ski resort
Small medical/dental building (generally single tenant or owner occupied under 7,500 s.f.)
Small office building (generally single tenant or owner occupied under 7,500 s.f.)
Small box shopping centre less than 100,000 s.f. minimum 3 box stores with one anchor
Specialty automotive shop/auto repair/collision service/car or truck wash
Standard industrial properties not specifically identified by other Industrial Property Companies
Steel mill
Surface parking lot - excludes parking facilities that are used in conjunction with another property
Surface parking lot - used in conjunction with another property
Tavern /public house/small hotel
Townhouse block - freehold units
Transit
Vacant industrial land
Vacant commercial land
Vacant land condominium (residential - improved)
Vacant land condominium (residential)
Vacant residential land not on water
Vacant residential/commercial/industrial land owned by a non-farmer with a portion being farmed
Warehousing
Water treatment/filtration/water towers/pumping stations
Mini-warehousing

Appendix B – CanVec+ distribution filenames (NRC, 2015)

Feature catalogue Entity name	Theme	GML – Entity name Shape – File name	Geometry		
			Point	Line	Area
Aboriginal Lands [GeoBase]	la	la_1690009			_2
Amusement park	lx	lx_2260009			_2
Blocked passage [GeoBase]	tr	tr_1780009	_0		
Botanical garden	lx	lx_2200009			_2
Building	bs	bs_2010009	_0		_2
Camp	lx	lx_2030009	_0		
Campground	lx	lx_2480009	_0		_2
Cemetery	lx	lx_1000039	_0		_2
Chimney	bs	bs_2060009	_0		
Contour	fo	fo_1030009		_1	
Contour imperial	fo	fo_2570009		_1	
Cross	bs	bs_2120009	_0		
Cut line	ve	ve_2290009		_1	
Domestic waste	ic	ic_1360019			_2
Drive-in theatre	lx	lx_2070009	_0		_2
Elevation point	fo	fo_1200009	_0		
Elevation point imperial	fo	fo_2610009	_0		
Esker	fo	fo_1080029		_1	
Exhibition ground	lx	lx_2510009			_2
Extraction area	ic	ic_1350039	_0		_2
Ferry connection segment [GeoBase]	tr	tr_1750009		_1	
Footbridge	lx	lx_2280009		_1	
Fort	lx	lx_1000049			_2
Gas and oil facilities	en	en_1360049	_0		_2
Glacial debris undifferentiated	fo	fo_1080039			_2
Golf course	lx	lx_1000089			_2
Golf driving range	lx	lx_2500009	_0		_2
Historical site/Point of interest	lx	lx_2220009	_0		
Hydrographic obstacle entity [GeoBase]	hd	hd_1460009	_0	_1	_2
Industrial and commercial area	ic	ic_1360039	_0		_2
Industrial solid waste	ic	ic_1360029	_0		_2
Island [GeoBase]	hd	hd_1490009			_2
Junction [GeoBase]	tr	tr_1770009	_0		

Landform	fo	fo_1080019			_2
Landmass	la	la_1150009			_2
Lookout	lx	lx_1000019	_0		_2
Lumber yard	ic	ic_2110009			_2
Manmade hydrographic entity [GeoBase]	hd	hd_1450009	_0	_1	_2
Marina	lx	lx_1000069	_0		
Mine	ic	ic_1350049	_0		_2
Mining area	ic	ic_2600009	_0		
Moraine	fo	fo_1080049			_2
Municipality[GeoBase]	la	la_1680039			_2
Municipality Regional area[GeoBase]	la	la_1680019			_2
Navigational aid	bs	bs_1250009	_0		
Named feature	to	to_1580009	_0	_1	_2
NTS50K boundary polygon	li	li_1210009			_2
Palsa bog	ss	ss_1320029			_2
Parabolic antenna	bs	bs_2000009	_0		
Park/sports field	lx	lx_2270009			_2
Peat cutting	ic	ic_1350059			_2
Permanent snow and ice	hd	hd_1140009			_2
Picnic site	lx	lx_2490009	_0		_2
Pingo	fo	fo_1080079	_0		
Pipeline	en	en_1180009		_1	
Pipeline (Sewage/liquid waste)	bs	bs_2310009		_1	
Pit	ic	ic_1350019			_2
Power transmission line	en	en_1120009		_1	
Quarry	ic	ic_1350029			_2
Rail Ferry [GeoBase]	tr	tr_1050009		_1	
Railway [GeoBase]	tr	tr_1020009		_1	
Railway Station [GeoBase]	tr	tr_1060009	_0		
Railway Structure [GeoBase]	tr	tr_1040009	_0	_1	
Residential area	bs	bs_1370009			_2
Road segment [GeoBase]	tr	tr_1760009		_1	
Ruins	lx	lx_2400009	_0		_2
Runway	tr	tr_1190009	_0		_2
Sand	fo	fo_1080059			_2
Saturated soil	ss	ss_1320039			_2
Shoreline [GeoBase]	hd	hd_1440009		_1	
Shrine	lx	lx_2210009	_0		
Silo	bs	bs_2440009	_0		
Single line watercourse [GeoBase]	hd	hd_1470009		_1	

Ski centre	lx	lx_1000029	_0		
Sports track/Race track	lx	lx_1000079		_1	_2
Stadium	lx	lx_2460009			_2
String bog	ss	ss_1320059			_2
Tank	bs	bs_2080009	_0		_2
Toll point [GeoBase]	tr	tr_1790009	_0		
Tower	bs	bs_2530009	_0		
Trail	lx	lx_2420009		_1	
Transformer station	en	en_1360059	_0		_2
Transmission line	bs	bs_2230009		_1	
Tundra polygon	fo	fo_1080069			_2
Tundra pond	ss	ss_1320019			_2
Underground reservoir	bs	bs_2380009	_0		_2
Upper Municipality[GeoBase]	la	la_1680029			_2
Valve	en	en_1340009	_0		
Wall/fence	bs	bs_2240009		_1	
Waterbody [GeoBase]	hd	hd_1480009			_2
Well	bs	bs_2350009	_0		
Wetland	ss	ss_1320049			_2
Wind-operated device	en	en_2170009	_0		
Wooded area	ve	ve_1240009			_2
Zoo	lx	lx_2560009			_2

Appendix C – Parameters Required for Determination of the Average Rainfall Intensity

Table 3c: Toronto Intensity-Duration-Frequency Curve Parameters. Adapted from City of Toronto (2006).

Return Period (Year)	A	B
2	21.8	-0.78
5	32	-0.79
10	38.7	-0.80
25	45.2	-0.80
50	53.5	-0.80
100	59.7	-0.80

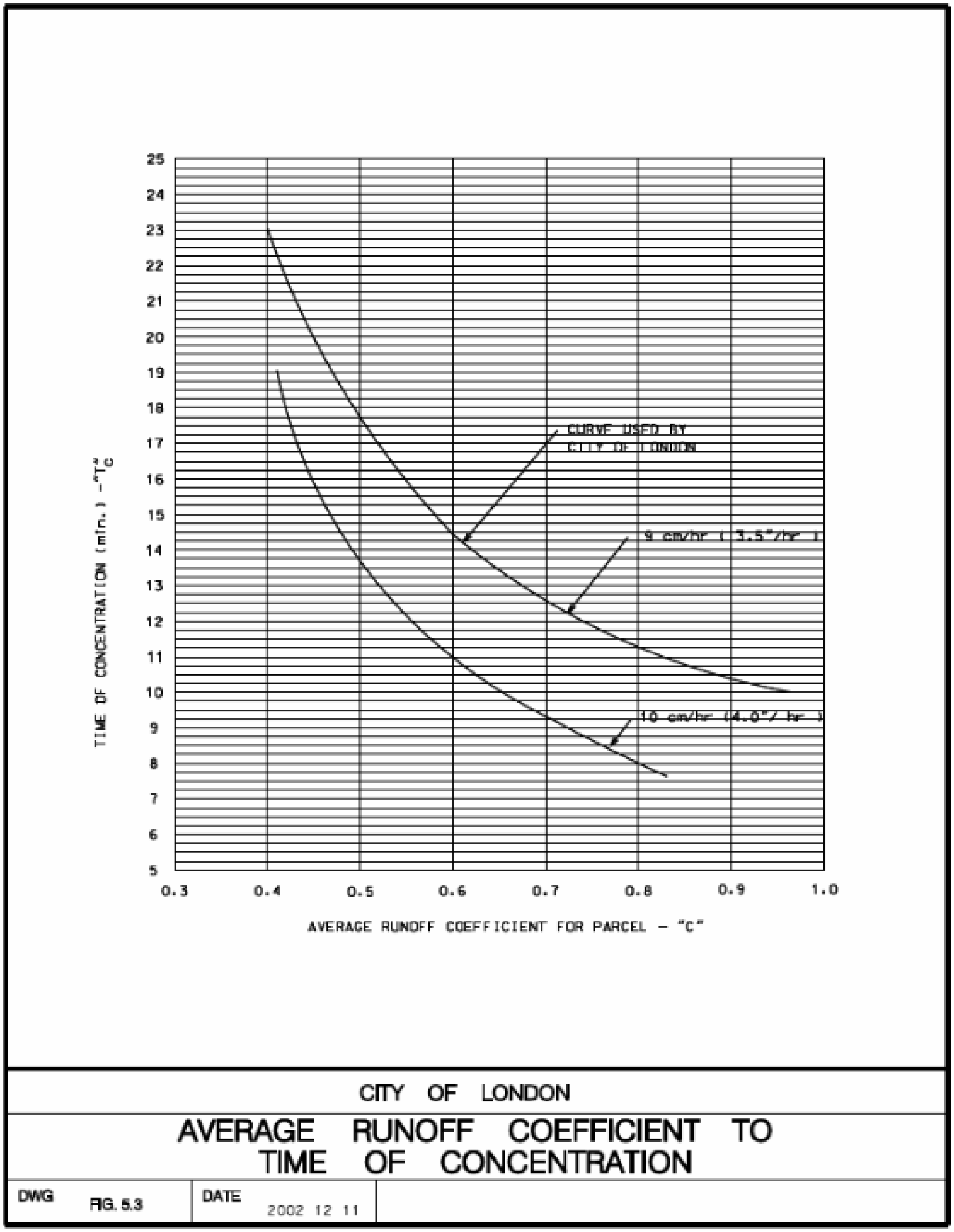


Figure 13c: Chart used to determine the time of concentration. Retrieved from the City of London (2015). Note: Use a runoff coefficient of 0.9 for post-development sites.

Appendix D - Stage-Damage Curves Used to Compute Physical System Performance. Adapted from Water's Edge *et al.*, (2007) Simonovic *et al.*, (2011).

Type 1					Type 2			
1 storey without Basement					1 storey with Basement			
Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)		Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)
-2.44	0	0	0		-2.44	174	916	1564
-2.13	0	0	0		-2.13	565	4475	9127
-1.83	0	0	0		-1.83	696	4907	9838
-1.52	0	0	0		-1.52	763	5605	11065
-1.22	0	0	0		-1.22	783	6042	13758
-0.91	0	0	0		-0.91	955	6538	15356
-0.61	0	77	85		-0.61	1040	6810	15891
-0.3	0	233	466		-0.3	1169	7047	16282
0	1787	3115	10257		0	3060	10517	22131
0.3	7959	15200	33700		0.3	12197	24364	42738
0.61	8779	16657	36253		0.61	13554	25914	45177
0.91	9498	19303	40585		0.91	15111	28049	48578
1.22	10750	22199	49774		1.22	17004	30910	53400
1.52	11835	24257	58540		1.52	18652	33257	57436
1.83	12441	25409	60726		1.83	19669	34461	59682
2.13	12682	25971	62070		2.13	20224	35225	60893
2.44	12924	26508	63328		2.44	20772	35960	62041

Type 3					Type 4			
2 stories without basement					2 stories with basement			
Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)		Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)
-2.44	0	0	0		-2.44	192	497	1542
-2.13	0	0	0		-2.13	1062	2715	5416
-1.83	0	0	0		-1.83	1278	3016	5843
-1.52	0	0	0		-1.52	1408	3510	6471
-1.22	0	0	0		-1.22	1511	3802	7111
-0.91	0	0	0		-0.91	1826	4254	7988
-0.61	27	27	31		-0.61	1928	4487	8209
-0.3	145	155	357		-0.3	2060	4723	8813
0	1991	2443	7183		0	4031	7811	16841
0.3	7293	12732	24699		0.3	11389	18539	38953
0.61	8041	14001	26515		0.61	12276	20124	42154
0.91	9047	15938	29179		0.91	13751	22277	45892
1.22	10357	18393	33887		1.22	15278	25057	50471
1.52	11472	20139	37555		1.52	16347	27327	54998
1.83	11998	21092	38564		1.83	16958	28417	56710
2.13	12335	21591	39000		2.13	17220	29140	58002
2.44	12630	22069	39364		2.44	17455	29794	59184

Type 5
Split Level

Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)
-2.44	630	681	2468
-2.13	2832	3140	9923
-1.83	3054	3489	10236
-1.52	3593	4107	10939
-1.22	4572	5225	13021
-0.91	7651	10206	17455
-0.61	8313	11135	18177
-0.3	8928	12119	18960
0	11474	14541	23142
0.3	17714	22510	33431
0.61	18686	23979	35385
0.91	20289	25314	37565
1.22	22573	28595	41509
1.52	25491	35143	50699
1.83	26260	36175	51659
2.13	26869	37096	52547
2.44	27584	38282	53359

Type 6
Townhouses

Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)
-2.44	0	517	943
-2.13	0	3038	5542
-1.83	0	3283	5988
-1.52	0	4145	7559
-1.22	0	4471	7659
-0.91	0	5071	8546
-0.61	0	5186	8628
-0.3	80	5263	8711
0	1306	6808	10282
0.3	5329	14080	18389
0.61	6071	14832	19189
0.91	7036	16572	21593
1.22	8793	18085	22970
1.52	9979	19077	25155
1.83	10424	19557	25705
2.13	10737	19782	25950
2.44	11031	19995	26163

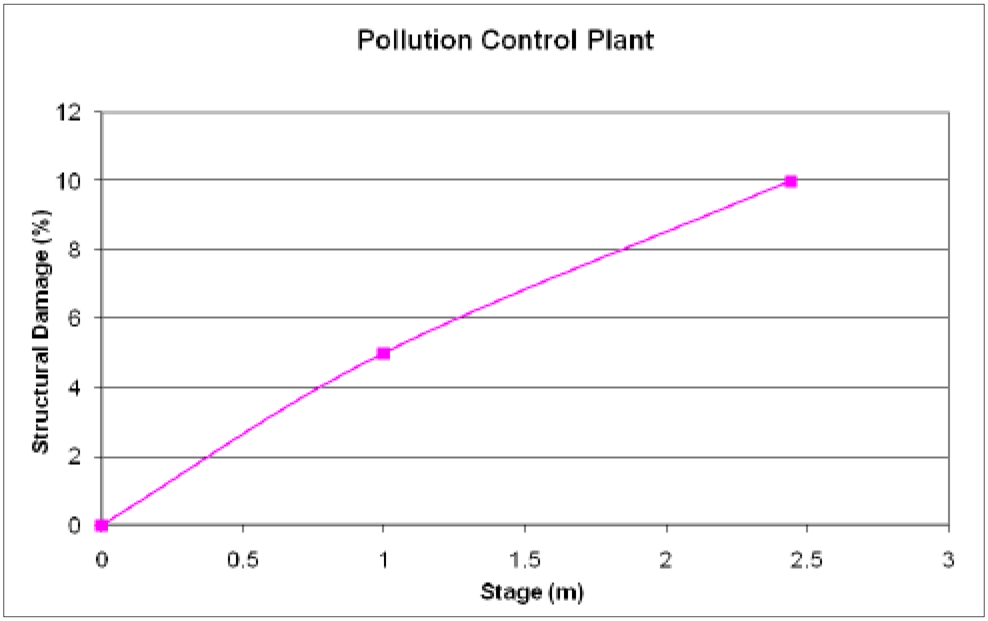
Type 7
Mobile Homes

Depth (m)	Low ($/m2)	Mean ($/m2)	High ($/m2)
0	0	2843	0
0.3	0	13431	0
0.61	0	14325	0
0.91	0	16401	0
1.22	0	18231	0
1.52	0	20058	0
1.83	0	20735	0
2.13	0	20808	0
2.44	0	20995	0

Type 8
commercial/industrial/institutional (contents + structure)
Fort McMurray: 2005$ per square metre

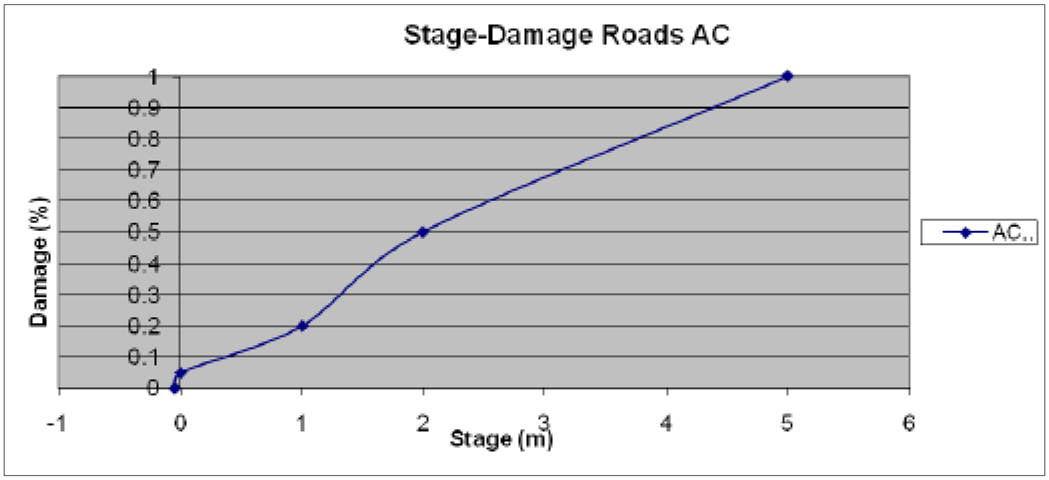
	Depth (m)								
Category	0.15	0.3	0.61	0.91	1.22	1.52	1.83	A	General Office
A	69.62	119.09	188.71	258.33	287.64	337.11	379.25	B	Medical
B	0	234.51	491.01	729.18	815.29	925.22	1049.81	C1	Shoes
C1	124.58	327.95	622.92	1013.16	1364.93	1755.17	1863.27	C2	Clothing
C2	278.48	593.61	850.11	1921.9	2119.77	2473.37	2748.18	C3	Stereo/TV
C3	183.21	269.32	379.25	635.75	780.48	1000.34	1295.31	C4	Paper Products
C4	106.26	214.36	414.06	635.75	798.81	905.07	1011.33	C5	Hardware/Carpte
C5	69.62	119.09	188.71	258.33	287.64	357.26	406.73	C6	Misc Retail
C6	199.7	403.07	622.92	824.46	1024.16	1205.54	1333.79	D	Furniture/Appliances
D	89.77	139.24	208.86	294.97	326.12	375.59	426.88	E	Groceries
E	69.62	119.09	208.86	333.45	456.2	600.94	729.18	F	Drugs
F	69.62	159.39	263.83	448.87	626.59	829.95	936.21	G	Auto
G	69.62	251	414.06	729.18	798.81	850.11	888.58	H	Hotels
H/I	31.15	64.12	95.27	124.58	135.58	166.72	199.7	I	Restaurants
J	69.62	119.09	229.02	333.45	551.47	696.21	785.98	J	Personal Service
K	49.47	100.77	150.23	240.01	287.64	357.26	445.21	K	Financial
L	89.77	175.88	263.83	408.56	456.2	509.33	547.8	L	Warehouse/Industrial
M	0	0	133.74	164.89	175.88	205.2	236.34	M	Theatres
N	89.77	234.51	320.62	353.6	0	0	0	N	Institutional/Other

Pollution Control Plant	
Structural Damage	
Inundation	Damage (&)
0	0
1	5
2.44	10
Equipment Damage	
0	0
0.2	90
2.44	100



Depth (m)	Damage (%)	Explanation
-0.05	0	Slight damage may occur to subgrade and substructure due to seepage
0	0.05	Presume there is no damage to the surface layer until water level is above paved elevation
1	0.2	Including modest damage due to water on asphalt surface
2	0.5	Higher degree due to floodwaters inundating paved surface
5	1	Upper boundary of road damage

* references made to elev'n of road surface; anything below which is assigned a (-)ve value and anything above the datum (+)



Depth (m)	Damage (%)	Explanation
-0.05	0	Very slight damage
0	0	Presume there is no damage to the surface layer until water level is above paved elevation
1	0.05	Including slight damage due to water on asphalt surface
2	0.1	Higher degree due to floodwaters inundating paved surface
5	0.25	Upper boundary of road damage

* references made to elev'n of road surface; anything below which is assigned a (-)ve value and anything above the datum (+)

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