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A Methodology for Municipal Flood Risk Assessment due to Climate Change: A City of London Case Study

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A Methodology for Municipal Flood Risk Assessment due to Climate Change: A City of London Case Study

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Methodology for Flood Risk Assessment due to Climate Change

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by

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of the requirements for the degree of
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THE UNIVERSITY OF WESTERN ONTARIO
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The thesis by

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ABSTRACT

Flooding has devastating physical, social, economic and environmental consequences. It is important to identify and understand the evolution of these risks as climate changes. Most municipal infrastructure is designed using historical data which may no longer accurately represent current climate conditions. As a result, municipalities may be at greater risk of flood damage. The purpose of this study is to develop and test a municipal-level risk assessment methodology considering climate change-caused impacts of flooding. Floodplain maps derived from climate, hydrologic and hydraulic analyses provide direct input into risk assessment procedure. Inundated infrastructure and high risk areas are identified in tables and maps for each climate scenario using quantitative and qualitative risk calculations. The developed risk assessment methodology is applied as a case study to the City of London, Ontario, Canada. Results provide support for climate change adaptation policy development, decision making and emergency management.

Keywords: climate change, decision making, emergency management, flood risk assessment, fuzzy set theory, infrastructure.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BMS	Bridge Management System
CC_LB	Climate Change Lower Bound scenario
CC_UB	Climate Change Upper Bound scenario
CCIAD	Climate Change Impacts and Adaptation Division
CCPE	Canadian Council of Professional Engineers
CDD	Canadian Disaster Database
CFCAS	Canadian Foundation for Climate and Atmospheric Sciences
CoA	Certificate of Approval
CVA	Cost Value Assessment
DA	Dissemination Area
EC	Environment Canada
FDA	Flood Damage Assessment
FDEG	Flood Damage Estimation Guide
FEMA	Federal Emergency Management Agency
GCM	Global Climate Model
GCSI	Global Climate Strategies International
GHGs	Greenhouse Gases
GIS	Geographic Information System
HAZUS-MH	Hazards U.S. Multi-Hazard
HEC-FDA	Hydrologic Engineering Centre Flood Damage Analysis Program
HEC-HMS	Hydrologic Engineering Centre Hydrologic Modeling System

HEC-RAS	Hydrologic Engineering Centre River Analysis System
ICLEI	International Council for Local Environmental Initiatives
ICLR	Institute for Catastrophic Loss Reduction
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
K-NN	K-Nearest Neighbour
MLD	Million Litres per Day (metric)
MNR	Ministry of Natural Resources
MO	Multi-objective
MPAC	Municipal Property Assessment Corporation
MSC	Meteorological Service of Canada
NaFRA	National Flood Risk Assessment
NFIP	National Flood Insurance Program
PCP	Pollution Control Plant
PIEVC	Public Infrastructure Engineering Vulnerability Committee
RASP	Risk Assessment of flood and coastal defense systems for Strategic Planning
RP	Return Period
USACE	United States Army Corps of Engineers
UTRCA	Upper Thames River Conservation Authority
UWO	University of Western Ontario
WG	Weather Generator
WLD	West London Dyke

NOMENCLATURE

α	Compromise programming weighting parameter
ALP	Acceptable level of performance function
CM	Compatibility measure
e	Infrastructure element of interest
EV_1	Economic value; loss of function
EV_2	Economic value; loss of equipment
EV_3	Economic value; loss of structure
FRE	Fuzzy reliability index
$g_i(x)$	Set of constraints
IM_1	Impact multiplier; loss of function
IM_2	Impact multiplier; loss of equipment
IM_3	Impact multiplier; loss of structure
LR_{max}	Reliability measure of acceptable level of performance
P	Probability
p	Compromise programming parameter
q	Area of interest
R	Set of real numbers
$R_{DA(100CC\_LB)}$	Risk index for 100 CC_LB scenario
$R_{DA(100CC\_UB)}$	Risk index for 100 CC_UB scenario
$R_{DA(250CC\_LB)}$	Risk index for 250 CC_LB scenario
$R_{DA(250CC\_UB)}$	Risk index for 250 CC_UB scenario

$R_{DA(250UTRCA)}$	Risk index for 250 UTRCA (current) scenario
RP	Return period
s	Climate change scenario notation
SS	System state function
t	Notation for type of impact
$WASS$	Weighted area of system state
WOA	Weighted overlap area
x	Set of decision variables
X	Feasible region
$YearY$	Monetary value of infrastructure for the year of interest
$YearB$	Monetary value of infrastructure for the base year
$YearYindex$	CPI value for year of interest (Statistics Canada)
$YearBindex$	CPI value for base year (Statistics Canada)
$Z(x)$	Objective function

Glossary

Geophysical Disasters	Events which originate from solid earth including: earthquakes, landslides and tsunamis as defined in the Canadian Disaster Database (CDD)
Hazard	A threatening, naturally-occurring physical event or phenomena
Infrastructure Element	A specific piece of infrastructure. For example: a single pedestrian bridge; Bridge A
Risk	Quantification of expected losses based on the intersection of hazard and vulnerability
Stakeholders	People who have a vested interest in the issue at hand; may exercise limited or involvement in the decision making process
Vulnerability	Degree of susceptibility to incurring losses or damages
Weather-Related Disasters	Events related to atmospheric processes including: cold waves, droughts, floods, hail/thunderstorms, heat waves, hurricanes/typhoons, avalanches, storms, tornados and wildfires as defined in CDD

CHAPTER 1

INTRODUCTION

1.1 Climate Change and its Role at the Municipal Level

Water management infrastructure is often designed based on values specified by regional Intensity Duration Frequency (IDF) curves (Prodanovic and Simonovic, 2007; Simonovic and Peck, 2009), which are created based on historical records of observed precipitation. Annual maximum precipitation values are extracted and fit to a probability distribution function from which rainfall intensity for various durations are obtained. Return periods (in years) are used to estimate the frequency of occurrence for a particular rainfall event (Environment Canada, 2010). However, IDF curves are developed under the assumption that historic records are accurate representations of future climate; in other words, the assumption that the climate is stationary. It is generally accepted that the climate is changing (IPCC, 2007; Government of Canada, 2007; ICLR 2010). There is much evidence that supports the fact that climate is changing, and that this change is reflected by increased temperatures, shifts in precipitation patterns and increased frequency of extreme precipitation events (IPCC, 2007). In light of these changes, historic IDF curves are no longer able to accurately represent current or future climate conditions. As a result, water management infrastructure is currently being designed with inadequate capacities to cope with the increased demand due to climate change. In addition, existing infrastructure is not able to perform at its designed or anticipated level of service. Compromised infrastructure has many repercussions on the overall hydrological response of a system, and may have catastrophic physical, economic and social consequences. It will likely be necessary to modify codes, update standards and create additional flood protection devices to accommodate additional climate loads (Simonovic and Peck, 2009).

Many municipal infrastructure systems are approaching the end of their useful lifespan and will require major upgrades, retrofitting, refurbishment, replacement or demolition. This is an expensive endeavor that will undoubtedly strain financial resources at the municipal level. For example, it is estimated that the Canadian water and waste water infrastructure would require between $80 and $90 billion (CAN) over a ten year period to update the existing systems, accommodate anticipated additional climate change loads and maintain the required level of service (Infrastructure Canada, 2004).

Changes must be made now to accommodate the future demands posed by climate change. Politically, implementation of new standards and codes of practice can be a slow process as stakeholders are especially resistant to changes with large financial implications (Auld and MacIver, 2006b). Adding to this challenge is the conflict between the time scales involving politics and infrastructure management. Elected council holds term for only four years at a time, and actions are generally driven by the desire to be re-elected. Often politicians provide short-sighted temporary solutions that are beneficial to the promotion of their political campaigns. Although these short and medium term actions are valuable, comprehensive emergency management, infrastructure design, maintenance and operations demand long term climate change planning and adaptation strategies.

1.2 Motivation for Thesis Research and Main Contributions

Previous studies assessing the impact of climate change have been conducted at the University of Western Ontario (UWO) under the support of the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). These studies suggested that London can expect the occurrence of more frequent and severe precipitation events as a consequence of climate change, as well as identifying riverine flooding in the basin to be the predominant issue (Cunderlink and Simonovic, 2005, 2007; Prodanovic and Simonovic, 2007; Simonovic and Peck, 2009). Recognizing that climate is changing, the City of London adopted a climate change adaptation plan and as a first step commissioned a study to assess the impact of climate change on the municipal infrastructure system. The study includes climate modeling, hydrologic modeling, hydraulic analyses and risk assessment. This thesis represents a part of risk assessment.

The purpose of the research presented in this thesis is to develop an infrastructure risk assessment methodology that will be used as the framework for risk-based decision making, emergency management and preparedness, and climate change adaptation policy development. Proposed methodology is inspired by Engineers Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC) national climate change risk assessment protocol (CCPE, 2007). The primary objective of the protocol is the assessment of the impact of climate change on infrastructure. However, the protocol approaches risk in qualitative terms with a very fine resolution and at the infrastructure-specific level. Its implementation is extremely time consuming and not suited for large-scale assessments. Therefore, a different and more generalized approach to risk assessment is proposed in this thesis that is also adaptable for use with multiple types of hazards. Risk is considered as the intersection between physical hazard, in this case flooding, and vulnerability (Simonovic, 2011). A risk index is developed for each infrastructure element based on response of the infrastructure system to flood conditions. System responses are influenced by flood levels as well as existing infrastructure conditions and characteristics. The existing conditions of the infrastructure elements are of importance in order to correctly assess their corresponding individual risk index, and how the response of the entire system may be affected.

The main contribution of this thesis is a methodology for risk index calculation that:

(i) Quantifies climate change caused flood risk to municipal infrastructure;
(ii) Integrates risk to various types of infrastructure into one measure;
(iii) Engages local authorities and stakeholders in risk assessment process;
(iv) Provides a range of risk impacts for possible future climates;
(v) Integrates quantitative and qualitative risk analysis;
(vi) Provides input for spatial assessment of climate change-caused flood risk; and
(vii) Can be used in multi-objective climate change adaptation policy development.

The methodology proposed in the following chapters describes quantitative and qualitative flood risk information and estimation to better represent climate change impacts and provide a comprehensive risk assessment. The study uniquely combines qualitative and quantitative measures of infrastructure risk into a single risk index for quick identification of high risk infrastructure elements. One limitation of risk assessments in literature is subscribing risk to a single climate change scenario. This places heavy emphasis on selection of the Global Climate Model (GCM) and emissions scenario. Alternatively, this research considers multiple climate scenarios for risk assessment analyses that represent the lower and upper bounds for a range of future possible climate scenarios. The purpose of this range is to identify many possible impacts that climate change may bring and expand analysis to be widely applicable. If desirable, decision makers can use the range to select acceptable level of risk and consequences. In this research, quantitative assessment considers economic value and impact multipliers to describe potential consequences to municipal infrastructure caused by flooding. Qualitative approach includes application of fuzzy set theory and involvement of municipal stakeholders to describe the condition of infrastructure elements and ways that condition affects flood response. Stakeholder involvement in the risk assessment process is an important contribution to this research. The input of various stakeholder preferences and perspectives illustrate elements of risk not captured by quantitative analysis alone. Stakeholder involvement is also important for the development of adaptation strategies and policy implementation. By involving municipal politicians and experts in the risk assessment process, they become more familiar and comfortable with its use. Also, stakeholders have the opportunity to express opinions and concerns that are used to help refine the risk assessment process. However, infrastructure risk should not be the only consideration in developing climate change policies or emergency planning. Hence, this research considers integration of infrastructure risk with social and environmental factors to determine effects on prioritization of risk areas.

The developed methodology is applied to a case study for the City of London, Ontario, for municipal infrastructure including: critical facilities (hospitals, schools, fire stations, ambulance stations), barriers (dykes), pollution control plants, buildings (residential, commercial, industrial, institutional), roads (arterial, primary) and bridges (vehicle, pedestrian, culverts). In the case study, risk assessment is carried out for two climate scenarios (derived from Global Climate Models) which represent lower and upper bounds of a range of possible future climates in the Upper Thames River Basin. These scenarios are developed for both the 100 and 250 year return periods (regulatory floodplains) for a total of five climate change scenarios (100 CC_LB, 100 CC_UB, 250 CC_LB and 250 CC_UB and 250 UTRCA). The current regulatory floodplain developed by the Upper Thames River Conservation Authority (UTRCA) is considered as an additional scenario that represents historical climate conditions. This particular scenario is used for comparison with simulation results to assess the direct contributions of climate change. To provide support for multiple types of stakeholders, risk assessment results are summarized both numerically in tables and spatially in maps. Results may be used to prioritize risk for efficient decision making, land use planning and in the development of effective municipal climate change adaptation strategies.

1.3 Organization of Thesis

The following chapters focus on the procedure for developing a methodology to assess infrastructure, environmental and social risk as a response to climate change. Relevant climate change and risk assessment literature is reviewed and put into the context of the research presented in the thesis. Then a risk methodology combining qualitative and quantitative data is explained using fuzzy set theory. Following this, a case study is presented that applies the risk assessment methodology to the City of London, Ontario, Canada under flood conditions driven by the impact of climate change. Two climate change scenarios and two regulatory return periods are considered in this case study to represent potential future climate impact. In addition, the floodplain that represents current 250 year floodplain regulation is considered as an additional scenario in comparison analyses to estimate the contributions of climate change. In total, five scenarios (expressed in the form of floodplains) are considered in the case study risk analyses. Key areas of high risk are identified within the City and a discussion of these regions is provided. A multi-objective tool is used to prioritize climate change risks and impacts of flooding on social and environmental vulnerabilities are also briefly discussed. Conclusions of the risk assessment for London are presented and recommendations are made to address and accommodate for climate change at the municipal level.

CHAPTER 2

LITERATURE REVIEW

A review of literature relevant to climate change and risk assessment methodologies is presented as it pertains to the research in this thesis. The review is intended to provide a succinct overview of climate change impacts on the global, national and regional scales and discusses disaster-related risk assessment approaches for mitigation and adaptation to climate change effects.

2.1 Climate Change

It is generally accepted that the climate is changing. Climate change impacts are affecting national policies, social activities, health, economics, cultural practices and the built environment. The Intergovernmental Panel on Climate Change (IPCC) is an internationally recognized body established by United Nations Environment Programme and World Meteorological Organization to provide current state and knowledge on climate change science and potential impacts. A recent report released by IPCC in 2007 states,

> *"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level."*

Climate change occurs over a long period of time and can be attributed to both natural and anthropogenic activities (IPCC, 2007). However, *"Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations"*

There is continued evidence that Greenhouse Gas (GHG) concentrations in the atmosphere will continue to grow in the future (IPCC, 2007). At present, even if GHG emissions were eliminated, the climate would continue to warm for many decades. Increasing global temperatures are expected to continue with greatest effects anticipated to occur in high latitudes at the North and South Poles (CCIAD, 2010). The longer this reduction takes, the longer it will take to stabilize or reduce climate warming (ICLR, 2010). Climate change may have devastating impacts on water resources, agriculture, forestry, fisheries, coastal zones, transportation infrastructure, biological systems and human health and well-being (Government of Canada, 2004). Determining the point where climate change effects become irreversible is subject to much controversy and discussion.

National

It is estimated that Canada's annual mean temperature may increase anywhere from 5 to 10 degrees over the next century (ICLR, 2010). Warming to that degree would affect the seasons and cause widespread environmental destruction. Canada spans a large area and is diverse in its geology, topography and climate. Thus, the country is subject to various types of natural disasters (including earthquakes, floods, droughts, storms, tornados) and climate change effects which are not distributed equally across the country. Impacts of climate change are already apparent across Canada (Government of Canada, 2007).

Observed impacts to biological and physical systems across the country include: reduction in glacier ice extent, reduced snow cover, reduction in the duration of lake ice cover, permafrost warming, increased length of growing seasons and increased coastal erosion (Government of Canada, 2007). The coastal provinces of Canada can also expect sea level rise as a consequence of climate change (IPCC, 2001; 2007; ICLR, 2010).

Regional

In the Upper Thames River Basin, previous studies by (Cunderlik and Simonovic, 2005, 2007; Eum and Simonovic, 2009) suggest climate change may contribute to:

- Increase in precipitation amounts during the spring and fall seasons;
- Decrease in precipitation during winter months;
- Increase in frequency of severe precipitation events;
- Shift in seasonality of precipitation events;
- Increase in overall annual average temperature;
- Increase in minimum and maximum expected temperature extremes, where winter months from November to April are expected to warm faster than summer months May to October (consistent with IPCC findings); and
- Shift in snowmelt timing.

These changes have the potential to damage natural, physical and social systems in the basin.

Municipal stakeholders and decision makers are often interested in regional climate change responses on shorter time scale than global models provide. GCMs outputs are often insufficient to accurately represent climate changes on a local level. Global models tend to be too coarse of resolution (spatially) and are sometimes temporally incompatible with regional scales of interest (Cunderlik and Simonovic, 2005). To study the impacts of climate changes on a local level, downscaling techniques are often implemented to interpret GCM outputs (Cunderlik and Simonovic, 2007; Prodanovic and Simonovic, 2007). There are multiple ways in which this may be achieved. This research adopts the use of a Weather Generator (WG) to downscale output from GCMs and addresses the spatial and temporal uncertainties to generate climate scenarios used in the case study.

2.2 Climate Change and Water

Economics, social well-being and health are dependent on the quality and quantity of our natural resources, including water (Government of Canada, 2004). The climate system has many complexities and feedbacks between people, environment, biology, physical processes, psychology and economics (Simonovic, 2009). The interest of this research is specifically on the interaction between climate and hydrological processes.

Global

The frequency of severe flood events has increased significantly in the twentieth century (Milly et al., 2002). However, globally, climate change does not affect all regions the same way (IPCC, 2001; 2007). There is unequal distribution of precipitation and warming events which vary from region to region. Some areas may expect increases in rainfall amounts while other areas can anticipate an increase in severe droughts. In 2007, IPCC released a Technical Paper describing and analyzing links between climate change and the water sector. The paper emphasizes that the hydrologic cycle is closely linked to changes in the climate system including: atmospheric temperature, radiation balance, and GHG responses; it is also associated with trends of climate warming. As climate warms, the atmosphere has a greater capacity to store water, which increases the possibility of more extreme precipitation events (Kundzewicz, 2003). In general, climate change is effectively intensifying the global hydrologic cycle and increasing widespread risk of flooding (Milly et al., 2002). IPCC (2007) studied precipitation records from 1900 to 2005 and reported that observed precipitation amounts significantly *increased* in Eastern, North and South America, Northern Europe and North and Central Asia. Precipitation was observed to *decrease* in parts of the Mediterranean, Southern Africa, and parts of South Asia. Climate models suggest an increased frequency in occurrence of extreme precipitation events - but not necessarily in overall average precipitation amounts - as a consequence of climate change (IPCC 2007; Gov. of Canada, 2007). Although frequency of high intensity precipitation events is expected to increase, average annual precipitation amounts in some of these areas has been actually observed to be decreasing (IPCC, 2007).

Climate change exacerbates extreme precipitation phenomena in regions already experiencing high incidence of floods and droughts. Flooding is considered to affect more people than any other natural disaster worldwide (SwissRe, 2010) and as population continues to increase in the 21st century, the demand for additional water puts pressure on the entire hydrologic system.

There are many global consequences of climate change, but most often climate change impacts and adaptation strategies are national and municipal-level responsibilities.

National

Projected effects of climate change on the Canadian water system as identified by Government of Canada, (2000) include:

- Warmer surface water temperatures (particularly in Southern Canada) and declines in stream flow during already low flow seasons;
- Decrease in ground water levels and groundwater quality;
- Greater frequency of high intensity precipitation events which would increase the frequency of severe flood events;
- Decrease in average rainfall amounts but increased severe flood events in vulnerable river systems (e.g. Red River, Manitoba);
- Sea level rise posing flood and erosion threats to the coast (particularly Atlantic Canada);
- Permafrost warming; and
- Shifts in freeze/thaw, snowfall and seasonal cycles.

These changes have potential to dramatically affect biological, infrastructural physical processes and systems. The number of natural disasters from 1900 to 2002 is on the rise in Canada, mainly as a result of flooding (ICLR, 2010). Public Safety Canada (PSC) published a figure which shows historical trends of geophysical and weather related disasters in Canada (Figure 2.1).

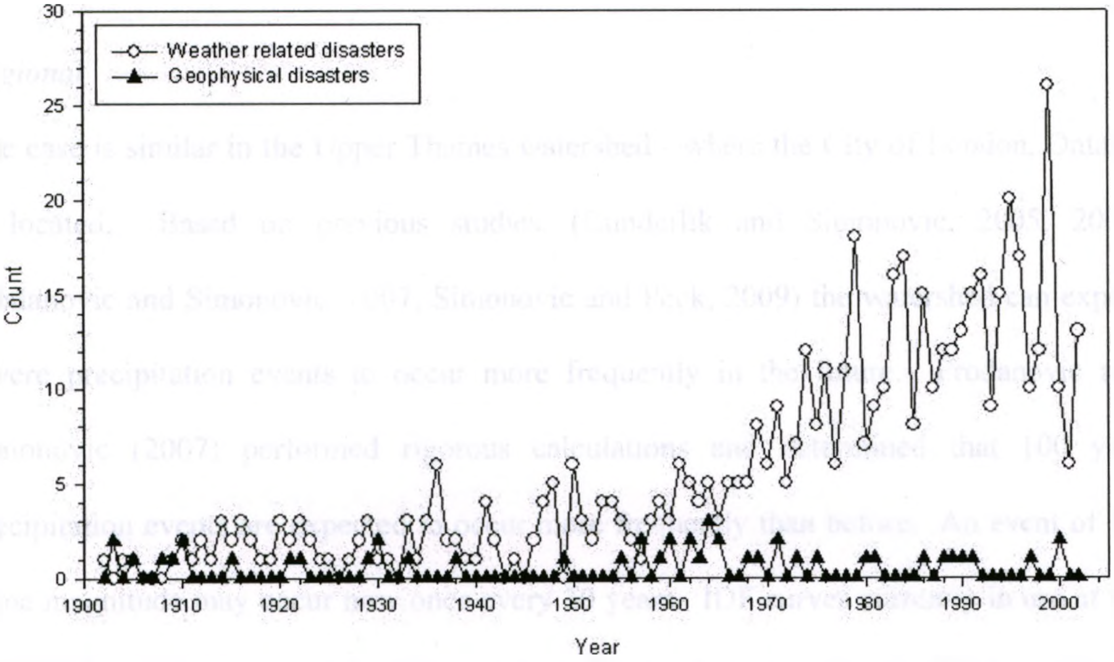


Figure 2.1: Trends in geophysical and weather related disasters (ICLR, 2010)

It appears that Canada is facing an increasing trend in weather-related disasters whereas geophysical disasters remain relatively constant for the country. It has been suggested that this increasing trend in weather-related disasters is related to climate change, however increasing development in the floodplains may also have contributed to this trend (ICLR, 2010). In Canada, flooding may be caused by any number of hydrological events including snowmelt, rainfall, rain on snow, ice jams, hurricanes, tornados and storms (ICLR, 2010). Climate change also affects the seasonality of rainfall patterns and localized flooding. These climate changes alter the spatial distribution of risk. Areas presently considered low or very low risk may experience a significant increase in risk as a consequence of climate change. These areas in particular may not be prepared to handle impacts of increased extreme events. The purpose of the proposed research is to identify these high risk areas to better prepare for potential climate change impacts.

Regional

The case is similar in the Upper Thames watershed - where the City of London, Ontario is located. Based on previous studies, (Cunderlik and Simonovic, 2005, 2007; Prodanovic and Simonovic, 2007; Simonovic and Peck, 2009) the watershed can expect severe precipitation events to occur more frequently in the future. Prodanovic and Simonovic (2007) performed rigorous calculations and determined that 100 year precipitation events are expected to occur more frequently than before. An event of the same magnitude may occur now once every 30 years. IDF curves currently in use at the City of London are based on datasets that are no longer available (Prodanovic and Simonovic, 2007). At the municipal level, climate change demands a review of current floodplain regulations, practices and management. Current storm sewer infrastructure may be exceeding its design capacity under new loads imposed by the climate. To reduce adverse effects of climate change and to prevent underperformance of critical infrastructure systems, it is necessary for stakeholders to understand potential climate change effects and develop adaptation strategies (Prodanovic and Simonovic, 2007). Regional risk assessment can help target particular locations and flag infrastructure for further climate change impacts research. Narrowing the spectra of locations and infrastructure can direct climate change adaptation efforts and finances in the appropriate direction.

In addition to climate change effects, land use changes and urbanization often reduce available water storage capacity further contributing to flood effects (Kundzewicz, 2003).

2.3 Climate Change Interactions with Infrastructure

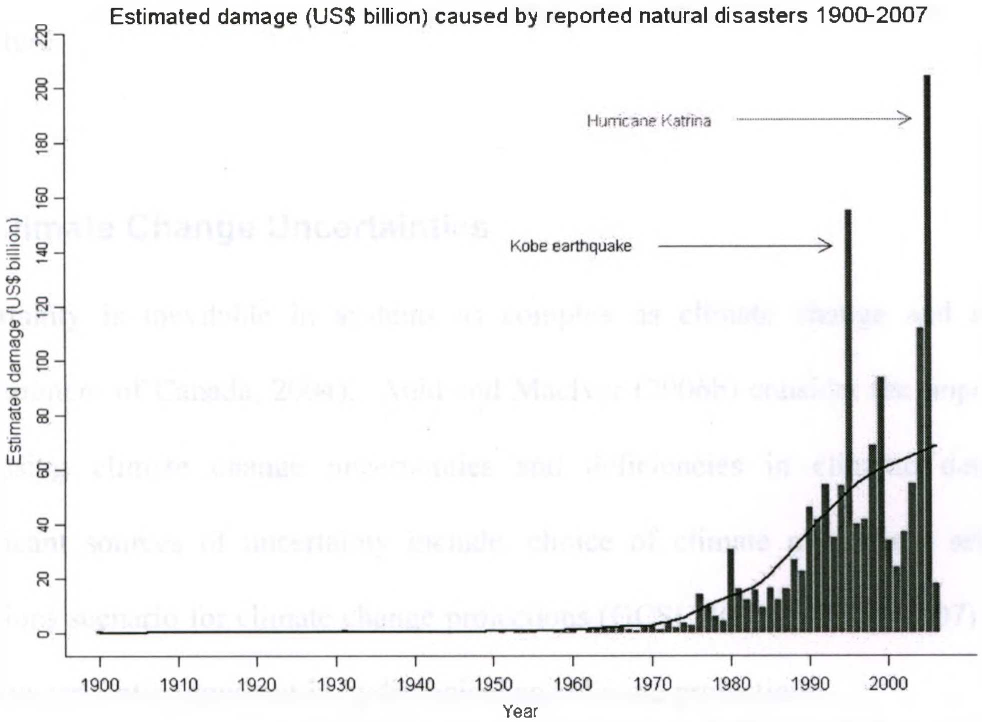
Infrastructure is currently designed to codes and standards developed many years ago according to historical climatic data under the assumption that this data reflects current and future weather patterns. With changes in weather patterns as well as increasing variability of extreme weather events, these assumptions no longer hold true. In many regions, as weather patterns change and the frequency of extreme events increases (IPCC, 2007), it is likely that the risk of infrastructure failure also increases (Auld and MacIver, 2006b). Society relies on the safety and integrity of infrastructure on a daily basis. Communities depend on infrastructure for shelter, work, access, emergency and culture. It is therefore important to understand the risks and consequences to municipal infrastructure under changing climatic conditions.

Auld and MacIver (2006) have a two paper series which discuss the impacts of climate change on municipal infrastructure and address the need to consider adaptation strategies to mitigate the consequences of extreme climate events.

Auld and MacIver (2006a) discuss the potential for extreme climate events to become natural disasters; disrupting local economy, safety, health and damaging infrastructure. The paper looks at global weather trends and climate extremes, their impact on infrastructure and considers potential strategies for prioritization of impacts in an attempt to mitigate the consequences. Suggestions include regular monitoring of weather on regional scales and updating design values to reflect the locally observed changes using the most current available data. The paper uses the ice storm of 1998 as an example to describe a forensic investigation of widespread consequences to both Canada and the United States from natural disasters.

Even a small increase in extreme events and climate variability can result in a great damage to municipal infrastructure (Freeman and Warner, 2001; ICLR, 2010). Auld and MacIver (2006) and National Flood Insurance Program (NFIP) of USA suggest, more specifically, that small changes in flood levels cause significant increases in flood damages in the magnitude of tens of thousands of dollars. Small changes compound and infrastructure networks are no longer able to handle increased loads. Floods in particular are considered to negatively impact municipal infrastructure including underground systems such as: water supply pipes, buried tanks, and pump equipment (Freeman and Warner, 2001).

An increase in cost of natural disaster losses has increased globally nearly ten-fold from the 1950's to 2004 as seen in Figure 2.2. Some of these losses can be attributed to increases in global wealth, population, reliance on material goods and services, development in high-risk locations and aging infrastructure (Freeman and Warner, 2001; Auld et al., 2006; Simonovic, 2011). Infrastructure quality of construction and material composition are two factors which cause variability in an infrastructures response to flooding and consequent damages sustained (Auld and MacIver 2006). Thus, damages can fluctuate greatly between countries as a result of differing construction practices.



EM-DAT: The OFDA/CRED International Disaster Database - www.emdat.be - Université Catholique de Louvain, Brussels - Belgium

Figure 2.2: Trends in losses from 1900's to 2007 caused by reported natural disasters (ICLR, 2010)

Auld and MacIver (2006) urge a "no regrets" adaptation approach to implementing climate change into practice. This may include updating codes, standards and design, land use planning, or regular infrastructure maintenance; those actions that serve to benefit a community as climate change occurs, even if the changes are not human-caused (IPCC, 2001). An adaptive learning approach is required to address activities that are outside of the coping capabilities of infrastructure to reduce climate change impacts and improve resiliency of the community. SwissRe (1998) and Auld and MacIver (2006b) recommend undertaking of more risk assessments by capable institutions to identify risky areas and develop a priori of adaptation actions for regions and their critical infrastructure with the intent of building the capacity of a community to respond to climate change in the future.

2.4 Climate Change Uncertainties

Uncertainty is inevitable in systems as complex as climate change and adaptation (Government of Canada, 2004). Auld and MacIver (2006b) consider the importance of addressing climate change uncertainties and deficiencies in climatic data. Two significant sources of uncertainty include: choice of climate model and selection of emissions scenario for climate change projections (GCSI, 2000). IPCC (2007) identifies a few uncertainties apparent in hydrological and climate projections.

To address some of the inherent uncertainty in selecting a particular climate emissions scenario, this research considers two different emissions scenarios. The purpose of selecting two scenarios is to identify the lower and upper bound to potential climate effects. These scenarios define a range for possible climate risk and impacts. This approach can provide insightful information into potential climate contributions and does not restrict analysis to a single climate change problem or solution (Simonovic, 2010).

A dynamic approach is beneficial to address climatic uncertainties. This requires an effort to regularly monitor climatic data and update calculations and climate models to use most recent and accurate climate data available. Regular monitoring and updating of data can be used to refine climate change models and continue to provide more accurate representation of climate change effects.

2.5 Risk Assessment Methodology

Institute of Catastrophic Loss Reduction (ICLR) (2010) provides a well-recognized definition of disasters as

> *...damaging event[s] that overwhelms the coping capacity of a community, such that it must seek outside aid in order to recover.*

It is the vulnerability of populations, infrastructure and property that determines the level of damage and loss during a natural disaster (ICLR, 2010). Risk, as mentioned in Kundzewicz (2003) and as considered in this research is considered the product of the probability of an extreme event occurring and its adverse consequences. Munich Re is one of the world's largest re-insurers of natural disasters. It is in their interest to assess regional risks to natural disasters, especially due to climate change, to determine insurance premiums. The Munich Re group defines geophysical and weather related risk as a combination of hazard, vulnerability and exposure. In flooding terms, hazard represents the probability of a flood occurring (Merz et al., 2007). This term does not convey the consequences as a result of such an event. Vulnerability and exposure are also considered important measures in addition to the hydraulic and hydrologic properties of the hazard and should be included in calculation of flood risk (Merz et al., 2007).

Evidence supports that areas facing economic difficulties are more vulnerable to climate change impacts (Freeman and Warner, 2001; IPCC, 2007). Risk assessment studies can be useful in indentifying these areas and preparing adaptation strategies and coordinating emergency preparedness measures.

Multiple climate scenarios can provide a broader perspective to risk assessment and flexibility to risk management. Effective flood hazard estimation requires at least the generation of inundation scenarios and hazard probability (Merz et al., 2007). However, methodologies which allow climate change scenario information to be incorporated into infrastructure design are rare (Auld and MacIver 2006b). The methodology presented in this thesis uses global climate model data incorporated with weather generator (WG), hydrologic and hydraulic modeling to produce climate scenarios and generate floodplains for use in municipal flood risk assessment. The purpose is for development of adaptation policy to address climate change impacts on infrastructure.

There are some risk assessment tools available to the public online including Hazards U.S. Multi-Hazard (HAZUS-MH) software program used by the United States Federal Emergency Management Agency (FEMA) to estimate potential losses from floods, hurricanes and earthquakes. HAZUS accesses a vast national inventory of GIS, numerical and statistical topographic, demographic and infrastructural data to estimate both riverine and coastal damages in the United States. Direct and indirect damages and losses to infrastructure and population are also assessed and the most recent model allows dam and levee analyses. Tools of this nature require large databases of spatial, statistical and numerical data to assess risk to a particular region; to the authors knowledge, most regions of Canada have insufficient data to warrant the use of such a comprehensive and specific risk assessment tool and such a tool is not nationally available.

England has Risk Assessment of flood and coastal defense systems for Strategic Planning (RASP) to develop and demonstrate methods for the performance of multiple flood defenses (or flood protection system) – as opposed to single defenses – to be used for national (England) flood risk monitoring. RASP provides estimates of flood risk contributed by each flood defense structure in the system and combines with socio-economic impact descriptors to calculate risk for each 1km by 1km impact zone. The assessment is based on work in part by Hall et al. (2005) related to a national-scale flood risk assessment for UK. The risk assessment is specific to the response of flood defense structures and does not consider widespread riverine flooding effects to municipal infrastructure in areas not protected by these structures.

The Environment Agency in England and Wales development of National Flood Risk Assessment (NaFRA) (2008) is currently one the most comprehensive methods of assessing risk based on annual expected flood damages, likelihood of flooding and location, type, condition and performance of flood defense systems in England and Wales.

Currently in Canada, there exists a shortfall between federal funds allocated for infrastructure investment and municipal maintenance requirements. Ontario Ministry of Public Infrastructure Renewal (2005) advocates that water systems infrastructure for province of Ontario alone demands an investment of over $35 million over the next 15 years. Thus, there is an interest to identify where the greatest threats may be to reduce losses, provide for effective emergency management, allocate resources and appropriate land use planning. In general, through consideration of available literature, it appears that the United States and European Union have much more comprehensive tools available and resources invested related to hazard risk assessment and damage analyses. Part of the discrepancy may be attributed to private and public insurance programs in countries whereas in Canada, floods are not considered an insurable risk.

2.6 Climate Change Caused Risk to Infrastructure

Population growth and economic development are driving an increase in construction of new infrastructure. Infrastructure management must consider recent climate changes and properly prepare for projected future climate and associated uncertainties. This is possible by applying climate change factors of safety in design (Auld and MacIver, 2006b), modifying codes, updating standards and retrofitting current infrastructure to accommodate new climate loads.

Infrastructure designed for longer return period extremes, such as hospitals, may be able to withstand increased loads while other structures built to lower return period standards incur greater damages (Auld and MacIver 2006b). Infrastructure will be constructed with different materials in the future and will need to be designed and constructed to withstand additional climate loads. Additional studies investigating the complex processes of weathering and time degradation to infrastructure would be economically beneficial and provide insight into appropriate adaptation strategies (Auld and MacIver 2006b).

The current research is inspired by Engineers Canada's PIEVC protocol. The protocol addresses qualitatively a very detailed low level fine resolution assessment of risk to individual infrastructure elements. While providing valuable information regarding components of infrastructure which are at risk, the studies do not provide a sufficient framework for a regional flood risk assessment. A drawback to implementing PIEVC protocol is the strict confidentiality agreement, qualitative nature of the assessment and requirement of very detailed, sensitive and specific data that requires a comprehensive database of accessible information.

2.7 Risk Reduction

The basis for effective flood damage reduction and mitigation measures is risk assessment displayed in a map which encompasses a broad spectrum of flood risk impacts including: hydrologic, hydraulic, economic, and social, among others (Merz et al., 2007). Risk mitigation measures are typically structural or non-structural in nature, or some combination of both (ICLR, 2010). Each of these methods has its own drawbacks. Structural measures have been criticized for providing residents with a false sense of security, encouraging development in flood prone areas and inadequate, expensive maintenance and monitoring programs (ICLR, 2010). Floodplain mapping and risk identification can be used to appropriately allocate resources in updating current infrastructure and be used to adjust development regulations. However, Merz et al. (2007) suggest that maps depicting hazard risk impacts and consequences are rare. Shrubsole et al. (1995) identify and discuss land-use regulation as a flood hazard mitigation approach in the city of London, Ontario. Emergency preparedness and organized response to a flood can also minimize damages.

Municipal governments face many challenges and barriers in implementing effective climate change policy and mitigation measures (Burch et al., 2010). At the municipal level, new councils are elected every three years which does not lend itself well to long term climate change planning and vision. Combined with strong desires to be elected, there are often conflicting priorities in climate change policy. Politicians should consider long term strategies in addition to short term goals to address the various time scales of climate change. New attitudes and values need to be established in relationship to climate change for effective policy development. It is pertinent (a) that stakeholders are able to relate to and (b) identify with climate change impacts and responses, to recognize the importance of related climate policy strategies and decisions (Burch et al., 2010).

Previous risk reduction measures placed an emphasis on reducing the rate at which climate is changing, whereas recent literature focuses on improving the resiliency of communities and developing climate change adaptation strategies (Rush, 2004; Government of Canada, 2007; ICLR, 2010). Crabbe and Robin (2006) consider water infrastructures community adaptation strategy and identify some of the challenges to adaptation strategy in a political context at various levels of Canadian government. Natural Resources Canada, Climate Change Impacts and Adaptation Division (CCIAD) released a new publication *Changing Climate, Changing Communities: Guide and Workbook for Municipal Climate Adaptation* (2010) which presents a five milestone approach to guide municipal climate adaptation plans. It is possible to cope with climate changes provided adequate preparations and adjustments are made (Government of Canada, 2004). It is generally recommended that a combination of mitigation and adaptation strategies be used in minimizing climate change impacts. The research presented in this thesis is intended to improve coping capability of municipalities by targeting areas of high climate change risk. It is a preliminary step to develop further climate change studies. The risk methodology contributes to climate change preparations at the municipal level.

Management of the Upper Thames River is generally the responsibility of the Upper Thames River Conservation Authority (UTRCA). However, provincial agencies have jurisdiction and control of surface and groundwater resource allocations in the watershed. The multijurisdictional nature of water resources management in the basin may complicate climate change adaptation strategies, delay mitigation efforts and reduce the effectiveness of water management unless there is organization and cooperation from all levels of government (Simonovic, 2011).

CHAPTER 3

OVERVIEW OF MODELING CLIMATE CHANGE IMPACTS ON MUNICIPAL INFRASTRUCTURE

Emergency Management Ontario provides guidelines to municipalities intended to protect public safety, health, property and promote disaster-resilient communities. These guidelines include identification of critical infrastructure and the development of: an approved emergency response plan, community emergency operations centre, and an emergency management public awareness program (City of London, 2010). The hazard and risk assessment and infrastructure identification section of the Emergency Management and Civil Protection Act mandates

> *In developing its emergency management program, every municipality shall identify and assess the various hazards and risks to public safety that could give rise to emergencies and identify the facilities and other elements of infrastructure that are at risk of being affected by emergencies. 2002, c. 14, s. 4.*

The objective of the proposed research is to identify these risks as they pertain to climate change-caused flooding, which has been identified as the most influential climate change hazard for the City of London. Historical infrastructure design and flood frequency analyses rely on the assumptions of climate stationary and homogeneity; the confidence in these assumptions is jeopardized as the climate is changing (Merz et al., 2007). This means current infrastructure is frequently designed under capacity, unable to compensate for, or cope with changes in the climate.

ICLR (2010) identifies snowmelt, extreme rainfall, precipitation (rain on snow), ice jams, dam failures, coastal storms and hurricanes as the causes of most flooding which occur in Canada. The most critical flooding occurs in conditions when the above events occur simultaneously in the same region. The focus of this research pertains only to the effects of riverine flooding on municipal infrastructure as a result of climate change. However, the same general approach to classifying climate change risk may be applied to additional types of flooding, or other natural hazards, where applicable. One of the significant advantages of the developed methodology is its generic nature; that is, its adaptability and applicability to many types of natural disasters which could occur at various locations. However, generic risk assessment methodology is effective only if it is made readily available, considered valuable from the perspective of each municipality and considered practically applicable; even if the information contained therein is scientifically accurate (Crabbe and Robin, 2006). In the case of the current work, individual municipalities are able to access the proposed methodology, assess its applicability, and apply it to their unique risk assessment situations.

The beginning of this chapter provides an overview of methodology developed for the entire City of London case study (Figure 3.1), including brief descriptions of the methods applied for the preparation of required input for flood risk assessment (Peck et al, 2010). The intent of the following sections is to provide the context for assessment and develop understanding of climate scenario selection and floodplain generation for use in flood risk analysis. Detailed presentation of these preprocessing steps is available in reports by Eum and Simonovic (2009) and Sredojevic and Simonovic (2009).

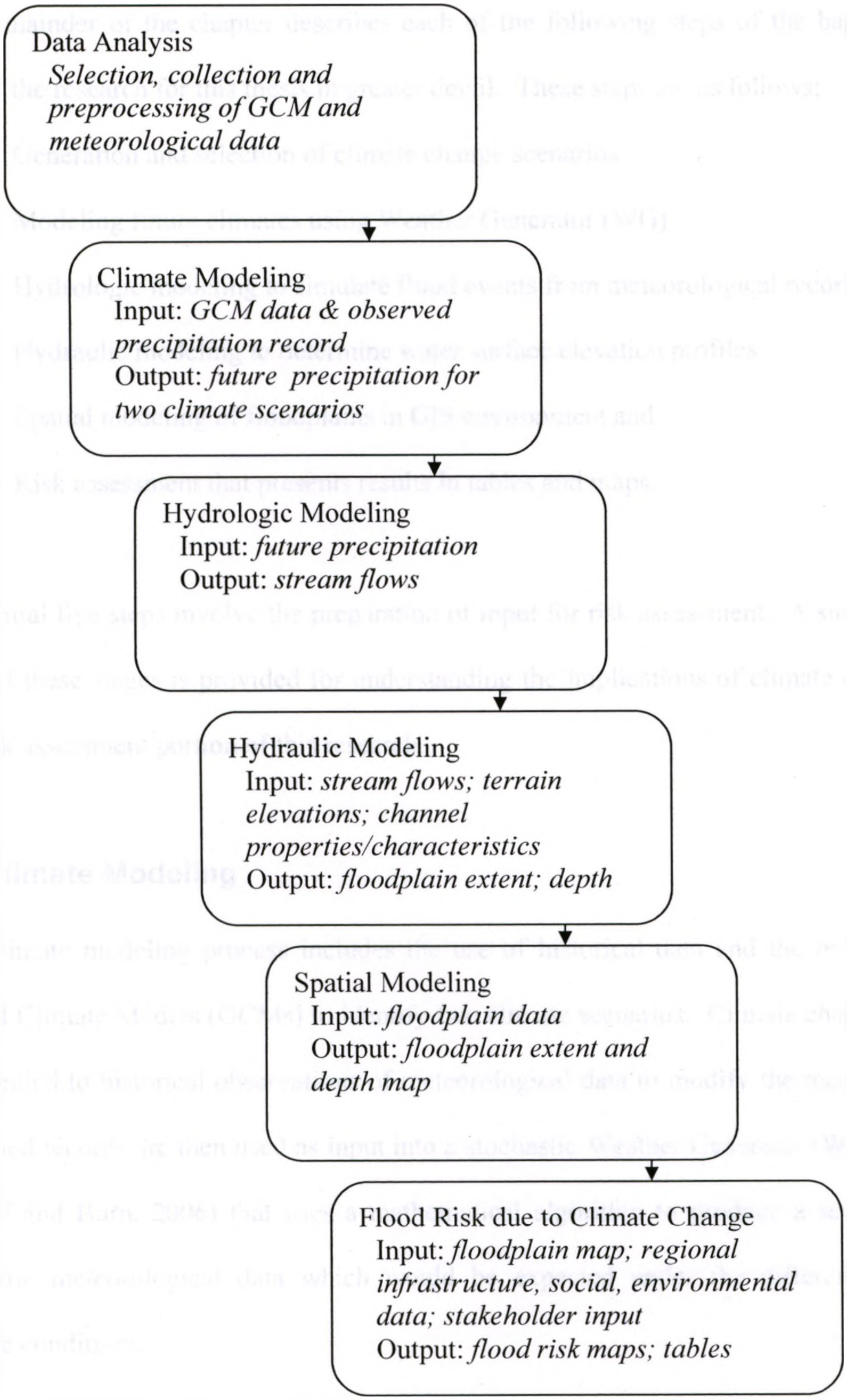


Figure 3.1: City of London flood risk assessment project overview

The remainder of the chapter describes each of the following steps of the background behind the research for this thesis in greater detail. These steps are as follows:

1) Generation and selection of climate change scenarios
2) Modeling future climates using Weather Generator (WG)
3) Hydrologic modeling to simulate flood events from meteorological records
4) Hydraulic modeling to determine water surface elevation profiles
5) Spatial modeling of floodplains in GIS environment and
6) Risk assessment that presents results in tables and maps.

The initial five steps involve the preparation of input for risk assessment. A summary of each of these stages is provided for understanding the implications of climate change to the risk assessment portion of this research.

3.1 Climate Modeling

The climate modeling process includes the use of historical data and the results from Global Climate Models (GCMs) to identify two climate scenarios. Climate change fields are applied to historical observations of meteorological data to modify the records. The modified records are then used as input into a stochastic Weather Generator (WG) model (Sharif and Burn, 2006) that uses a mathematical algorithm to produce a sequence of synthetic meteorological data which would be expected under the different climate change conditions.

Climate Change Scenarios

Climate change scenarios are estimations of possible future climatic conditions and are based on results of Global Climate Models (GCMs). GCMs mathematically represent physical processes and their relationships in the global climate system (IPCC, 2001). They have the ability to model climate system responses to changing greenhouse gas (GHG) concentrations and other climate-related factors. GCMs are coarse resolution 3D models, but are useful at the regional level when used in conjunction with regionally developed models derived using statistical downscaling methods (IPCC, 2001). For the current work, climate scenarios are derived from GCM output and used to modify historical precipitation records on a monthly time scale to account for shifting precipitation magnitudes and patterns under changing climate.

Based on the previous studies (Cunderlink and Simonovic, 2005, 2007; Simonovic, 2010) two climate scenarios were selected which best represent future possible climate in the Upper Thames River Basin. A wide range of GCM models were run and selection of scenarios was based on the fact the first scenario represents a lower bound of potential climate change impacts, and the second scenario an upper bound. The ***lower bound climate change*** **(CC_LB)** scenario is produced by shuffling and perturbing local historical climate data. The ***upper bound climate change*** **(CC_UB)** scenario is generated by applying climate change factors to the observed historical climate record to produce a modified record. A flow chart which illustrates the lower and upper bounds of potential climate change impacts is shown in Figure 3.2.

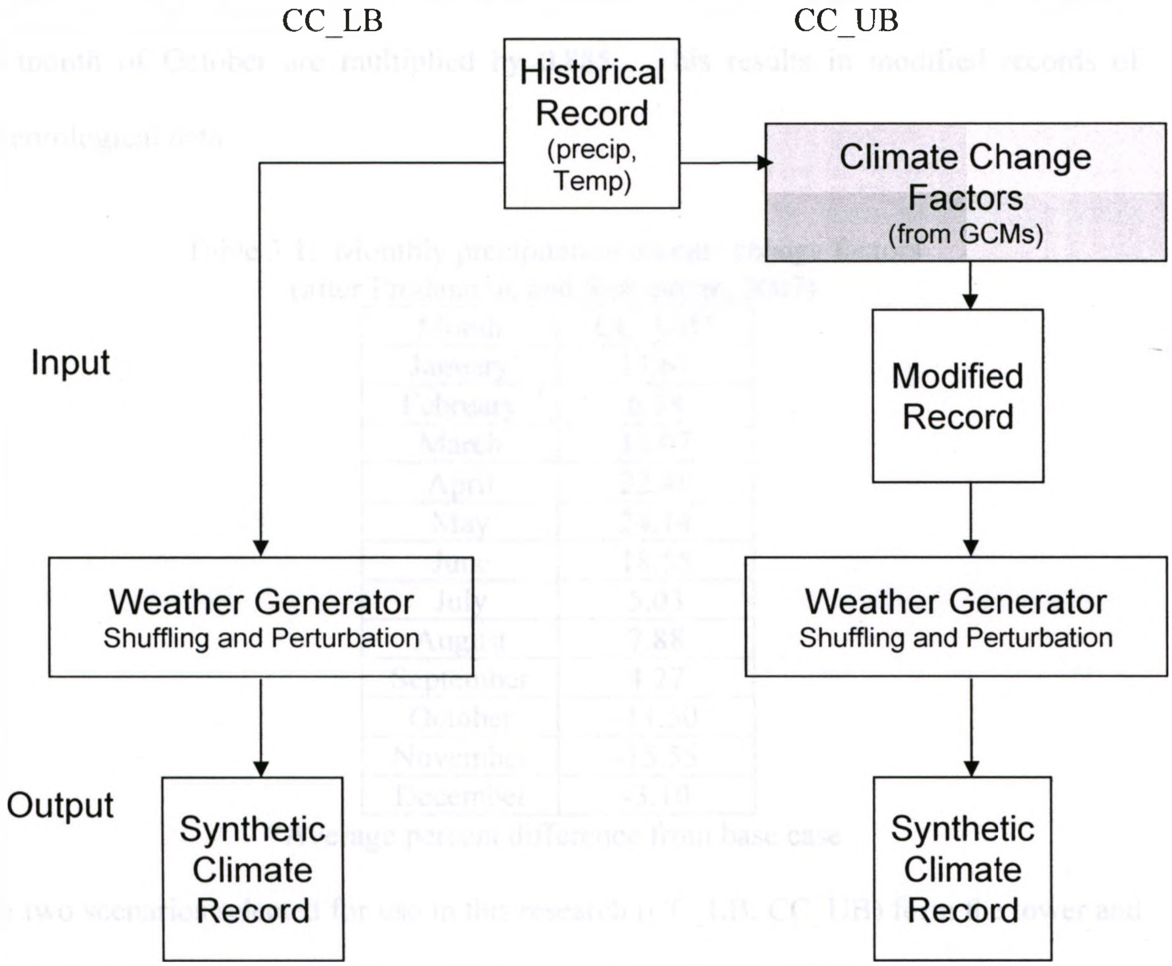


Figure 3.2: Process of generating two climate scenarios

GCM CCSRNIES B21 global model data is used to prepare the CC_UB scenario. This scenario represents a wetter climate that frequently leads to increased incidents of flooding. In the preprocessing stage, climate change factors (Table 3.1) are applied to the locally observed historical precipitation records before being input into the WG. For example, the climate change factor for CC_UB scenario for March is +15%. Therefore all precipitation values in the historical record for the month of March are multiplied by 1.15, representing a characteristically wetter climate. Negative percent difference indicates a month where precipitation is suggested to decrease. Similarly, if the climate change factor for October is -11.5%, then the historical monthly precipitation values for the month of October are multiplied by 0.885. This results in modified records of meteorological data.

Table 3.1: Monthly precipitation climate change factors
(after Prodanovic and Simonovic, 2007)

Month	CC_UB*
January	17.67
February	6.38
March	15.07
April	22.48
May	24.14
June	18.55
July	5.03
August	7.88
September	4.27
October	-11.50
November	-15.55
December	-3.10

*Average percent difference from base case

The two scenarios selected for use in this research (CC_LB; CC_UB) form the lower and upper bounds of a range of possible climate change impacts for the region; all of the climate scenarios within these bounds are equally likely to represent future climate (Eum and Simonovic, 2009). The CC_LB scenario represents future climate where GHG concentrations are reduced, development monitored and clean-practice policies implemented. The CC_UB scenario on the other hand, represents a potential future climate where GHG emissions continue to grow, combined with rapid urbanization and growth. The CC_UB scenario may be considered the most critical case for precipitation magnitude and frequency analyses (Prodanovic and Simonovic, 2007). It should be noted that climate change scenarios are not intended to predict the future (Hall, 2005). The scenarios function as future climate possibilities used in this research to better understand the range of potential climate change impacts. Modified meteorological records are used directly by the WG tool to synthesize climate for an arbitrary length of time.

Weather generators are stochastic simulation tools used to generate weather for future climate on a regional scale (IPCC, 2001). They are also known as downscaling tools A common drawback of most flood frequency analyses is they typically rely on short historical time series which are often insufficient to generate extreme weather events for scenarios of high return periods with much reliability (Merz et al., 2007). As noted by Prodanovic and Simonovic (2007), the use of short historical records to predict future climate may underestimate extreme climate events important in the design of infrastructure and risk assessment. To address this problem, the WG uses a perturbation mechanism and the results of global models (GCMs) to push climatic data outside the bounds observed in the historical data, resulting in the generation of extreme values not yet observed. This process is based on the assumption that shorter time series data does not capture all of the potential extreme possible events of the future (Prodanovic and Simonovic, 2007). The WG used in the case study has been successfully applied by Yates (2003) and Sharif and Burn (2006).

Weather Generators are classified as either parametric or non-parametric. Non-parametric WGs rely on sampling algorithms whereas parametric WGs use site specific parameters and assume probability distribution functions. Sharif and Burn (2006) identified a drawback of parametric WGs; they cannot reliably synthesize weather for long periods of extreme precipitation events (drought and floods). Therefore the case study presented in this thesis adopts a non-parametric K-Nearest Neighbour (K-NN) WG tool to downscale global impacts of climate change to the local level.

Historical records of meteorological data are modified using factors derived from GCMs to account for the effects of climate. These modified records are used as input into an adopted WG tool, which has the ability to shuffle daily data, perturb the data and generate weather for a specified length of time. This method prevents same-day replication of historical observations and pushes data outside the historically observed range using perturbation mechanism.

The WG is based on work originally developed by Yates et al. (2003) and a modified version by Sharif and Burn (2006). The WG adopted for the case study was a modification of Sharif and Burn (2006) done by Eum and Simonovic (2008). It incorporates Principle Component Analysis (WG-PCA) into the model to reduce computational burden. It uses 43 years of historical precipitation data (1946-2006) recorded at 15 stations in the Upper Thames River Basin (Figure 3.3) for three climate variables: precipitation, minimum temperatures, and maximum temperatures. Modifications are made to the historical data as described earlier using GCM climate change factors, which generates a modified record and simulates potential future weather.

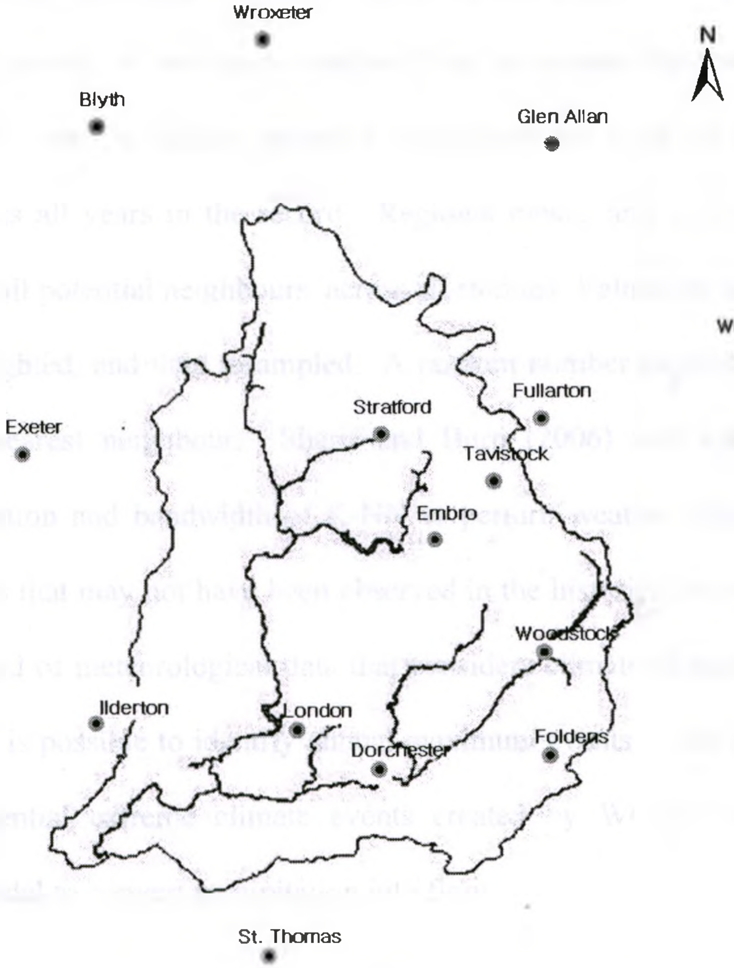


Figure 3.3: Location of 15 stations within and surrounding the Upper Thames River Basin considered in the case study

The WG requires a meteorological dataset free of missing values for the stations considered. Locally available datasets may be sparse for various reasons: disrupted instrument readings; malfunction of gauging equipment; or erroneous measurements from recording devices. As such, extensive preprocessing of the datasets is completed prior to use with the WG. The WG operates using the following procedure as described in Prodanovic and Simonovic, 2007; Eum and Simonovic 2009; Simonovic and Peck 2009. The WG starts by selecting the current day from the record and a search algorithm looks for other days in the record with similar statistical characteristics. From this set, WG calculates regional mean of meteorological variables across all stations for every day in the historic record. A two week window from the current day (but not including the current day) is used to define potential neighbours for each of the meteorological variables across all years in the record. Regional means and a covariance matrix are calculated for all potential neighbours, across all stations. Values are sorted from smallest to largest, weighted, and then resampled. A random number generator is used to aid in selection of nearest neighbour. Sharif and Burn (2006) also introduce conditional standard deviation and bandwidth of K-NN to perturb weather variables and generate extreme values that may not have been observed in the historical record. The result is a synthetic record of meteorological data that considers climate change effect. From this new record, it is possible to identify annual maximum events. The synthesized records of future potential extreme climate events created by WG are used as input into hydrologic model to convert precipitation into flow.

3.2 Hydrologic Modeling

US Army Corps of Engineers Hydrologic Engineering Centre Hydrologic Modeling System (HEC-HMS) is a widely recognized precipitation-runoff simulation program. The program has many successful applications in simulating precipitation-runoff for watersheds (USACE, 2008). HEC-HMS uses meteorological data as input and transforms it into an estimation of corresponding runoff. The program works by mathematically representing natural hydrological processes and then breaking them into smaller, more manageable pieces.

Event and continuous versions of HEC-HMS hydrologic model are available for use and both have been successfully developed for the Upper Thames watershed (Cunderlik and Simonovic, 2005, 2007). The event version of HEC-HMS is designed for use with single rainfall-runoff events and high flow analyses. It does not account for moisture recovery processes and is therefore not suitable for dry weather modeling. The emphasis of the event-driven model is on direct runoff whereas the continuous model considers both direct and indirect runoff. The continuous-driven version of HEC-HMS takes into account moisture recovery and losses between precipitation events and is well suited for long period low flow analyses.

An event-form of HEC-HMS uses the future precipitation produced by WG output to generate equivalent runoff and subsequent stream flows. The program requires input of hourly precipitation data; it was therefore necessary to disaggregate daily precipitation data generated by WG using the method of fragments (Svanidze, 1977). HEC-HMS uses the disaggregated precipitation data to simulate flood events at hourly intervals for the two climate scenarios (CC_LB; CC_UB). An event version of the model is adopted to simulate rainfall-runoff events and calculate corresponding stream flows. The City of London is divided into 72 sub-basins, 49 junctions, 45 reaches and 3 reservoirs for HEC-HMS modeling (Eum and Simonovic, 2009). The simulation results provide the essential hydrologic information for each sub-basin and each control point for two climate scenarios and a 200 years time horizon. Within the City of London 171 locations of interest are identified – mostly representing input profiles for the hydraulic analysis (Eum and Simonovic, 2009). Frequency analysis is used to relate the magnitude of extreme events to their frequency of occurrence. The results of the hydrologic analyses (using the HEC-HMS model) are used as input into the hydraulic model (HEC-RAS) that calculates extent and depth of flood inundation for two regulatory flood return periods, 100 and 250 years and two climate change scenarios. Flood frequency analysis of the hydrologic model output is conducted to provide the input for hydraulic analysis. The method of L-moments and Gumbel extreme event probability distributions are used (Eum and Simonovic, 2009). The hydrological model was calibrated using locally observed historical events to ensure accurate calculation of stream flows.

The output of hydrologic modeling is in the form of stream flow data for two climate scenarios (CC_LB; CC_UB) and two regulatory flood return periods (100- and 250-year). Stream flows are used as inputs into hydraulic modeling to develop floodplain maps, as discussed in the following section.

3.3 Hydraulic Modeling and Floodplain Mapping

Hydraulic modeling incorporates stream flow data produced from the hydrologic analysis with channel geometry, hydraulic structures data, digital terrain models and boundary conditions to generate water surface elevation profiles (floodplains) which are used for risk assessment purposes. This study uses Hydrologic Engineering Centre River Analysis System (HEC-RAS) software as a tool to calculate one-dimensional water surface calculations for steady or gradually varied flow in natural and constructed channels (USACE, 2002). A recent survey of water infrastructure (e.g. dams; bridges; …) and channel characteristics are required to assess flow characteristics, water-infrastructure impacts and accurately represent flood conditions in the river reach (Figure 3.4).

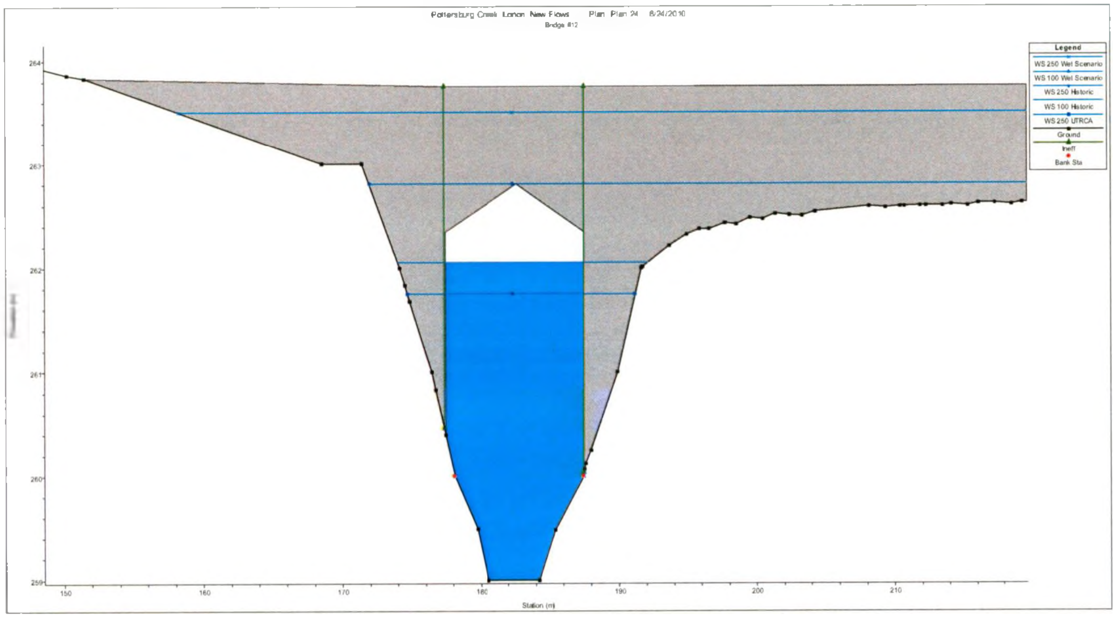


Figure 3.4: Sample bridge infrastructure from HEC-RAS program

The 100-year and 250-year regulatory floods are analyzed for both climate scenarios (CC_LB; CC_UB). Many municipalities prohibit development within the 100 year floodplain area, including the City of London as defined in the Conservation Authorities Act 97/04,

> *Subject to section 4, a regulation shall prohibit development in or on ... the 100 year flood level, plus allowance in meters, determined by the authority...*

Development in this restrictive area requires special permissions as granted by the authority. The 250 year floodplain represents a limited, but not entirely restricted area, whereby certain development is acceptable. For the City of London as set out in the Conservation Authorities Act 157/06, *The applicable flood event standard used to determine the maximum susceptibility to flooding of lands or areas within the watersheds in the area of jurisdiction of the Authority is the observed 1937 flood event...*

One more scenario representing current conditions is considered in addition to four climate scenarios (the two climate change scenarios for two return periods). The current scenario – named historic flood event - corresponds to roughly a 1:250 year return period flow for the City of London. Manually delineated maps of this floodplain are available at local Conservation Authorities – the Upper Thames River Conservation Authority.

The water surface profiles generated in HEC-RAS are exported and processed spatially in GIS using HEC-GeoRAS software; this provides a link between HEC-RAS output and geospatial location. The depth of water for each grid cell location is calculated by intersecting the water surface profile with regional topography represented by Digital Elevation Model (DEM) (Figure 3.5) to produce maps of both spatial extent and inundation level (Figure 3.6). These maps are used as input into risk assessment procedure.

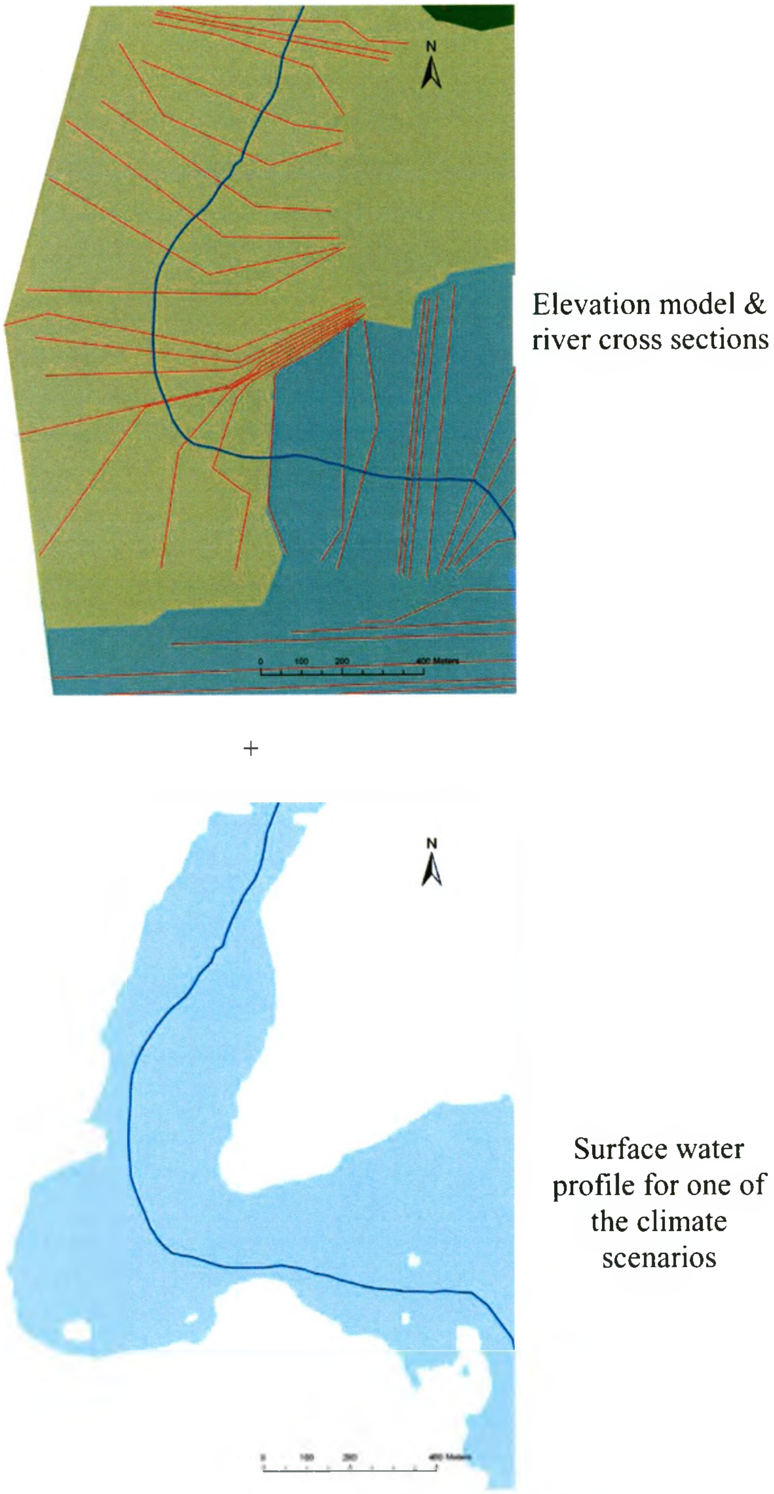


Figure 3.5: Combining elevation and cross sectional data with water surface profile in GIS

Figure 3.6: Product of combining two maps as shown in Figure 3.5; map of 100 year CC_LB floodplain inundation levels in GIS combined with an aerial photograph near the University of Western Ontario

The summary of the hydraulic modeling results is presented in Table 3.2. It is clear that the change in climate scenarios result in significant increase in flooded area.

Table 3.2: Comparison of flooded areas for two climate scenarios

River/Creek	**Flooded area (m^2)**					
	100-Year Return Period			250-Year Return Period		
	CC_LB	CC_UB	Difference	CC_LB	CC_UB	Difference
Main Thames River	2,717,208	3,228,637	511,429	3,189,657	3,342,766	153,109
North Thames River	4,951,784	6,327,229	1,375,445	6,144,150	6,497,384	353,234
South Thames River	2,676,651	2,885,980	209,329	2,886,324	3,128,588	242,264
Medway Creek	1,143,686	1,170,080	26,394	1,219,177	1,242,106	22,929
Stoney Creek	974,141	1,008,950	34,809	1,030,558	1,104,061	73,503
Pottersburg Creek	2,853,112	3,063,310	210,198	3,069,149	3,283,552	214,403
Mud Creek	72,339	123,697	51,358	124,241	226,260	102,019
Dingman Creek	7,750,220	8,011,897	261,677	8,302,463	9,061,872	759,409
Total	**23,139,141**	**25,819,780**	**2,680,639**	**25,965,719**	**27,886,589**	**1,920,870**

For a more detailed description of hydraulic analysis procedure, geo-referencing and geospatial representation refer to Sredojevic and Simonovic (2009) and Sredojevic (2010).

3.4 Risk Assessment

The proposed risk assessment methodology incorporates the floodplain maps produced from hydraulic modeling to assess climate change caused flood impacts on the municipal infrastructure within the City of London. The assessment is data intensive and driven by the quality, reliability and robustness of the available data. Nevertheless, the methodology provides a framework for risk assessment and useful input into climate change adaptation policy development. Flood plain maps and flood risk assessment results provide for: (a) climate change adaptation policy, (b) increase of public awareness, (c) encourage floodplain land use planning, and (d) help prioritize emergency response efforts and facilitate decision making. The following chapters provide details related to risk assessment methodology and its application to the City of London.

CHAPTER 4

CLIMATE CHANGE CAUSED FLOOD RISK ASSESSMENT METHODOLOGY

Flood hazard may occur anywhere, but riverine flooding is especially prevalent in low-lying areas close to watercourses and downstream from dams (FEMA, 2010). The Thames River and the protection provided from Fanshawe Dam means the City of London fit these criteria. The risk assessment methodology proposed in this thesis only considers riverine flooding. To determine the effects of localized flooding (e.g. basement flooding; sewer backup to manhole outlets) would require very detailed hydrologic and hydraulic modeling that is not within the scope of this thesis.

Risk Assessment Procedure

In general, the risk assessment procedure is demonstrated in Figure 4.1 similar to procedure in the generally accepted way of calculating annual expected flood losses. Flow-frequency (Figure 4.1; Graph 1) is provided in this research through hydrologic analysis; flow-stage (Figure 4.1; Graph 2) is provided by hydraulic analysis; stage-damage (Figure 4.1; Graph 3) data is provided by local studies and interviews with technical experts. Combining curves (1) and (2) provides the stage-frequency curve (Figure 4.1; Graph 4) which is represented in this research as floodplains generated through hydraulic analysis. Combing curves (4) and (3) provides the frequency-damage curve (Figure 4.1; Graph 5) and information related to infrastructure risk and expected losses.

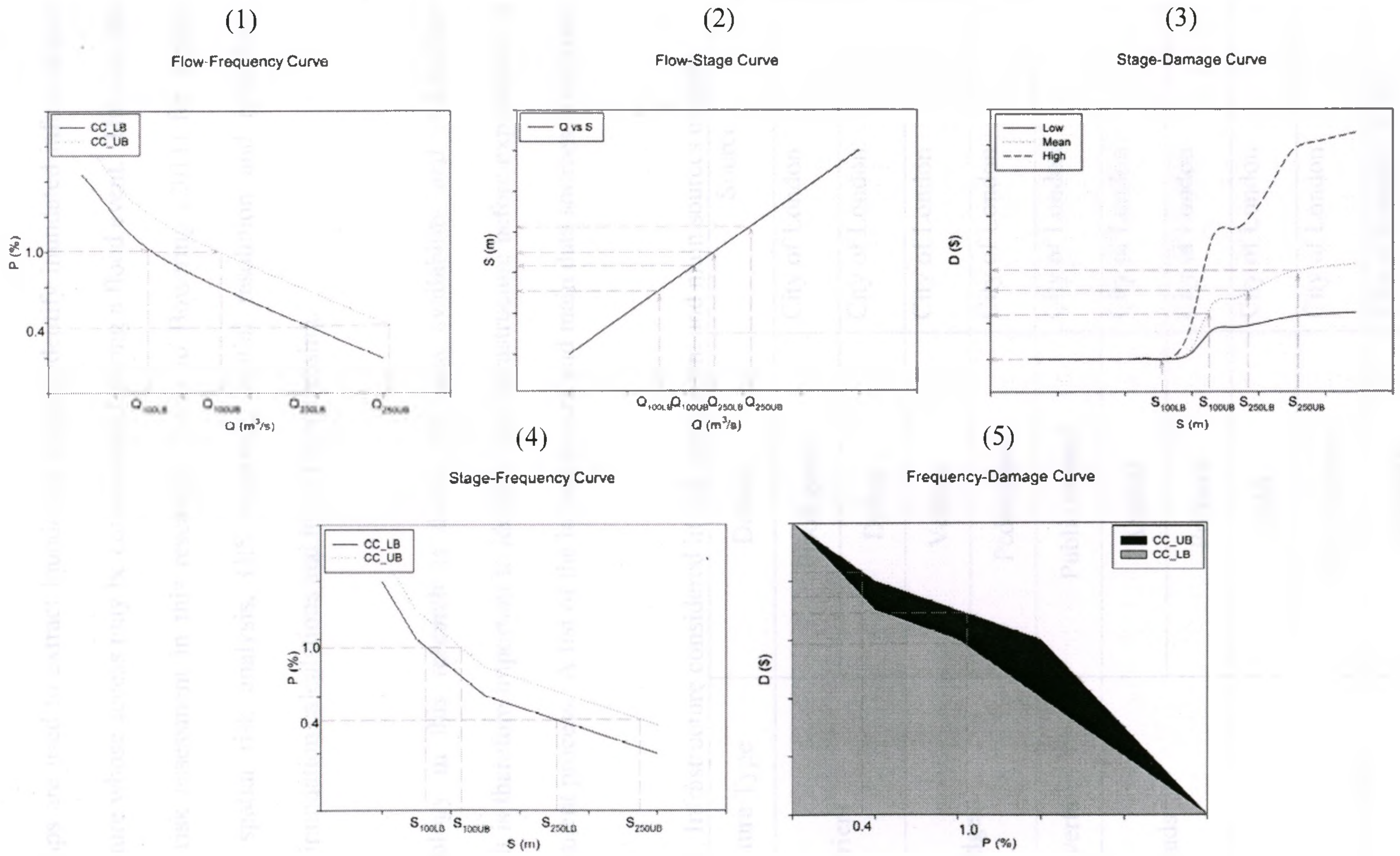


Figure 4.1: Graphical representation of the risk assessment procedure

Floodplain maps are used to extract inundation depths, identify inundated infrastructure and infrastructure whose access may be compromised during a flood event. They are the basis for the risk assessment in this research. Refer to Bowering (2011) for details pertaining to spatial risk analysis, GIS mapping, spatial resolution and reliability, infrastructure inundation calculations and input preprocessing.

Risk methodology in this research is driven by data availability and stakeholder preferences. It is therefore important to identify this infrastructure before explanation of the risk assessment process. A list of the infrastructure and main data sources is included in Table 4.1.

Table 4.1: Infrastructure considered in risk assessment and main sources of data

Infrastructure Type	Details	Source
Barriers	Flood gates	City of London
	Dykes	City of London
Bridges	Vehicle	City of London
	Pedestrian	City of London
Culverts	Public owned	City of London
Roads	Arterial	City of London
	Primary	City of London
Critical Facilities	EMS	City of London
	Fire Stations	City of London
	Hospitals	City of London; LHS
	Schools	City of London

Water Treatment	Pollution Control Plants	City of London
Non-critical Structures	Commercial	City of London; MPAC
	Industrial	City of London; MPAC
	Institutional (not incl. schools)	City of London; MPAC
	Residential	City of London; MPAC

The infrastructure was selected through an iterative interviewing process with politicians and technical experts from the City of London. The general risk methodology to be presented is developed in relation to these infrastructure, but is flexible and may be adapted to include additional infrastructure where appropriate.

4.1 Risk Index

One of the main contributions of this thesis is the introduction of an original risk measure, the risk index (RI). This index is calculated for each flooded infrastructure element (each individual piece of infrastructure; for example, Bridge A) and incorporates quantitative and qualitative data to address both objective and subjective types of uncertainty. Impacts of flooding vary and may be direct or indirect, and include losses ranging from inconvenience to structural damage to loss of life. The proposed risk index captures various consequences and damages to infrastructure as a result of flooding. Mathematical expression of risk in general terms:

$$Risk = Probability\ of\ hazard \times Consequence \tag{4.1}$$

Consequence is considered to be comprised of a variable pertaining to the economic value of an infrastructure and the damage impact a disaster may cause. Thus, a more descriptive calculation of the risk index is:

$$Risk\ Index = Probability\ of\ hazard \times \Sigma(Economic\ Value \times Impact\ Multiplier) \quad (4.2)$$

Or general form of risk index in mathematical notation:

$$RI = P \times \Sigma(EV \times IM) \quad (4.3)$$

Where,

RI is risk index for each infrastructure element

P is probability of hazard occurring in any given year

EV is the economic value associated with consequences

IM is the impact multiplier associated with level of consequence

Impact multiplier variable, IM is based on potential consequences occurring as a result of an infrastructure being flooded. It is calculated based on three main consequences, t that are associated with a natural disaster:

IM_t Impact a natural disaster may have on infrastructure

IM_1 Impact on infrastructure's ability to function;

IM_2 Impact on infrastructure's equipment; and

IM_3 Impact on infrastructure's structural components.

More discussion pertaining to these multipliers is provided later in this chapter. Similarly, economic value EV is based on potential economic losses incurred as a result of an infrastructure being flooded. Each consequence may have an associated economic impact. Therefore the economic values (EV) are represented as three variables related to the aforementioned consequences (IM):

EV_t	Economic value related to the three main consequences of natural disaster
EV_1	Monetary value related to infrastructures ability to function;
EV_2	Monetary value related to infrastructures equipment; and
EV_3	Monetary value related to infrastructures structural components.

Risk index, RI is calculated for each infrastructure element, e in the risk assessment based on maximum inundation depth from a particular climate change scenario, s. This research considers four climate change scenarios plus an additional scenario to represent current state as follows:

$s = 1$ Climate change scenario one (100 CC_LB)

$s = 2$ Climate change scenario two (100 CC_UB)

$s = 3$ Climate change scenario three (250 CC_LB)

$s = 4$ Climate change scenario four (250 CC_UB)

$s = 5$ Climate scenario five (250 UTRCA)

Therefore the calculation of risk index, RI for a particular element under a given scenario can be described by the equation:

$$(RI_e)_s = P_s \times \sum_{t=1}^{3}(EV_t \times IM_t)_s \tag{4.4}$$

Risk indices are combined for all infrastructures elements, e within a specific area and results are displayed spatially using GIS in the form of risk maps. Risk index is used to prioritize areas of high infrastructure risk. Equation 4.5 shows risk as it relates to a specific area, q, for all infrastructure elements of interest.

$$\left(RI_q\right)_s = \left(\sum_{e=1}^{m} R_e\right)_{q_s} \tag{4.5}$$

Where,

RI_q is risk for a particular spatial unit of area

q is a defined unit of area;

s is particular climate scenario;

e is the infrastructure element in consideration; and

m is the total number of infrastructure elements in area, q

The following sections describe in greater detail the components of RI.

4.2 Probability of flood hazard

In this research the probability variable is the likelihood of a flood hazard occurring in any particular year. This value is independent of infrastructure type, as it pertains to the physical flood hazard. In this research it is related to the return period (RP) of an extreme flow event. Precipitation events of a particular RP are represented by floodplains. Floodplains delineate the spatial extent of a specific precipitation event by connecting points in space that are exposed to the hazard of the same RP. These points are driven by local topography and physical, hydraulic, climate and river characteristics. Probability is represented by the following equation:

$$P_s = \frac{1}{RP} \tag{4.6}$$

Where,

P is probability of hazard occurring in any given year

s is the climate change scenario of interest

RP is the return period of hazard event

For a 100 year flood event the exceedence probability P, of occurrence in any given year is 1 in 100 (or 1%). Similarly, P for the 250 year flood in any given year is 1 in 250 (or 0.4%).

4.3 Impact Multipliers

Infrastructure response is different during and after a flood event. Infrastructure type, style, state and construction quality all affect the impact a flood event has on an infrastructure element (Auld and MacIver, 2006). The second part of the risk equation represents the consequence of flood hazard, or the interaction between the flood impact and infrastructure response. Three variables (IM_1, IM_2, IM_3) are considered to describe these consequences, keeping in mind the focus of this research is only on those consequences affecting municipal infrastructure.

The loss of function (IM_1), loss of equipment (IM_2) and loss of structure (IM_3) impact multipliers are measured as percent loss [0,100%] and calculated using both quantitative and qualitative data. They are incorporated into the risk index as demonstrated by expanding equation (4.3) to:

$$(R_e)_s = P_s \times (EV_{1e} \times IM_{1e} + EV_{2e} \times IM_{2e} + EV_{3e} \times IM_{3e})_s \tag{4.7}$$

Refer to Table 4.2 for some of the many factors that may affect infrastructure response (and consequent damage) to flooding. Various modes of failure that an infrastructure element may experience are a function of inundation depth and duration. This research does not explicitly focus on those failures related to duration of exposure (or progressive failures), however it is important to understand these failures could increase the rate at which an infrastructure may deteriorate in the event of a flood. Quantitative data includes estimates of an infrastructures' ability to withstand direct damages caused by flooding and additional consequences related to inundation depth. The qualitative data includes information gathered through interviews relating to the decision makers' expertise and experience. This data provides more detailed input into the condition of the infrastructure and how it may affect its response to flooding. Inundation depth is extracted using GIS tools to obtain information such as the length, depth and area (if appropriate) of inundation. The specifics of each impact multiplier are described below. It is important to note that the measure of the impact multiplier may be different across infrastructure types; however they are consistent within any one particular infrastructure type.

Loss of Function (IM_l)

Loss of function impact multiplier, IM_l is designed to capture the ability of infrastructure to function under various flooding conditions. Infrastructure serves various purposes in the community: transportation infrastructure is designed to provide safe travel routes from one location to another; barriers to protect people and property ; buildings to provide safe shelter; pollution control plants (PCPs) to treat raw sewage; and critical facilities to provide essential emergency services. There are consequences/impacts associated with infrastructure if it loses its functionality.

The variable IM_l can take the value [0, 1]; where 0 represents complete functionality and a value of 1 represents entire loss of function. In this research, transportation, buildings and flood protection infrastructure are considered to have IM_l equal to 1 once they are inundated. Buildings and critical facilities are assigned an IM_l of 1 if they are inundated or if all access to the structure is cut off. Flood protection structures (dykes) have an IM_l value of 1 once their design capacity has been reached.

Some infrastructure types can function at partial capacity during a flood event - some functionality of the infrastructure may be preserved even when it is inundated. Partial loss of function may include limited access to an essential building and interrupted service. For example in the case of critical infrastructure, partial loss of function occurs when some, but not all, of the access routes to fire stations, emergency management services (EMS), hospitals and schools loose are blocked by floodwaters. The directionality of access describes the nature of the infrastructure. For example, firefighters and EMS have vehicles and personnel leaving the location to service an emergency, whereas schools (serving as emergency shelters) and hospitals receive people in the case of an emergency. The ability of each to provide services is the determining factor in calculation of IM_I.

Table 4.2: Infrastructure type, function and impact multipliers – explained

Infrastructure	Function	Loss of Function	Loss of Equipment	Loss of Structure/ Possible Modes of Failure
Barriers – Dykes	Provide protection to structures immediately behind dyke from encroaching river waters during high-flow events	Overtopping; piping; washout; breach	N/A	Scour (earthen embankments); debris impact
Bridges – Pedestrian	Provide safe crossing location across water to pedestrians	No longer safe for pedestrian crossing	N/A	Overturning; pier scour; abutment scour; debris impact
Bridges – Vehicular	Provide safe crossing location across water to vehicular traffic	No longer safe for vehicle crossing	N/A	Overturning; pier scour; abutment scour; debris
Bridges – Culverts	Provide safe crossing location across water to pedestrian and/or vehicular traffic	Water conveyance over capacity; clogging; no longer safe for vehicle/pedestrian crossing	N/A	Scour; debris
Buildings – Commercial & Industrial	Provide safe location for conducting business; providing services; storing goods	Water entering building envelope, no longer safe for business	Inundation of building contents	Foundation cracks & displacement; moisture damage; collapse of support walls; debris
Buildings – Residential & Institutional	Provide safe shelter for families	Water entering building envelope, no longer safe to inhabit	Inundation of furniture and contents	Foundation cracks & displacement; moisture damage; collapse of support walls; debris

Critical Infrastructure – Fire Stations & EMS	Provide timely, reliable, safe emergency services; provide safe location of dispatch	Water entering building envelope, no longer safe to dispatch; access lost	Inundation of emergency response equipment	Foundation cracks & displacement; moisture damage; collapse of support walls; debris
Critical Infrastructure – Hospitals	Provide safe, accessible services and shelter to persons in need	Water entering building envelope; access lost	Inundation of contents	Foundation cracks & displacement; moisture damage; collapse of support walls; debris
Critical Infrastructure – Schools	Provide safe learning environment and transportation to students	Water entering building envelope; access lost	Inundation of contents	Foundation cracks & displacement; moisture damage; collapse of support walls; debris
Pollution Control Plants	Treat raw sewage with primary and secondary treatment and discharge into receiving waters	Water entering building envelope; access lost; loss of major functional equipment; raw sewage bypass	Inundation of any water treatment components; inundation of building contents	Foundation cracks & displacement; moisture damage; collapse of support walls; debris
Roads – Arterial & Primary	Provide safe route for vehicles to drive between intersections	Washout; No longer safe for vehicles to drive	N/A	Embankment scour; settlement; asphalt moisture damage;

Loss of Equipment (IM_2)

The second impact multiplier, IM_2, is an estimate of the fraction of equipment lost as a direct result of inundation. Equipment is considered building contents or in general, non-structural components of the infrastructure. For residential buildings, equipment refers to personal belongings, furniture, small electrical appliances, tools or anything that would generally be expected to be taken during a move (Water's Edge, 2007). Infrastructure that does not possess equipment (e.g. roads) is assigned a value of 0 for IM_2 variable. This reduces risk index calculation to,

$$(R_e)_s = P_s \times (EV_{1e} \times IM_{1e} + EV_{3e} + IM_{3e})_s \tag{4.7}$$

Loss of Structure (IM_3)

The final impact multiplier, IM_3 measures the degree to which the structural integrity of an infrastructure is compromised as a result of flooding. To recall, this research considers flood depth as the main flood-caused load parameter used in risk assessment. The IM_3 variable is a measure of both quantitative and qualitative structural loss. The methodology takes an innovative approach in the incorporation of qualitative and subjective data with quantitative data. Qualitative analysis uses fuzzy set theory to adjust values based on subjective input and differences in risk perception. The result of qualitative analysis is used to modify quantitative risk to capture stakeholder opinions. This approach considers the condition of an infrastructure, its failure mechanisms and its response to flood loads. The calculation of IM_3 includes the impact that an infrastructure's condition has on its response to flooding. Condition of an infrastructure may be based on its age, maintenance and other important factors relating to an infrastructure's ability to resist and recover from damage. For this research, the specific factors influencing an infrastructures condition were obtained during interviews with City of London experts. The combination of qualitative data with quantitative data provides for a more comprehensive representation of risk.

The quantitative deterministic component of IM_3 is calculated using stage-damage curves. These curves use the inundation depth as input to estimate the level of damage an infrastructure may sustain as a result of being flooded. Stage-damage curves should be specific to the infrastructure type, construction material and the structure's location. These curves are commonly used in the assessment of flood-based damage and provide more accurate information when they have been developed for a specific municipality.

Recently updated stage-damage curves are available from the Flood Damage Estimation Guide (Water's Edge et. al., 2007) for residential, commercial and industrial buildings in Ontario. The curves are based on data from Southern Ontario and the results have been updated to account for inflation. They were prepared for the Ontario Ministry of Natural Resources. These curves are provided in Appendix A.

Stage-damage curves are required (Figure 4.1) for all infrastructure types to quantify the deterministic component of structural damage (IM_3). However, these curves are not available for each infrastructure type encompassed by this research. Therefore, stage-damage curves were created for use in the case study for transportation structures (roads, bridges and culverts) and PCPs. This was done by examining regional flooding case studies and through interviews with local infrastructure experts in each field. An example for a concrete bridge stage damage curve is shown in Figure 4.2 below. The remainder of stage-damage curves used in this research are provided in Appendix A.

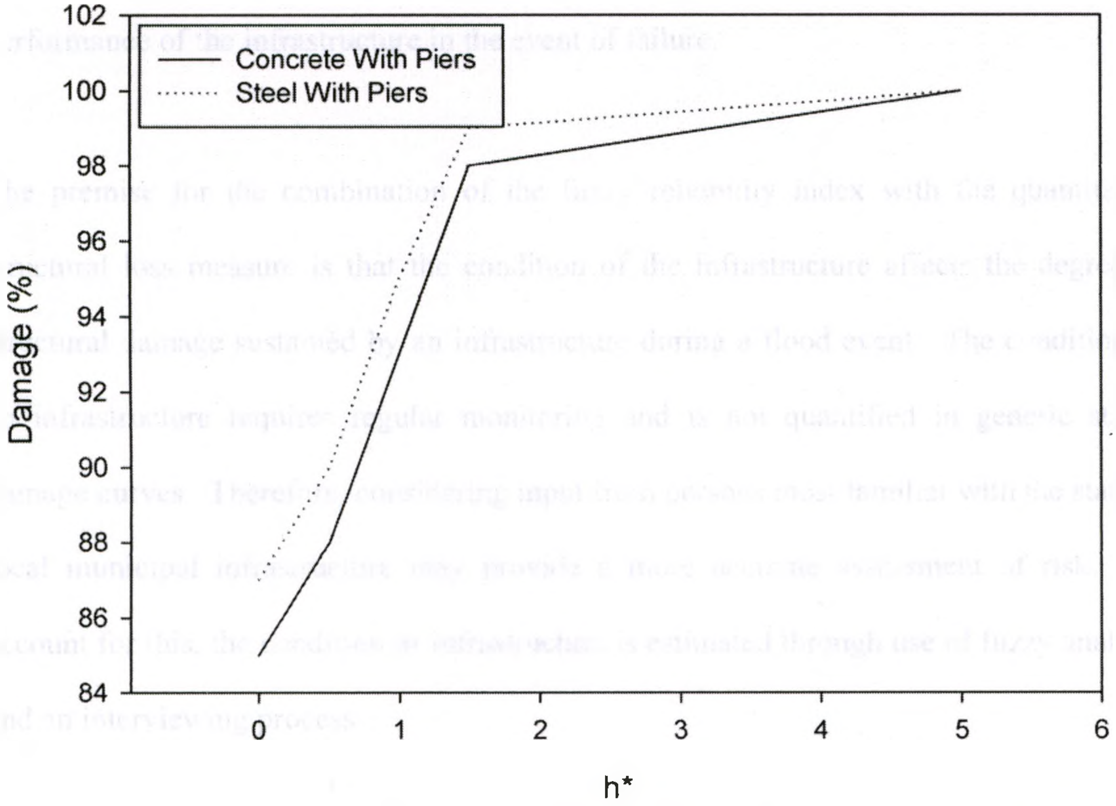


Figure 4.2: Stage-damage curve for a bridge with piers, above the bridge deck; explanation in Appendix A.

These curves are used to estimate the percent of structural damage that may be expected based on the experience and opinion of experts and they are used in estimation of IM_3 during the calculation of the final risk index.

The qualitative element of IM_3 is used to quantify the subjective uncertainty associated with potential failure of the infrastructure system. Assessment of subjective uncertainty is conducted with the assistance of experts. The qualitative component of IM_3 allows for the measure of partial failure as well as for the impact of the structure's current conditions on its response to flooding as perceived by experts in the field. This qualitative component is termed the fuzzy reliability index (*FRE*) (El-Baroudy and Simonovic, 2003). The fuzzy reliability index uses fuzzy set theory to measure the performance of the infrastructure in the event of failure.

The premise for the combination of the fuzzy reliability index with the quantitative structural loss measure is that the condition of the infrastructure affects the degree of structural damage sustained by an infrastructure during a flood event. The condition of an infrastructure requires regular monitoring and is not quantified in generic stage-damage curves. Therefore, considering input from persons most familiar with the state of local municipal infrastructure may provide a more accurate assessment of risk. To account for this, the condition of infrastructure is estimated through use of fuzzy analysis and an interviewing process.

Fuzzy set theory is used to address ambiguity and uncertainty in data (Simonovic, 2009). It allows for partial membership in a set or subset by quantifying the degree of belonging to the set (Zimmerman, 2001). As applied in this methodology, fuzzy set theory is used to measure the extent of failure of an infrastructure element upon inundation; enabling the response to be characterized as complete failure (a membership of 1 in the set of failure), no failure at all (a membership value of zero) or some partial failure – membership between 0 and 1.

The use of the fuzzy set theory allows for different opinions on what constitutes acceptable failure. It is used to define the degree to which the system has failed while taking into consideration how individuals perceive a degree of "acceptable" failure. The ability to measure varying levels of failure is particularly significant when a very large number of infrastructure elements are under consideration. It assists in the prioritization of infrastructure by separating infrastructure that may be less resilient to flooding.

Functions describing the membership of an element to a certain set are created through interviews. An individual's responses are based on previous experiences and current risk perceptions. The belonging of an element to a particular set are functions otherwise known as membership functions. The *FRE* (second component of IM_3) uses two membership functions to measure an infrastructure's performance: system-state membership function and acceptable level of performance membership function (Figure 4.3). The *FRE* is calculated based on the area of overlap between these two curves (shaded area in the Figure 4.3). This overlap is considered acceptable partial system failure. In most cases, the larger the acceptable partial failure, the more risk the expert is willing to accept.

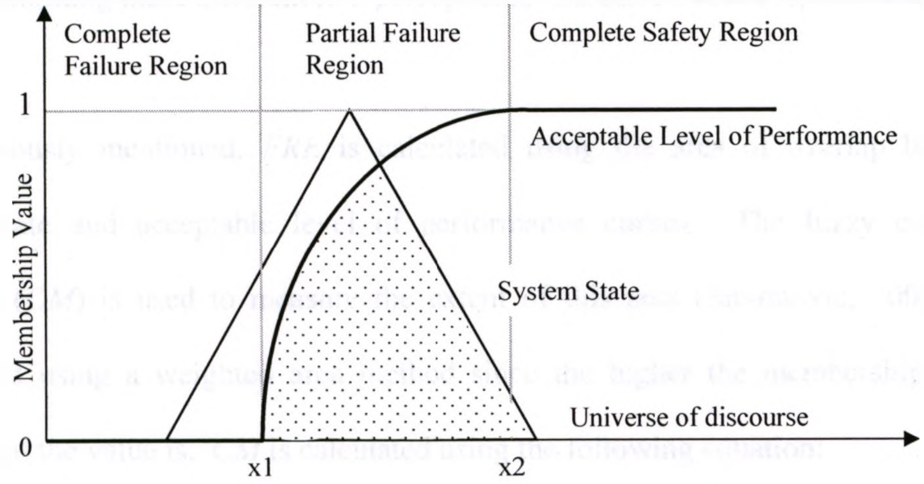


Figure 4.3: Theoretical fuzzy membership function

Membership functions are created that describe the current state of each infrastructure as well as its acceptable level of performance. The system-state membership function describes the condition of an infrastructure element based on factors such as age, material, maintenance and design life; each of these factors may contribute differently. Some factors may influence the condition of an infrastructure more than others. To determine what these factors are and to what level they contribute to the condition of infrastructure, interviews were conducted with various departments within the City of London. Interviews with experts assisted in the development of system-state curves for the City of London case study (see Appendix B).

The second set of curves – the acceptable level of performance functions – is created for each infrastructure type. These curves are also created using input from City experts. These curves are used to define what the acceptable performance of an infrastructure is. This definition is subjective and responses may be different for each decision maker based on their previous experience, education, expertise and personal perception of risk. By incorporating these different risk perceptions, risk can be better represented.

As previously mentioned, *FRE* is calculated using the area of overlap between the system-state and acceptable level of performance curves. The fuzzy compatibility measure (*CM*) is used to measure the extent of this area (Simonovic, 2009). *CM* is calculated using a weighted area method since the higher the membership, the more significant the value is. *CM* is calculated using the following equation:

$$CM_e = \frac{WOA_e}{WASS_e} \tag{4.8}$$

Where,

WOA is the weighted overlap area between system state membership function and acceptable level of performance curve; and

WASS is the weighted area of system state function

In instances where there are multiple acceptable levels of performance, the fuzzy reliability index can be calculated using the equation derived by El-Baroudy and Simonovic (2003):

$$FRE_e = \frac{\max_{p\epsilon K}\{CM_1, CM_2, \dots, CM_p\} \times LR_{max}}{\max_{p\epsilon K}\{LR_1, LR_2, \dots, LR_p\}} \tag{4.9}$$

Where,

LR_{max} is the reliability measure of acceptable level of performance with which the system-state has the maximum compatibility value (CM);

LR_p is the reliability measure of the 'p' acceptable level of performance;

CM_p is the compatibility measure for system-state with the 'p' acceptable level of performance; and

K is total number of defined acceptable levels of performance.

In this case, there is only a single value for acceptable level of performance provided from interview responses. Therefore, *FRE* is directly calculated as the shaded area from Figure 4.3. This can be represented in set notion as follows:

$$FRE_e = ALP_e \cap SS_e \tag{4.10}$$

Where

ALP is the area under acceptable level of performance membership function; and

SS is the area under system state function for a particular infrastructure element of interest, e.

A *FRE* value of 1 indicates that the system-state is fully within the acceptable region of level of performance; indicative of a safe system. Conversely, an *FRE* value of 0 signifies no overlap between the system-state and acceptable level of performance, indicating the system in a complete failure state. Therefore the desirable state is when there is maximum overlap between the system state and acceptable level curves; a high FRE value.

This thesis assumes a triangular distribution shape to represent the system state for a particular infrastructure, other distribution shapes are described in Simonovic (2009). This shape describes the state of an infrastructure element based on its age, structural properties and infrastructure-specific factors which contribute to an infrastructures current state of condition. Condition is measured on a relative scale of zero to ten [0-10], where a value of 10 represents an infrastructure in perfect condition. The acceptable limit state curves are trapezoidal and are based on what is considered to be acceptable condition for each infrastructure type; a value of 0 is completely unacceptable and a value of 10 considered completely acceptable. The combination of acceptable level of performance and system state curve provides for the calculation of fuzzy compatibility measure mentioned previously. When acceptable limit state curve increases to 1 (most acceptable condition), an increase in CM indicates an increase in the infrastructure's condition being acceptable (i.e. likely to incur less damage).

Once combined with a flood event, the condition of the infrastructure will affect its structural loss measure (IM_3). Therefore, to calculate IM_3 the fuzzy risk component and the deterministic components must be combined. An increase in the compatibility measure indicates less risk to a particular infrastructure. Thus, an infrastructure element that is considered to be in unacceptable condition will experience higher damage than an infrastructure element considered to be in excellent condition. To represent this inverse relationship in the calculation of the loss of structure impact multiplier (*IM₃*), the following equation is used:

$$IM_{3e}(CM_e) = \begin{cases} 1, & CM_e = 0 \\ \mathrm{Min}\left(1, LS_e \times \frac{1}{CM_e}\right), & CM_e > 0 \end{cases} \qquad (4.11)$$

Where

IM_3 is the impact multiplier related to loss of structure;

CM is compatibility measure; and

LS is percent damage from the stage-damage curves (Appendix A) for a particular infrastructure element, e.

When CM is 0, the structure is considered completely unsafe or experiencing total loss ($IM_3 = 1$). The stage damage curves are assumed to represent damage to a structure at a completely acceptable limit state. As such, for $0 < CM < 1$, risk to the infrastructure will increase proportionally. A CM value of 1(completely acceptable) will yield $IM_3 = LS$.

This innovative procedure of combining qualitative and quantitative measures of risk provides a more representative estimate of climate change flood risk to infrastructure. The condition state of an infrastructure just prior to a flood event can be used to better estimate the response, failure mode and potential damages in the event of a flood.

4.4 Economic Value

Economic values (EV) refer to potential monetary impacts incurred to an infrastructure element as a result of a flood event. It is used to provide greater importance to infrastructure that is expensive to repair or replace. It is included in flood risk assessment to reflect the City's priority in protecting and investing in infrastructure that could potentially cause the most interference as a result of a flood event. Three variables (EV_1, EV_2, and EV_3) are used to define potential economic loss associated with a particular infrastructure. These variables are described as potential monetary loss as a consequence of: infrastructure losing its function (EV_1); infrastructure losing associated equipment (EV_2); and infrastructure losing structural integrity (EV_3). These terms are explained in further detail below.

There is an associated economic impact value that correlates to each impact multiplier (IM_1, IM_2, and IM_3) as shown in equation 4.12:

$$(R_e)_s = P_s \times (EV_{1e} \times IM_{1e} + EV_{2e} \times IM_{2e} + EV_{3e} \times IM_{3e})_s \tag{4.12}$$

The potential economic losses due to loss of function (or partial loss of function), EV_1, considers possible indirect monetary consequences associated with the structure no longer performing the function it was designed for. These values may vary for each type of infrastructure depending on its particular function and how its function is affected by flooding. It is possible that these values may include the cost of traffic rerouting, alternative transportation arrangements, relocation or lost profits. Recalling the infrastructure included in the case study, economic losses related to the function of an infrastructure like residential buildings would also include costs of evacuation, sheltering and food. In transportation costs due to road closure are associated with mobility and consequently lost economic activity. Flooded roads and bridges that are essential to access businesses would also result in lost profits and reduced economic activities. Economic losses resulting from the loss of pollution control plants and critical infrastructure are related to inconvenience, mitigation costs and supplemental or emergency measures.

Economic value associated with loss of equipment, EV_2, is the potential economic impact as a result of equipment which may be lost or damaged in a flood event. This value often assumes the minimum repair value or the replacement equipment cost. Those infrastructure elements that do not have equipment associated with them (e.g. roads) have a value, EV_2 of zero. This reduces the risk equation to:

$$(R_e)_s = P_s \times (EF_1 \times IM_1 + EF_3 \times IM_3)_s \tag{4.13}$$

The value of EV_2 for infrastructure is based on stage-damage curves, technical reports, budgets and interviews with technical experts. Considering the City of London case study, often content value of commercial, residential, institutional, industrial buildings and critical facilities is expressed as a percentage of the total value of the infrastructure. This assumption is consistent with content values as expressed in the region specific Glengowan assessment (Marshall, 1983). Some personal belongings (especially in residential buildings) have significance that extends beyond the items' monetary value. Items like photographs, keepsakes, art and letters are at increased susceptibility of being damaged during a flood, but their importance is not captured in this study. Loss of these items may have social, rather than economical, consequences and there is a potential to extend this risk assessment to include consideration of social consequences.

The final economic loss value, EV_3, is related to the loss of structure. This value assumes the minimum of the replacement cost or repair cost for rehabilitating the infrastructure in the event of damage. The replacement cost for an infrastructure acts as a threshold value for repairs. The assumption is that the less costly of these two options would be used in the event of recovering from damage. These values are available from technical reports, local maintenance logs, construction project documentation and budgetary documentation. In the case study the value of EF_3 for buildings is provided by the Municipal Property Assessment Corporation (MPAC) as the present value of an infrastructure, not the monetary value that the structure would sell for on the market. This is to provide an estimation of the actual cost of rebuilding the building, not selling it. Road cost data was provided in a report prepared for Transport Canada by Applied Research Associates, Inc (2008). Road repair costs are calculated on a per square meter basis. To incorporate this into the assessment the inundated lengths and areas of each infrastructure element are determined for each climate change scenario.

Data comes from different sources and reflect monetary values recorded for various years. Thus, all economic impact values (EV) are updated to reflect 2009 dollar value based on the Consumer Price Index (CPI) provided by Statistics Canada (2010). In this way, the values are comparable and do not skew the risk index calculations. The relationship used to update economic impact values to reflect the CPI is as follows:

$$YearY = YearB \times \left(\frac{YearYindex}{YearBindex}\right) \tag{4.14}$$

Where,

$YearY$	Monetary value of infrastructure for the year of interest ($);
$YearB$	Monetary value of infrastructure for the base year ($);
$YearYindex$	CPI value provided by Statistics Canada for the year of interest; and
$YearBindex$	CPI value provided by Statistics Canada for the base year.

Once all *EV* values are determined, all variables are substituted into risk index equation (4.11) and calculation completed for each infrastructure element. Each infrastructure element has a separate *RI* for every climate case, s. In this way, the difference in climate change effects can be assessed.

All risk indices are calculated in spreadsheet format which is easily relatable to attribute tables in GIS. This provides a convenient link so that every time the spreadsheet (risk tables) is updated (pending on data availability), spatial risk maps will be corrected for appropriately.

CHAPTER 5

CITY OF LONDON CASE STUDY

5.1 Introduction

Previous studies by Cunderlink and Simonovic (2005; 2007), Prodanovic and Simonovic (2007), and Simonovic and Peck (2009) suggest that the City of London can expect to experience more frequent severe flooding events as a consequence of changing climate.

As weather patterns shift and floodplains change, it is important to understand how local infrastructure may be affected. The objective of this case study is to determine the impact that climate change, specifically flooding, may have on municipal infrastructure in the City of London. The case study considers two climate change scenarios for two different return periods, based on regulatory flood guidelines.

5.2 Background

The following section is intended to provide background details pertaining to the flood risk assessment case study to better understand the context of local risk within the City of London.

5.2.1 Description of the Study Area

The City of London is in the Upper Thames River basin, located in South western Ontario nested between lakes Huron and Erie (Figure 5.1; Figure 5.2). The 3,500km^2

Produced by:
The Cartographic Section
Department of Geography
University of Western Ontario

Figure 5.1: City of London, Ontario, Canada on the globe (Cartographic Section, Dept. Of Geography, UWO)

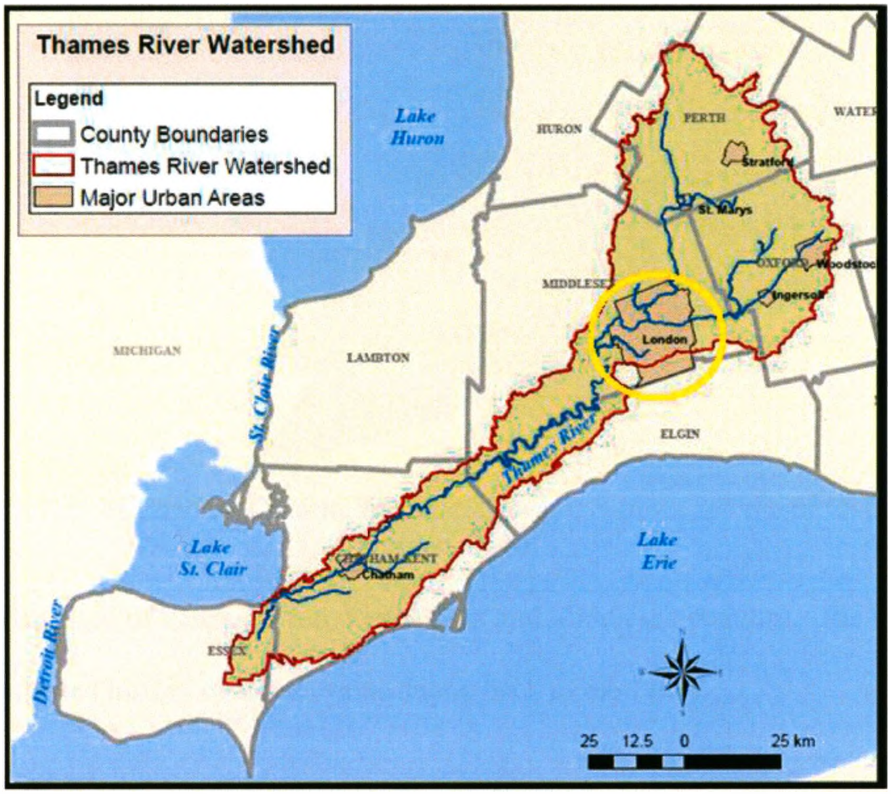


Figure 5.2: City of London, Ontario in the Thames River basin (UTRCA, 2010)

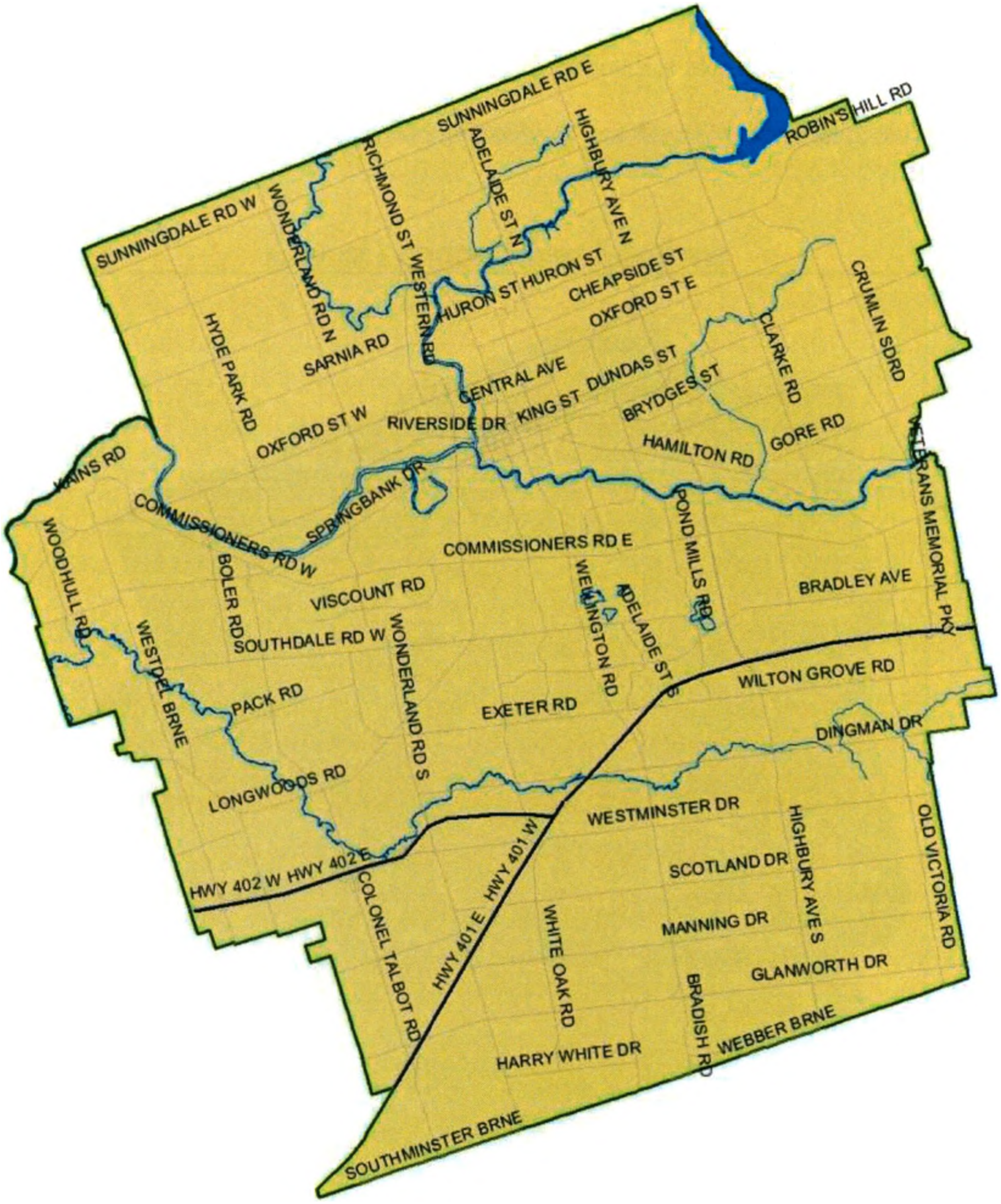


Figure 5.3: City of London, Ontario; boundaries, water courses and major roads (City of London, 2010)

basin is comprised of Essex, Huron, Perth, Kent and Middlesex counties. The basin has a well documented history of flood events dating back to the 1700s.

The City is characterized by a network of rivers including the Thames River and its tributaries. The Thames also comprises many tributaries also considered in this study, including: Dingman, Stoney, Pottersburg, Medway and Mud Creeks (Figure 5.4).

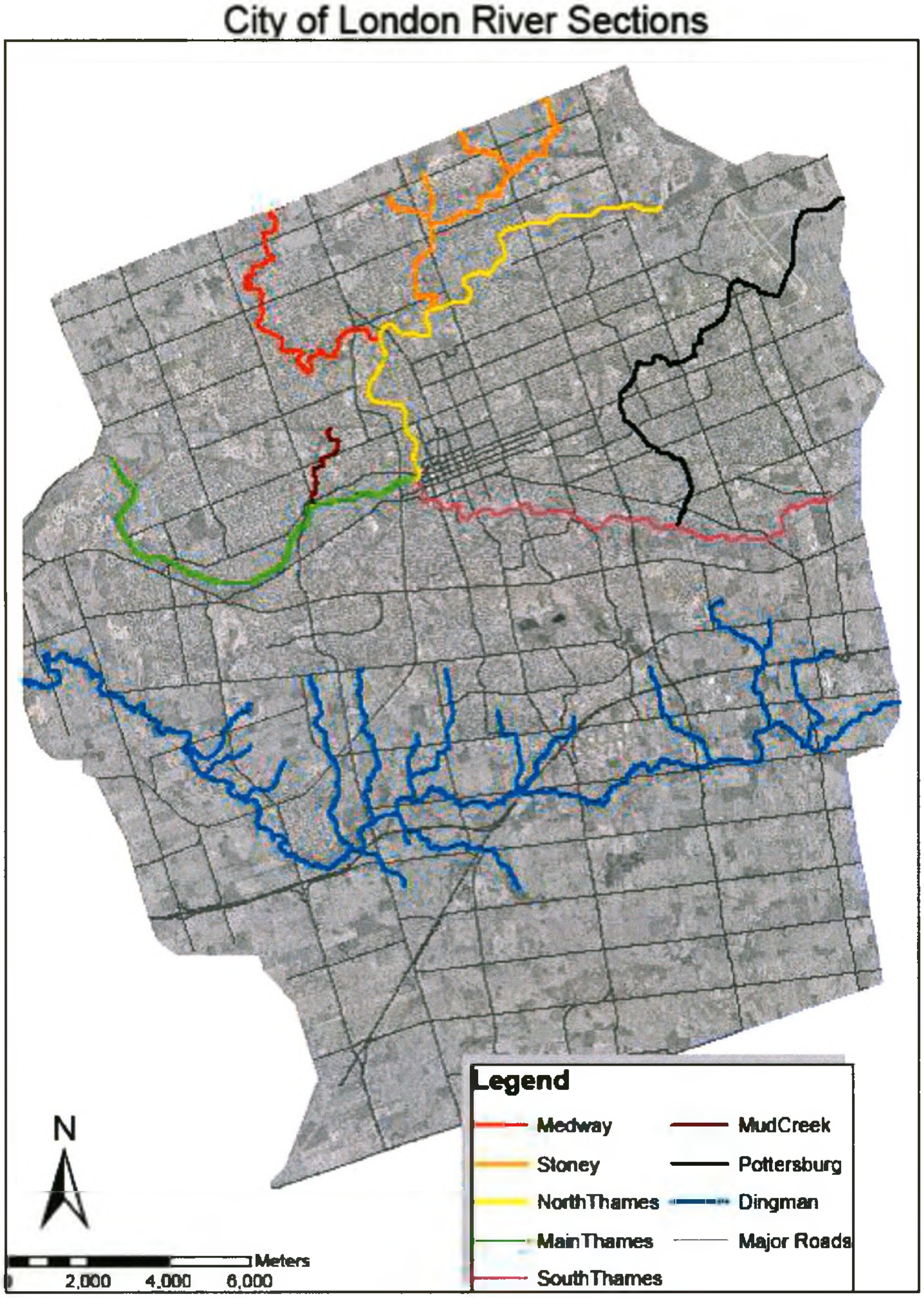


Figure 5.4: Thames River and tributaries in the City of London

The Thames River originates North of Stratford and just East of Woodstock in the wetlands of Tavistock (CLEAR, 2009). Most of the City of London drains into the Thames, with a small portion (16%) draining into Kettle Creek (CLEAR, 2009). The Thames is often referred to by its branches; North, South and Main. The North and South branches join near the downtown core of the City at a location referred to as "The Forks" and flow into Main Thames which passes through multiple municipalities before draining into Lake St. Clair. It can take anywhere from 4 to 10 days for water at the Forks watershed to reach its final destination at Lake St. Clair (UTRCA, 2007). The water quality of Thames and tributaries is generally considered poor, though improving. Waters are impacted by agricultural fertilizer runoff, construction waste (consequence of rapid development and urban sprawl), industrial spills and pollutants, bank erosion and storm water runoff contaminants.

The river is attenuated by three major flood-protection structures: Wildwood Dam, Fanshawe Dam and Pittock Dam. Fanshawe Dam is the only one of these dams within the City boundaries (Figure 5.5). The others are located upstream of London. There are other dams in the City, including Hunts and Springbank dams, which are generally used to control river levels during low-flow periods for recreational activities. The City places high dependence on Fanshawe Dam to control water levels during high and low flow periods to satisfy consumer demands and prevent flooding. Fanshawe Dam has direct impact on the City of London properties and people; the failure of this structure could have devastating consequences.

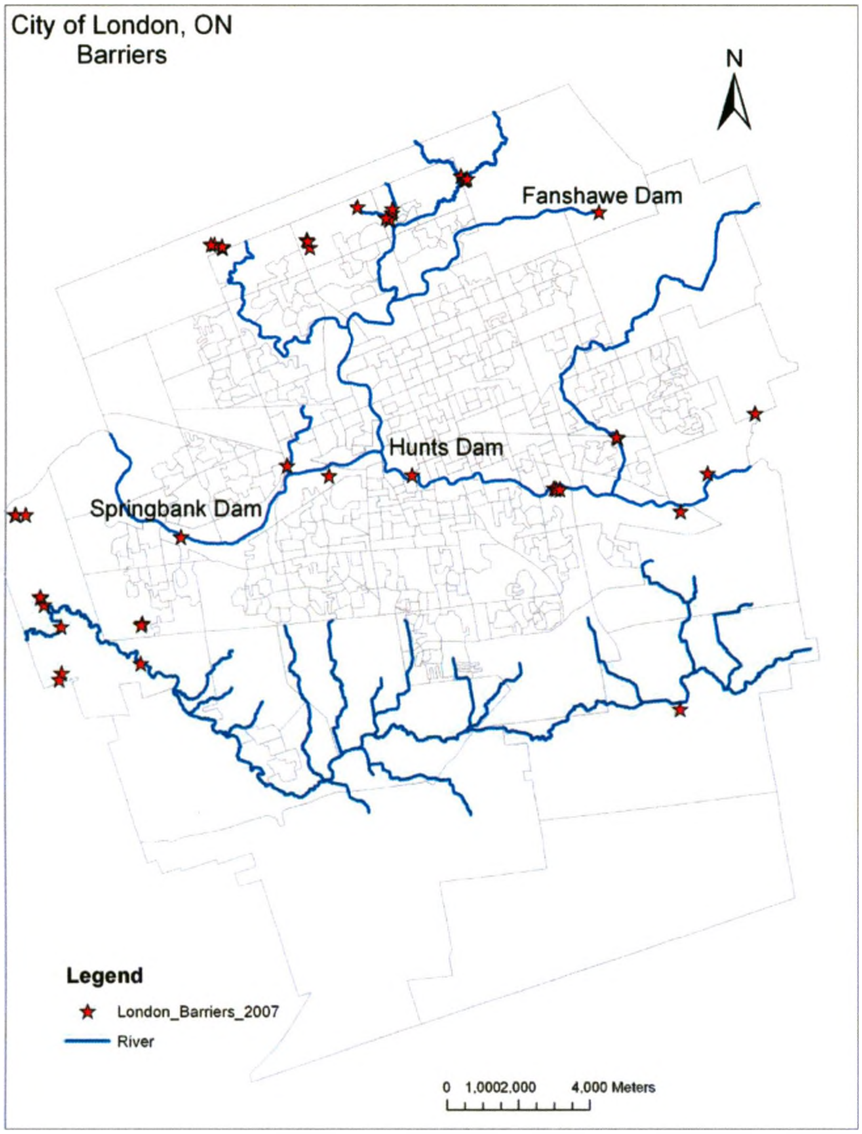


Figure 5.5: Flood control structures in the City of London (including minor structures)

The City of London is considered rich in culture and natural heritage. The Thames is a multi-purpose river used for a diverse number of recreational activities (swimming, rowing, sailing, hunting, boating, fishing), wastewater discharge receiving waters, local water supply, agricultural irrigation and natural habitat (CLEAR, 2009). Despite poor water quality often associated with the Thames River, it has been declared one of

London's greatest assets and the Forks has for a long time served as a historical landmark for the City (Celebrate the Thames, 1999).

The City of London is diverse in its people, culture and entertainment. The City has experienced substantial growth within the last 40 years (CLEAR, 2009) and has a population of about 352,000 persons (City of London, 2010). Urban sprawl continues to spread outwards from the downtown core into suburbs and onto agricultural land. Fanshawe College, The University of Western Ontario and its affiliates bring large populations of students to the area, many of whom are renters concentrated near campuses in high density housing. Some university students live in proximity to the North Thames River, in flood-prone areas. As a national leader in healthcare services, the City is also home to an increasing elderly population.

The region has a history of flooding which dates back to the 1700s. The flood of 1857 is known to have swept away bridges and damaged other major infrastructure components. A major flood event occurred in 1883 after many days of heavy rainfall which washed out London West homes and killed 16 people. This flood is responsible for the first construction of the dyke network at the downtown Forks location (Celebrate the Thames, 1999). One of the worst floods in London's history is the flood of 1937 (Figure 5.6) which saw flows over 120 times greater than average (CLEAR, 2009) and 4000 people evacuated with an estimated cost of $51 million in damages caused to flooded roads, railways and businesses (Environment Canada, Canadian Disaster Database V. 4.0, 2010). Thames flooded again in 1947, and 1948 damaging dams, cutting transportation lines, closing businesses and disrupting utilities. Since then there continues a well documented history of flood events occurring every decade; one of the most recent minor flood events happened in spring 2008 (Figure 5.7; Figure 5.8) inundating pedestrian walkways/bike paths, non-critical infrastructure and brought water levels precariously close to bridge decks.

Figure 5.6: House submerged in 1937 flood in the City of London (City of London, 2010)

Figure 5.7: Flooding at Adelaide Street Bridge, January 2008 (Angela Peck, 2008)

Figure 5.8: Flood event at Harris Park, December 2008 (Dragan Sredojevic, 2008)

Based on flood history and future climate projections for the area, the City of London could benefit from flood risk assessment. Portions of the risk assessment procedure are iterative (Figure 5.9). Selection of infrastructure considered in this case study is driven by stakeholder input and available data. Municipal politicians and technical experts are involved in infrastructure selection process. List of infrastructure included in this case study has been refined to suit municipal preferences and data availability. Some data requires preprocessing before being used as input into the municipal infrastructure risk index calculation. Risk indices are calculated in comprehensive spreadsheets and used to prepare tables and maps. Areas of high risk as identified and can be used in climate change policy and water resources management. As more information becomes available, the entire process can be repeated.

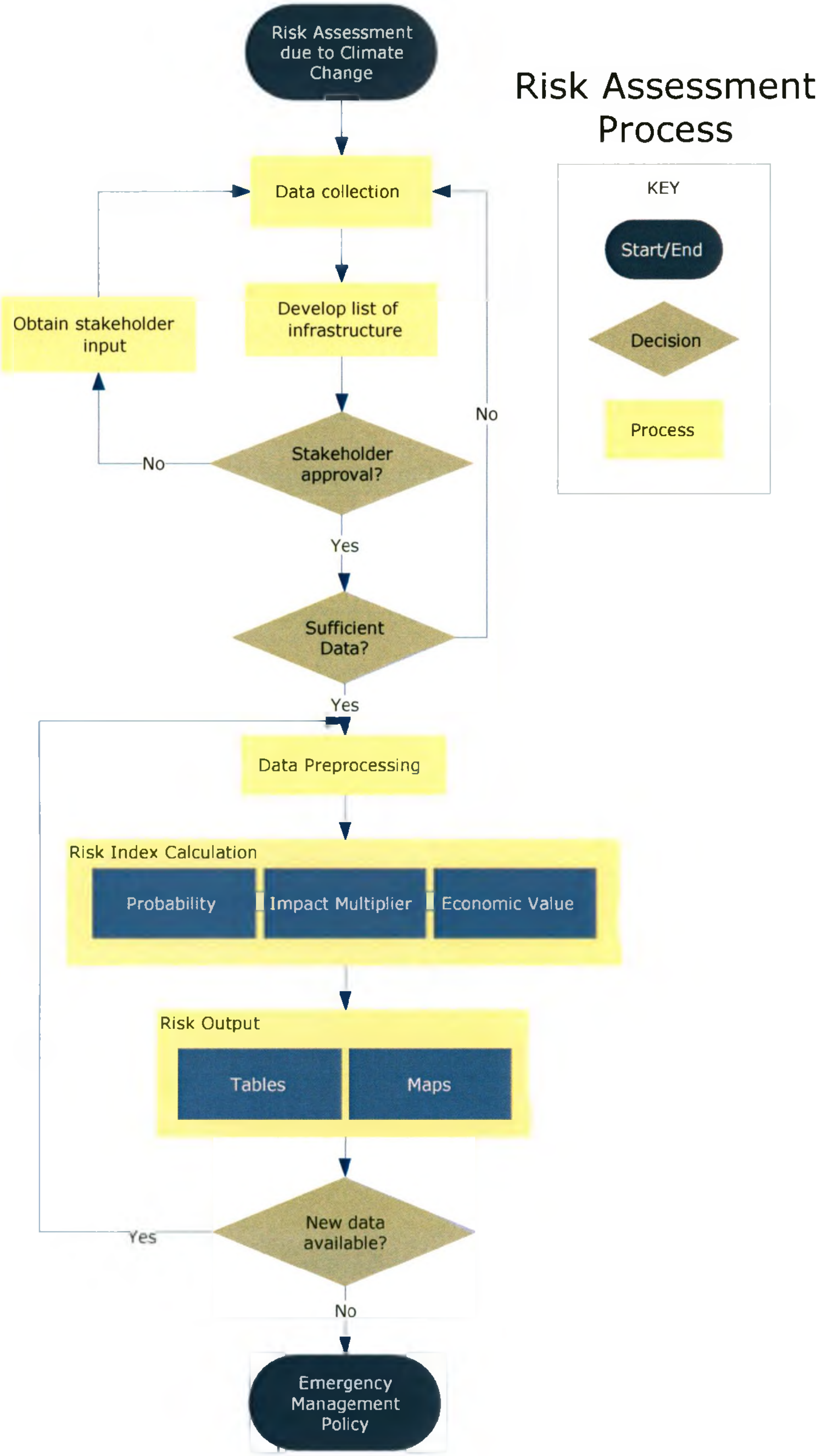


Figure 5.9: Schematic flow chart of procedure

5.2.2. Spatial Representation of Risks

Risk information is spatially presented in geographical units defined by Statistics Canada as Dissemination Areas (DA). There are 19,177 DAs located within Ontario; 527 of these units are within the City of London. Dissemination areas cover the entire territory of Canada; each region identifiable by a unique 4-digit code. Statistics Canada defines DAs as small, relatively stable geographic regions. The DA is selected as the unit for disseminating risk information because it is the smallest standard geographic area for which all Statistics Canada Census data are disseminated. They generally have populations between 400 to 700 persons while respecting the boundaries of the larger census subdivisions and census tracts (Statistics Canada, 2001). Dissemination area units remain relatively stable over time and are considered small enough to remain significant to risk assessment and decision making. For additional details pertaining to spatial representation of risk, the reader is referred to Bowering (2011).

5.2.3. Infrastructure Considered for Risk Assessment

The City of London played a significant role in selecting the infrastructure considered in this case study. As a stakeholder, the City wishes to consider infrastructure that generally satisfy their interest in providing reliable public service and protecting people. The selection process was iterative; the City was consulted and infrastructure list created and continually revised. Infrastructure owned by the City was important to include as well as those infrastructure elements pertaining to emergency response and those infrastructure elements which may require financial compensation after a flood event.

Data availability and reliability also drove infrastructure selection. Hydrologic and hydraulic analysis made assumptions which for consistency and accuracy, are adopted in this case study. Some water infrastructures such as select pedestrian bridges and beaver dams were not considered in the hydraulic analysis. This case study also does not consider these infrastructure elements to maintain consistency between floodplain representation and risk analysis. As more data became available, additional infrastructure was added to the study. Where data was insufficient, some infrastructure elements required removal from the study while still considering stakeholder interests.

Infrastructure in transportation, flood protection structures, critical infrastructure, buildings and pipe networks are considered in this study. A more detailed list of the infrastructure in each of these categories is provided in Table 5.1. A brief description of current infrastructure in the City is given in the following sections.

Table 5.1: List of Infrastructure categories and types considered in study

Infrastructure Category	Infrastructure Type	Details
Protection Structures	Barriers	Flood gates
		Dykes
Transportation	Bridges	Vehicle
		Pedestrian
	Culverts	Public owned
	Roads	Arterial
Buildings	Critical Facilities	EMS
		Fire Stations
		Hospitals
		Schools
	Water Treatment	Pollution Control Plants
	Non-critical Structures	Commercial
		Industrial
		Institutional (not incl. schools)
		Residential

Pipe Network *	Water	Drinking water pipes under bridges
	Storm	Combined sewers
	Sanitary	Combined sewers

* Not considered in the same capacity as other infrastructure

For a more detailed description of the data used in this study and stakeholder input and recommendations, the reader is referred to Peck et al (2010).

Barriers

Barriers are an important component of flood management infrastructure. Reservoirs behind dams are used to moderate flow and deliver water based on downstream demand. Operations generally manage to store water during wet periods for gradual release during low-flow periods and to reduce downstream flood effects during periods of extreme precipitation and runoff. During flood events, there are multiple types of failure barriers could experience; overtopping, undermining, piping, and ultimate breach failure are a few. Failure of any flood protection component could compromise the entire defense system and cause catastrophic damage. It is also possible that barriers intended to keep water out of an area could end up trapping water behind the defense system, keeping water in. This may lead to sustained damages and slow down response and recovery efforts. The failure of the dyke system during hurricane Katrina event caused much of the New Orleans City to be inundated and incur high damages as a result of flooding. Although important for risk analyses, dam breach and dam break analyses are not considered in this study, but are recommended for future work and investigation. Dyke and levee failures are greatly influenced by flood duration and rate of water rise (Merz, 2007).

Fanshawe Dam, combined with smaller local dams like Springbank and Hunts, and the extensive river dyking network comprise the majority of water regulation and flood protection in the City of London. Brief descriptions of these infrastructure elements are provided.

West London Dyke

The West London Dyke (WLD) is approximately 2.2km long making it the longest dyke in the City. The dyke protects over 1100 structures located within the historical 250 year regulatory floodplain (Goldt, 2006) on the West side of the Thames at downtown Forks location (Figure 5.10). The dyke is owned by the City of London and the UTRCA is responsible for its regular maintenance and repair (Goldt, 2006). WLD is a gravity structure consisting of earth fill with poured in place concrete facing supported by a concrete toe (Stantec, 2006). There are also concrete blocks located along portions of the dyke to reduce erosion and provide additional structural support. The WLD was not entirely built to the same protection level. The majority of dyke sections provide protection for the 1:250 year event and some other sections are only capable of protecting from 1:100 year events; without considering climate change effects. The regulatory flood level is based on the flood event of 1937; WLD is capable of protecting just below that level (UTRCA, 2010). On average the dyke is approximately 0.7m below the Regulatory Flood Plain for the region (Stantec, 2006). However, regulations require 1:250 year protection level for the dykes. The 2004 condition report identified sections which required repair or replacement along WLD, including section N of Queens Ave. A 2005 investigation revealed that the structure had come to the end of its useful life and maintenance would not be sufficient; the section required replacement (Stantec, 2006). The WLD rehabilitation project occurred in 2006, at a cost of over $3 million (Stantec, 2006).

Broughdale Dyke

Broughdale dyke is situated on the East side of the North Thames River. The structure protects a number of commercial, residential and institutional buildings as well as the Adelaide Pollution Control Plant (PCP). Initially, the dyke had been built to inadequate protection level but in the early 1990s the dyke was raised to meet the regulatory floodplain level.

Ada-Jacqueline Dyke

The Ada-Jacqueline dyke is situated along the South side of the South branch of the Thames River. The structure protects mostly low-income residential houses.

Nelson-Clarence Dyke

The Nelson/Clarence dyke is on the South branch of the Thames, on the North side of the channel. A majority of the area directly behind the dyke is open green space belonging to a golf course. There are a few residential structures also protected by the dyke.

Riverview Dyke

The Riverview dyke is located along the South side of Main Thames just past the confluence of North and South branches at the Forks (Tchir, 2009). This earthen dyke is responsible for protecting older residential neighbourhoods and the Childrens Museum of London. There is limited vegetation growth on the dyke and it is under the threat of structural instability as a result of local urbanization and rapid erosion, (Tchir, 2009). Many of the trees that currently grow on dyke slopes are in poor condition and are a potential debris hazards during a flood event (Tchir, 2009).

Coves Dyke

Just downstream of Riverview dyke is the Coves dyke and floodgates. These structures work together to protect a low-income permanent trailer park located on the low-lying land behind the structure.

Fanshawe Dam

The Thames River is attenuated by Fanshawe Dam which controls flow at the North end of the City. Dam construction was initiated in 1950 after the flood of 1937 with the purpose of controlling water flow and to reduce flooding downstream in the City of London. During heavy precipitation events, the dam releases less water and stores it in the upstream reservoir for release at a later time and to minimize the magnitude of flood events. Although flooding may still occur during extreme events, the dam has been credited with reducing peak flood levels downstream by up to 40% (UTRCA, 2008).

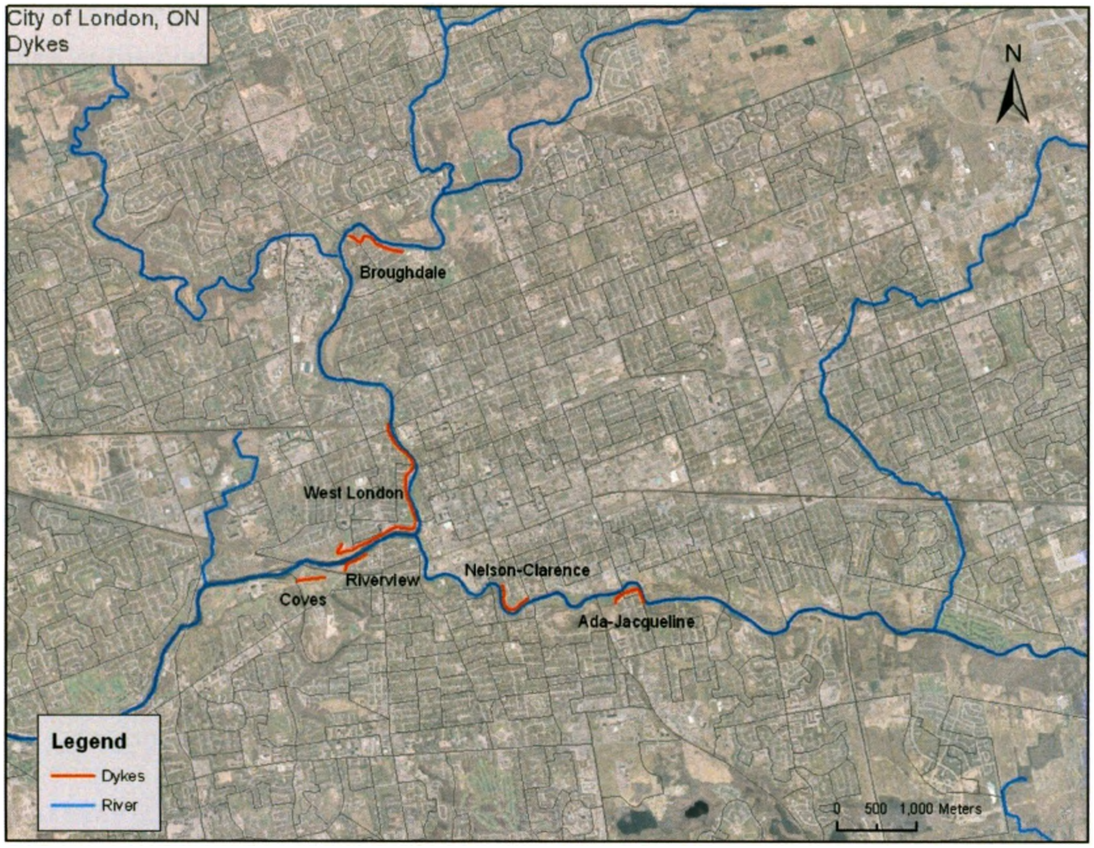


Figure 5.10: Location of dykes on the Thames River in GIS

The hydrologic analyses used as input into this case study include flood control operations but output is considered for Thames River downstream of Fanshawe Dam. Therefore this particular piece of infrastructure, although very significant to flood management, is not directly considered in the infrastructure risk assessment.

Buildings

The City of London has grown significantly in the past 40 years, bringing new residential and commercial developments to the area. Urban sprawl consumes the West end City limits but the densest development is in the downtown City core. This area consists mainly of commercial structures, offices and apartment buildings. The City is in a period of revitalization of the downtown core as part of a recent rehabilitation plan. Many buildings in the core are considerably older than the rest of London and some appear to be in very poor condition.

The level of damage buildings experience during a flood event is quantified using stage-damage curves. These curves are often used to estimate annual expected damage due to disastrous events. The City of London is fortunate enough to have regionally developed curves that better represent flood damage to buildings than the generic curves provided in literature. The Flood Damage Estimation Guide (Helsten and Davidge, 2007) provides the recent stage-damage curves for the City of London and surrounding area based on the original Glengowan flood report (UTRCA, 2007). The curves in the Estimation Guide are the curves adopted in this case study for use in risk calculations.

Non-critical building infrastructure considered in this case study include: commercial, residential, industrial, and institutional. Over 3000 buildings are affected by the floodplains, most of which are residential single family detached homes or condominiums. As indicated in data provided by MPAC, the average age of residential buildings in the City is approximately 50 years. The older structures are often found in the downtown area near the Forks and newer buildings are on the fringe of the City boundaries.

Although not directly owned by the City, inundated buildings that are severely damaged may require some financial compensation in the recovery phase of a flood. Therefore it is important to identify those structures that may be more susceptible to incurring flood damages. Identifying buildings at risk is also useful to improve emergency preparedness and response in case of a disaster.

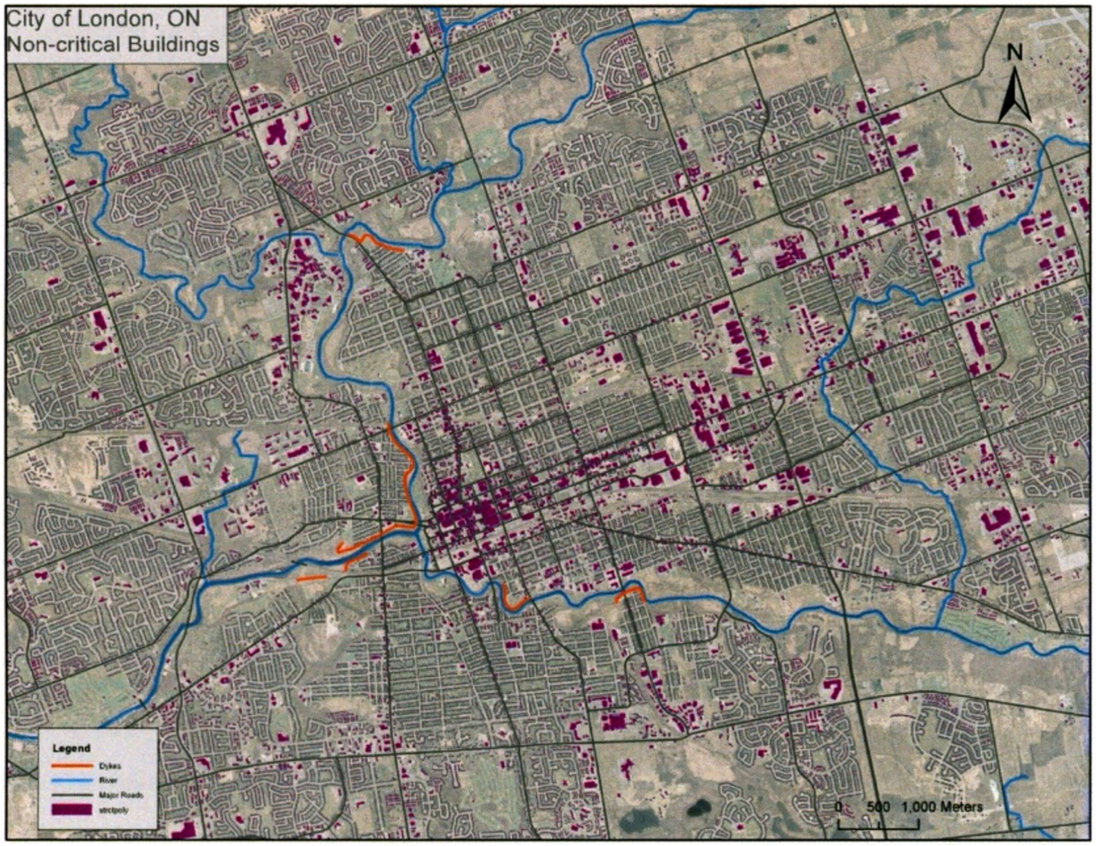


Figure 5.11: Location of non-critical buildings on the Thames River in GIS

Access to commercial and industrial buildings may be limited during a flood event as transportation routes become flooded or closed. Access issues to a property during a particular flood event are determined visually using GIS software. More details on building accessibility during flood events are provided in Bowering (2011). Businesses can lose profit during these disruptions and this is taken into account in this case study.

Bridges and Culverts

To be considered in case study, the bridges must satisfy the following criteria:

(a) City-owned

(b) Located over Thames river or major tributaries

(c) Included in City of London Bridge Management System (BMS)

There are three types of City-owned bridges considered in this study: those that carry vehicular traffic, pedestrian-only footbridges and culverts. As per request by the City, those structures documented in the City of London Bridge Management System (BMS) are included in the study. All other privately owned or new bridges not included in the BMS are not considered as part of this case study. The main failure mechanisms of bridges exposed to floodwaters include embankment, abutment and pier scour (Annandale, 1996). Other failure mechanisms include overturning once the bridge deck is overtopped and damage due to debris (Annandale, 1996). Floodwaters can contain high amounts of debris and result in localized damming effect (Figure 5.12). Fast flowing waters can carry large debris long distances and turbulent waters may heave debris into structural and non-structural bridge components with potential to cause significant damages. The functionality of a bridge is compromised when floodwaters submerge the bridge deck, rendering the bridge unsafe and impassable. This may inconvenience people and become less safe if there are no alternate routes.

Figure 5.12: Photo of debris that was moved down Thames River and caused buildup behind Springbank Dam (UTRCA, 2000)

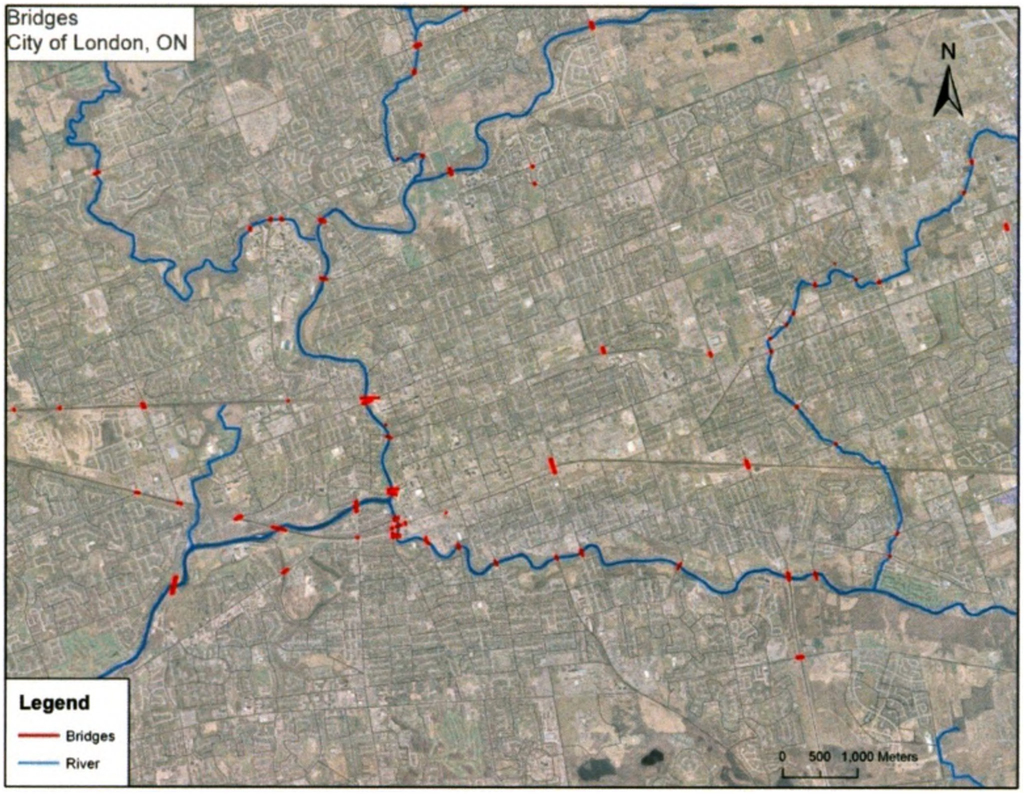


Figure 5.13: Location of bridges and culverts on the Thames River in GIS

Critical Facilities

Critical facilities infrastructure provides essential services which often play a significant role in emergency preparedness, response and recovery actions of a disaster; they are therefore considered separately from building infrastructure. The physical building structures response is similar to residential and commercial infrastructure and can fail by similar mechanisms. The equipment in critical facilities is often more expensive and not necessarily stationary (e.g. fire trucks).

The function of this infrastructure is to aid people in emergency situations and help the community; a flood event will increase the demand for these services. Structural failure mechanisms may include foundation scour or building envelope failure.

Schools

A school's function is to provide a safe learning environment for students. This purpose is compromised in a flood event if floodwaters enter the school and it becomes inundated. Schools require evacuation before a flood event to avoid injury or loss of life; therefore the function of a school is considered compromised when any water is in the building. Schools often contain a large quantity of furniture and expensive equipment (computers, books, lab materials) that may become damaged in case building is flooded. The structural failure mechanisms of inundated schools are similar to any other building with similar structural characteristics. The impact of flooding on schools in particular is not well documented. Along with potential for structural damage, flooding also has psychological side effects on students. The duration of a flood event plays a significant role in school and student recovery. Long duration events cause greater inconvenience. In extreme cases, inundation may result in extensive structural repairs, replacing school materials and rescheduling of missed classes. Flooding of schools places large financial and psychological burden on the community.

Hospitals

London Health Sciences Center (LHSC) in London's primary teaching hospital and is recognized as one of the largest acute teaching hospitals in Canada (LHSC, 2010). The LHSC consists of the following facilities: South Street Hospital, University Hospital, Victoria Hospital and Children's Hospital, Byron Family Medical Centre and Victoria Family Medical Centre. The function of hospitals is jeopardized when floodwaters encroach the property. Access is a critical component to the function of a hospital for people coming for treatment as well as possible evacuation. These structures respond similarly to other buildings. Hospital contents generally include very expensive medical equipment and supplies. Flooded hospitals potentially contribute dangerous materials picked up and carried by floodwaters. This affects the water quality of the floodwaters with potential for hazards to environment and human health. The assessment of what types of contaminants and their transport during a flood requires further investigation; it is not considered as a component of risk in this case study. Regional stage-damage curves are available for these types of structures.

Fire Stations & EMS

Fire Services London manages the fire stations in the City. Fire services are in higher demand during response and recovery to natural disasters. The consequences are increased response time and psychological burden. Risk is lower to these structures than it is to the people and places they service. However, to predict services during a disaster is riddled with uncertainty and therefore not directly considered in this study.

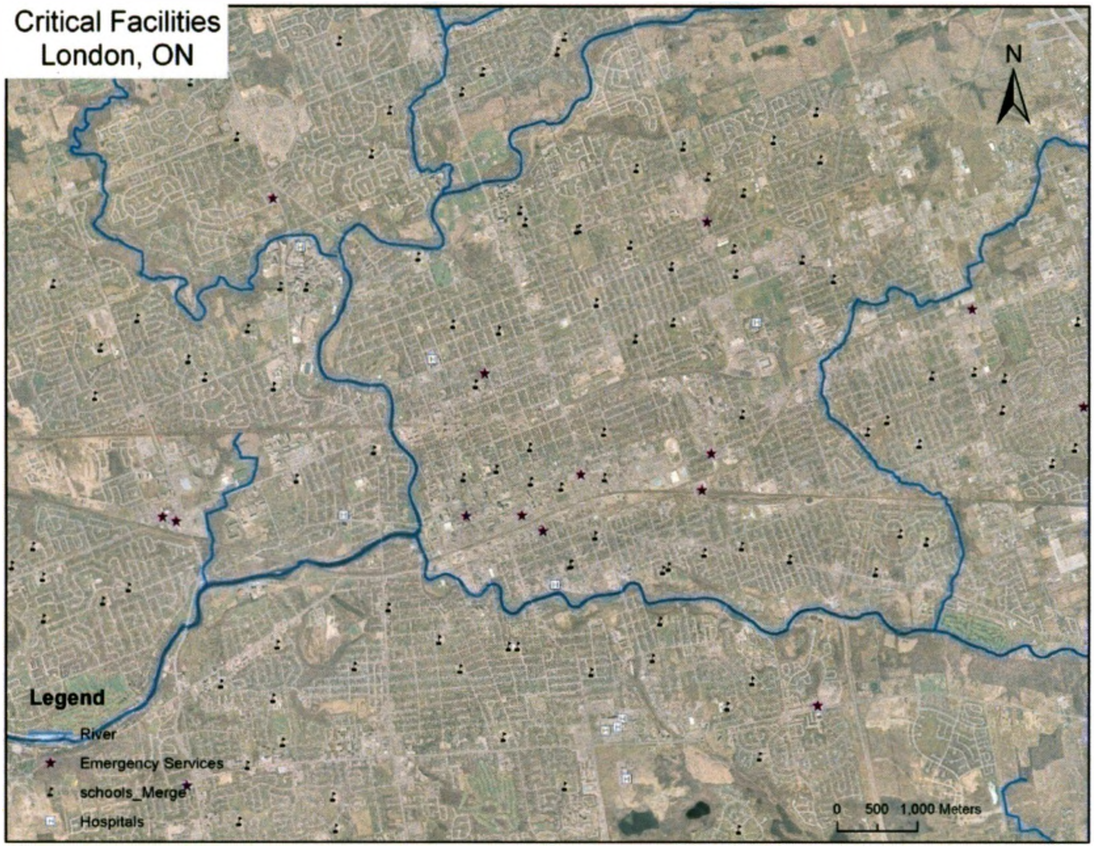


Figure 5.14: Location of critical facilities on the Thames River in GIS

Accessibility is another potential hazard of flooding. These critical services depend on accessible transportation routes to and from the facility to provide proper service. If emergency access routes are cut off, this increases response time and the facility may lose partial functionality if their vehicles cannot be dispatched. In the event of school bus routes being flooded, the school day may be canceled. Refer to Bowering (2011) for further discussion of accessibility in GIS.

PCPs

Currently, the City of London has 6 active Pollution Control Plants (PCPs): Greenway, Vauxhall, Adelaide, Oxford, Pottersburg and Southland (also referred to as Lambeth). An additional plant has been proposed for construction in 2020 for water treatment in the south of London (Clear, 2006). Combined, the system of PCPs average 216,000 MLD (million litres per day) (City of London, 2009). The treatment capacity varies for each plant and has changed over years of service; the most current capacities can be found in Table 5.2. The effluent from each plant in the City is discharged into the Thames River, directly affecting water quality. All active plants currently meet or exceed MoE guidelines for suspended solids, biochemical oxygen demand and phosphorous levels (City of London, 2009). However, during periods of high flows, sewage systems can become overloaded and bypass treatment allowing raw sewage to discharge directly into the Thames River without any form of treatment (Clear, 2006).

Table 5.2: PCP capacities and construction dates (adapted from City of London, 2010)

PCP	Initial Year of Construction	Allowance* (m3/day)	Actual Flow** (m3/day)	Percentage of Allowance (%)
Greenway	1901	152,175	122,000	80.2
Vauxhall	1916	20,900	17,500	83.7
Pottersburg	1956	39,100	27,292	69.8
Adelaide	1958	36,400	27,399	75.2
Oxford	1960	17,250	9,880	57.2
Lambeth/Southland***	1963	564	271	48.0

* Based on Certificate of Approval (CoA)
** Average annual flow observed in 2009
*** Actual performance limit of 375m3/day based on performance tests

PCPs in London have been constructed in low-lying areas close to the river rendering them susceptible to flooding (Figure 5.15). Pottersburg, Adelaide and Greenway currently experience difficulties during high flow situations from extreme events in combination with serving London's growing population. In 2009, Greenway PCP averaged peak flows of about 238,000 m^3/day – over the daily allowance set out in CoA (City of London, 2010b). This means on multiple occasions, raw sewage has bypassed the plant and been discharged directly into the Thames. Raw sewage bypass events can cause unpleasant odors, affect aquatic biota and in extreme cases, become hazardous to human health.

Direct flooding and inundation of PCPs interferes with primary and secondary treatment processes and equipment (clarifiers, tanks, electrical, etc.). The Water Environment Research Foundation suggests that roughly 4ft (1.2m) of water is enough to short out electrical equipment. As a result of their proximity to the river, access to and from the plants during a flood event is a major concern for emergency management, safety of PCP personnel and for maintaining plant functionality.

There is the potential for PCPs to function at full, partial or zero capacity. The degree of failure of PCP is dependent on multiple factors. Pumping stations (primary sewage conveyance) can also become overwhelmed during wet weather and bypass PCPs and discharge directly into the Thames River. However, this case study does not consider these pumps and recommends that they are included in future flood risk assessment work.

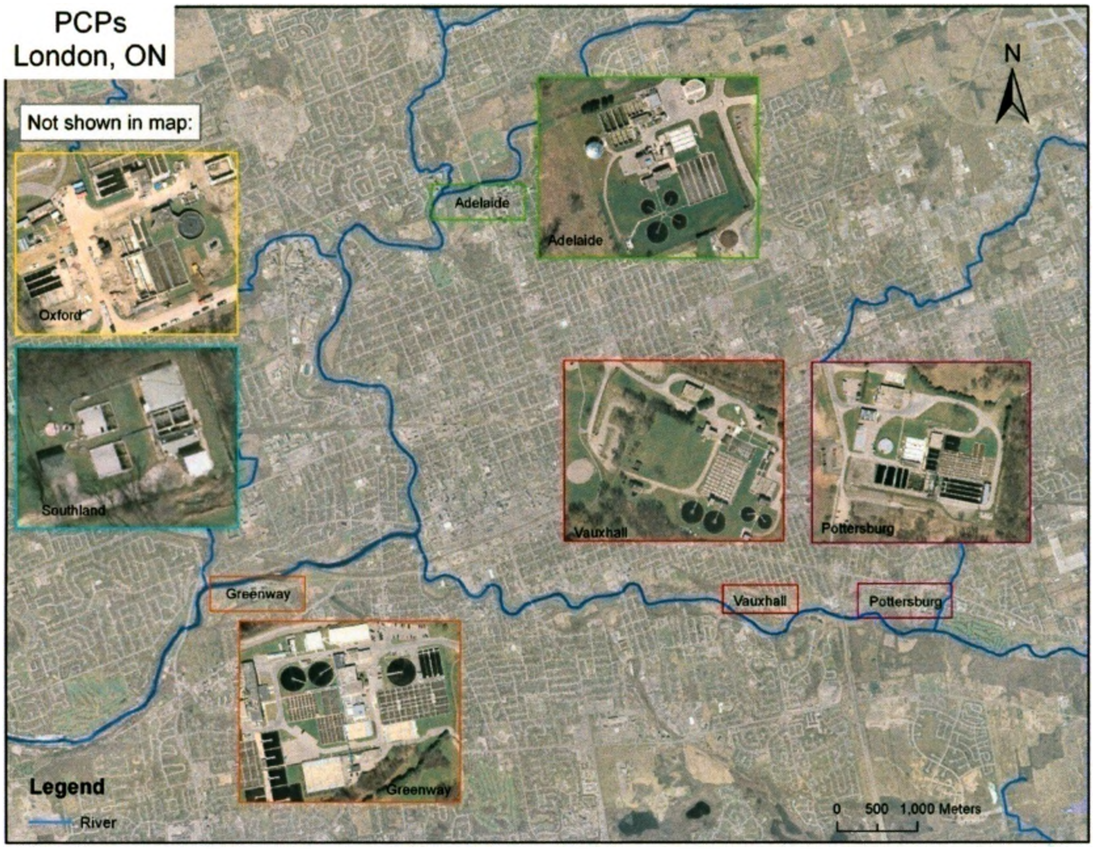


Figure 5.15: Location of PCPs on the Thames River in GIS

Roads

Roads are important to a city for communication, travel, transportation of goods and business. The City of London's arterial road network can be seen in Figure 5.16. During natural disasters roads are critical to: (a) emergency preparedness; (b) emergency response, especially in rescuing stranded individuals, transporting the sick or injured, and providing access to critical facilities; (c) recovery actions, such as transporting goods and providing essential services. This case study focuses on primary and arterial roads, at the recommendation of the City of London. These roads are all paved asphalt or concrete.

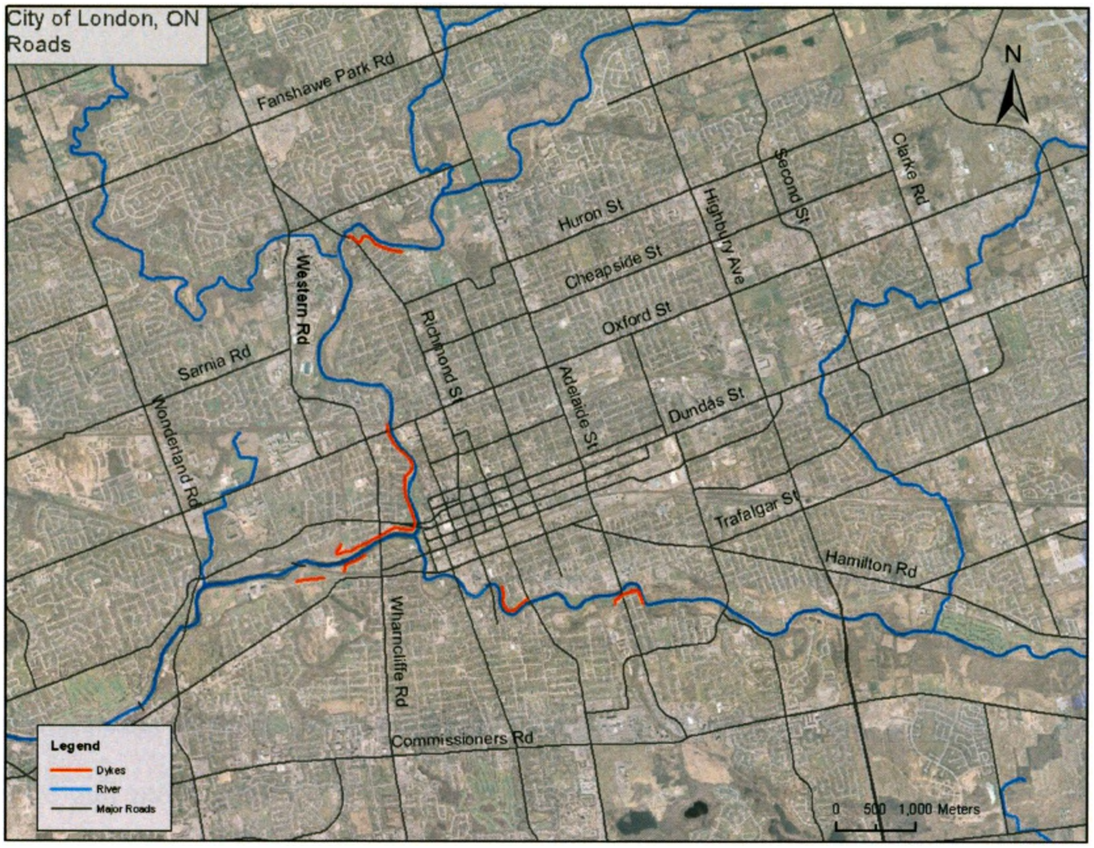


Figure 5.16: Road network on the Thames River in GIS

Roads subject to flooding may incur damage due to embankment scour, rutting or surface debris damage (Transport Canada, 2008). The Southern U.S. has documented road damages due to flooding where hurricanes make flooding a regular occurrence. The primary failure mechanisms for roads subject to flooding include embankment scour, subsurface soil washout and rutting (Figure 5.17). Although roads may not experience complete failure, floods may reduce their useful lifespan and inundated roads will likely require repair and replacement sooner than anticipated.

Figure 5.17: Road collapses at Springbank Dam in July, 2000 (UTRCA, 2000)

Roads that are inundated are hazardous to vehicle and pedestrian safety. Vehicles are more likely to experience hydroplaning on wet roads or get stuck or washed away in deep and fast moving waters. The City is interested in the risk to arterial and primary roads only. Arterial roads may be classified as those experiencing high volumes of intra-urban traffic and moderate volumes of inter-neighbourhood traffic. Primary collector roads accommodate light to moderate volumes of inter-neighbourhood traffic. More specific details may be found in Table 5.3. There are over 250km of arterial and primary roadways in the City. The City of London released a Transportation Master Plan in 2004 which identifies personal vehicles as the primary mode of transportation for London residents. This emphasizes the need to keep roadways safe and maintained in good condition.

Table 5.3: Details of arterial and primary collector roads (adapted from City of London Official Plan, 2007)

Type	Function	Lanes	Speed (km/hr)	Pedestrian Access	Cyclists Access	Intersection Policy
Arterial	High volume intra-urban traffic Moderate volume of inter-neighbourhood traffic Bus routes	2+	50-80	Sidewalk one or both sides	May have wide curb or bike lane	Intersects freeways, expressways, arterial roads and primary collectors
Primary Collector	AADT less than 15,000 Light to moderate volume inter-neighbourhood traffic Bus routes	2-4	50-60	Sidewalk one or both sides	May have wide curb or bike lane	Intersects arterial, collector, and local roads

Pedestrians are also in danger and inconvenienced when roads are flooded or closed. It is possible that flood waters sweep people away or they get stranded due to access roads being cut off. Marco (1994) suggests persons may be swept away by flood water with velocities greater than only 0.5m/s. It is important to identify which roads may become inundated and cut off access to critical facilities during the disaster and to plan road closures to protect civilian safety and identify alternate routes during a flood event.

Transportation division should be prepared for an increase in flood events and subsequent road closures. Spatial access is described in Bowering (2011).

5.3 Risk Assessment

The process for applying the risk assessment methodology to the case study area includes:

(1) Data collection and sufficiency analyses

(2) Preparation of input and preprocessing of data

(3) Extraction of flood inundation levels for all infrastructure elements in the flood plains

(4) Calculation of the infrastructure risk index

(5) Presentation of risk results in tables and maps

(6) Risk prioritization

5.3.1 Data sufficiency, collection and preprocessing

This case study is data intensive and required detailed data pertaining to all major infrastructures in the City of London. Data was collected from a variety of sources including, but not limited to: UTRCA, City of London, Statistics Canada, UWO Serge A. Sauer Map Library and MPAC in a multitude of formats: GIS shape files, budgetary information, interviews, reports, numerical and statistical tables. Resolution and quality of the data varies by source and preprocessing was required to make data compatible. The year 2009 was used as a benchmark for data and wherever possible, data was corrected to reflect most recent changes. The data limited the level of detail in the risk assessment. Data contained in GIS shape files (including inundation depths) was extracted by procedures described in Bowering (2011). Floodplains produced in hydraulic analysis are used directly as input into the risk assessment methodology (Sredojevic and Simonovic, 2009).

5.3.2. Probability of flood hazard under climate change

Probability represents the likelihood of a particular flood event occurring in a given year. This value is based on the RP of each climate scenario. The five climate change cases considered in this study are:

(i) 100-year Climate Change Lower Bound (CC_LB)
(ii) 250-year Climate Change Lower Bound (CC_LB)
(iii)100-year Climate Change Upper Bound (CC_UB)
(iv) 250-year Climate Change Upper Bound (CC_UB)
(v) Additional 250-year UTRCA (250 UTRCA)

For the 100 year CC_LB and CC_UB scenarios, the probability is 1%, calculated as follows:

$$P = \frac{1}{RP} \tag{5.1}$$

$$= \frac{1}{100}$$

$$= 0.01 \rightarrow 1\%$$

This indicates the 100 year CC_LB scenario is *equally likely* as the CC_UB scenario as potential future climate for the region. Every 100 year event between CC_LB and CC_UB are also equally likely to represent future climate; providing a range of possible future climate scenarios. Similarly, for the 250 year CC_LB, CC_UB and UTRCA scenarios, the probability, P of flood hazard occurrence is 0.4% for a given year. These values are used directly in the risk assessment calculation. Upon applying probability of hazard the risk equation becomes:

$$R_e = 0.01 \times \sum_{i=1}^{3}(EF_i \times IM_i) \tag{5.2}$$

$$R_e = 0.004 \times \sum_{i=1}^{3}(EF_i \times IM_i) \tag{5.3}$$

These equations are used to represent risk for all five climate change cases (100 CC_LB; 100 CC_UB; 250 CC_LB; 250 CC_UB; 250 UTRCA).

5.3.3. Economic data

Economic data related to potential flood losses was obtained from municipal budget reports, Municipal Property Assessment Corporation (MPAC) and interviews with City experts. For the level of detail this case study requires, it was necessary to obtain some sensitive and confidential data (particularly related to economic value of properties). Where necessary, an attempt is made to best describe the data used in the assessment for a comprehensive understanding of risk methodology without releasing confidential information.

The parameters used to describe EV for the City of London application is provided in Table 5.4. More comprehensive, consistent and reliable input data is desirable.

Table 5.4: Description of Economic Value (EV) for infrastructure type and their data sources

Infrastructure	EV_1	EV_2	EV_3	Data Source
Residential Bldgs	None	Value of contents	Value of structure	MPAC
Commercial Bldgs	Profit losses	Value of contents	Value of structure	MPAC
Industrial Bldgs	Profit losses	Value of contents	Value of structure	MPAC
Schools	None	Value of contents	Value of structure	MPAC; LDSB
Hospitals	None	Value of contents	Value of structure	MPAC; LHS
Fire Stations/EMS	None	Value of contents	Value of structure	MPAC; City of London
Dykes	Value of structures it protects	Value of contents it protects	Value of structure	UTRCA
PCPs	Value of bypass and emergency procedures	Value of equipment	Value of structure	City of London; MPAC
Bridges	None	None	Value of bridge	City of London BMS
Roads	None	None	Value of road	Transport Canada

Value of residential, commercial, industrial, institutional (schools, churches, etc.), critical facilities structures and contents are provided my MPAC corporation. As a result of data sensitivity and confidentiality agreements, exact values for EF is not released. They are, however, included in calculation of the risk indices and are reflected in the value of the overall risk discussed in more detail in the following sections. Economic impact values for PCP structures and contents are available in municipal budgetary reports and documents. Bridge EV_3 values are obtained from the City of London Bridge Management System (BMS) internal municipal documents.

Some data collected requires some economic impact values to be adjusted to reflect value in year 2009 to account for inflation. The Consumers Price Index (CPI) is used to reflect these changes (equation 4.13). Updating these values ensures risk indices are not skewed to give preference to newer (more inflated) structures.

The following tables provide the average yearly value of the Consumer Price Index (CPI) for the previous 25 years (Statistics Canada, 2010). Note the case study uses CPI from 2009 as reference year; value of 113.7.

Table 5.5: List of CPIs from Statistics Canada

Year	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
CPI	113.7	113.3	110.8	108.8	106.9	104.6	102.7	100.0	98.0	95.1

Year	1999	1998	1997	1996	1995	1994	1993	1992	1991	1990
CPI	92.4	90.6	89.8	88.2	86.8	84.7	84.7	83.2	82.4	78.7

Year	1989	1988	1987	1986	1985
CPI	75.1	71.0	67.8	64.6	61.8

On the whole, as the flooding depth increases, the infrastructure sustains greater damages.

5.3.4. Impact Multipliers

This study focuses on those damages affecting municipal infrastructure and considers three variables as a measure of these consequences (defined as impact multipliers): the loss of function (IM_1), loss of equipment (IM_2) and loss of structure (IM_3). Each IM is measured as a percent loss and calculated using both quantitative and qualitative information.

Loss of Function (IM_1)

The function is specific for each type of infrastructure. The function of a road is different than the function of a building (Table 4.1). Regulations, perceived danger and dictate the point at which the infrastructure losses its ability to perform its designed function. In this study, infrastructure performance is often considered either completely functional and assigned a IM_1 value of 0, or completely not functional and assigned IM_1 value of 0. (Table 5.7). PCPs and critical facilities may operate at partial capacity and therefore may assume an IM_I value between 0 and 1, if some, but not all, of the access routes are blocked by floodwaters. This methodology assigns a fractional value of IM_1depending on the number of incoming or outgoing major routes and the number of routes that are flooded. The process in determining these values is described in Bowering (2011).

Loss of Equipment (IM_2)

Buildings and critical facility values are estimated using methods from regional Glengowan Study (Marshall Macklin Monaghan, 1983) that are based on building type. Generally, contents are estimated to be a fraction of the damage incurred by the entire infrastructure element; typically, these losses are estimated to be about 30%. Equipment loss for pollution control plants are estimated based on the City of London's 2009 Wastewater Budget (London, 2009). The height at which electrical equipment becomes submerged significantly increases IM_2 losses as equipment shorts and can causes irreparable damages. Transportation and flood protection infrastructure does not have any equipment or contents directly associated to it and therefore this impact multiplier does not apply.

Loss of Structure (IM_3)

Fuzzy risk component is used to modify the stage-damage curves. Fuzzy membership functions are created by combining the current state of infrastructure with interview responses from experts in various departments at the City of London. System state curves represent the present condition of the infrastructure elements. Condition of an infrastructure element is based on characteristics like age, material, maintenance and weathering. These values are used in creating a system state fuzzy membership curve for each infrastructure element. Each response defines a point on the system state curve, in this case a triangular distribution.

Experts were asked a series of questions pertaining to the current condition of infrastructure. Respondents were requested to rank criteria that affects the overall condition of an infrastructure on a scale from zero (does not affect at all) to ten (critically affects). Using these rankings, it is possible to develop system state fuzzy membership curves for each infrastructure element based on its age, maintenance, material and weatherability. In a second round of interviews, experts were asked to provide their personal perception of risk and define what level of risk is considered "acceptable". Using responses, it is possible to create acceptable limit state fuzzy membership curves

(Figure 5.18). When the system state curves (triangular functions in Figure 5.18) are in complete overlap with the acceptable performance curve, there is complete agreement between state and perception; the infrastructure is considered to be entirely acceptable (Figure 5.18; Bridge 3). System state curves that intersect the acceptable level of performance curve are in partial agreement and considered somewhat acceptable (Figure 5.18; Bridge 2). Those system state curves that are entirely outside of the acceptable level of performance curve have no agreement and are considered completely unacceptable (Figure 5.18; Bridge 1). To achieve low qualitative risk index, it is desirable that all infrastructure are in complete agreement with acceptable level of performance.

One drawback of this approach includes suppression of individual perceptions of risk when administering questions to groups of people. Individual responses from the City experts were observed to be suppressed during interviews. Rather than express individual responses, often agreement or consensus responses were provided. This limits the value of interview responses and fuzzy approach; where a greater number of respondents is more desirable to capture variances in risk perception. In the case that more than one response was not provided in an interview, a lower and upper bound were assumed around original response provided by interviewees.

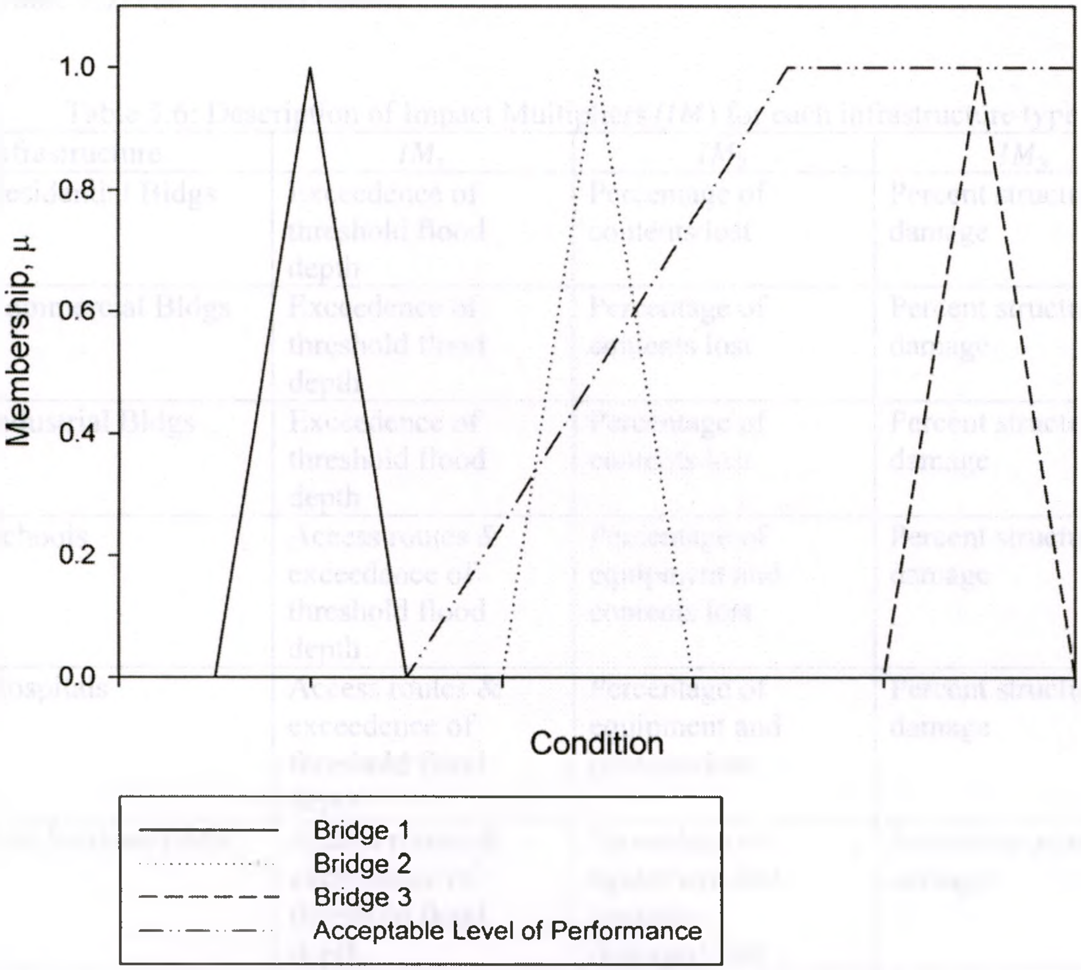


Figure 5.18: Theoretical fuzzy membership functions for bridges

Loss of structure impact multiplier IM_3, is then obtained by relating the maximum level of stage in a building to expected damages incurred to the built infrastructure for a given flood event. These values are obtained from regional stage-damage curves provided by Flood Damage Estimation Guide (Helsten and Davidge, 2007). The value for IM_3 for transportation infrastructure, barriers and PCPs is estimated from interviews with technical experts. These values are then input into risk index equation.

A description of all impact multipliers (Table 5.6) and the range these values may take (Table 5.7) can be found below.

Table 5.6: Description of Impact Multipliers (IM) for each infrastructure type

Infrastructure	IM_1	IM_2	IM_3
Residential Bldgs	Exceedence of threshold flood depth	Percentage of contents lost	Percent structural damage
Commercial Bldgs	Exceedence of threshold flood depth	Percentage of contents lost	Percent structural damage
Industrial Bldgs	Exceedence of threshold flood depth	Percentage of contents lost	Percent structural damage
Schools	Access routes & exceedence of threshold flood depth	Percentage of equipment and contents lost	Percent structural damage
Hospitals	Access routes & exceedence of threshold flood depth	Percentage of equipment and contents lost	Percent structural damage
Fire Stations/EMS	Access routes & exceedence of threshold flood depth	Percentage of equipment and contents damaged/lost	Percent structural damage
Dykes	Exceedence of threshold flood depth	Percentage of equipment and contents damaged/lost	Percent structural damage
PCPs	Loss of essential equipment; access roads; exceedence of threshold flood depth	Percentage of equipment damaged/lost	Percent structural damage
Bridges	Exceedence of threshold flood depth	None	Percent structural damage
Roads	Exceedence of threshold flood depth	None	Percent structural damage

Table 5.7: Range of Impact Multipliers (IM) for each infrastructure type

Infrastructure	IM_1	IM_2	IM_3	Sources*
Residential Bldgs	[0,1]	[0-100%]	[0-100%]	London S-D curves
Commercial Bldgs	[0,1]	[0-100%]	[0-100%]	London S-D curves
Industrial Bldgs	[0,1]	[0-100%]	[0-100%]	London S-D curves
Schools	[0-1]	[0-100%]	[0-100%]	London S-D curves; LDSB
Hospitals	[0-1]	[0-100%]	[0-100%]	London S-D curves
Fire Stations/EMS	[0-1]	[0-100%]	[0-100%]	London S-D curves
Dykes	[0,1]	[0-100%]	[0-100%]	Interview S-D curves; London S-D curves; reports
PCPs	[0-1]	[0-100%]	[0-100%]	Interview S-D curves; reports
Bridges	[0,1]	None	[0-100%]	Interview S-D curves; HEC-RAS; reports
Roads	[0,1]	None	[0-100%]	Interview S-D curves; reports

*S-D curves refer to Stage-Damage curves. These curves are commonly used to assess damage to structures. Interview S-D curves refer to curves developed in interviews with technical experts and local reports pertaining to previous damages and financial statements.

Once impact multipliers (IM) have been determined, it is possible to calculate the risk index, RI for each infrastructure element. Every infrastructure within the floodplains will have its own RI for each of the climate cases (100 CC_LB; 100 CC_UB; 250 CC_LB; 250 CC_UB, 250 UTRCA). In this way it is possible to observe changes in risk across all cases to determine infrastructure at high risk. Risk indices of all infrastructure within a spatial unit (DA) are summed together to determine locations of high risk.

5.4 Results

The following sections describe the assumptions made during the risk assessment and results from risk assessment calculations. The tables and maps show in detail the risk indices for each climate scenario. In addition, five comparison analyses are conducted to assess the contribution of climate change to increase in risk to municipal infrastructure, described as analysis one through five.

5.4.1. Summary of Scenario Impacts

The extent of flooding varies for each climate scenario and the number of infrastructure elements inundated and depth to which they are flooded also changes (Table 5.8).

The flood extent and absolute number of structures affected, however, does not represent climate risk. Infrastructure risk due to climate change is affected by the probability of the hazard event occurring (as described in 5.2.2). The final risk indices, including all infrastructure elements, e across the entire City of London (all t) is presented in Table 5.9.

Table 5.8: Summary of flood extent and infrastructure impacted for each climate case

Climate Case	Area Flooded (km^2)	Type of Structure Affected	Number of Structures Affected
100 CC_LB	22.95	Buildings	1110
		Bridges	85
		Critical Facilities	3
		Dykes	1
		PCPs	4
		Roads	112
100 CC_UB	25.79	Buildings	2535
		Bridges	88
		Critical Facilities	6
		Dykes	4
		PCPs	4
		Roads	152
250 CC_LB	25.95	Buildings	2517
		Bridges	89
		Critical Facilities	6
		Dykes	4
		PCPs	4
		Roads	151
250 CC_UB	27.87	Buildings	2706
		Bridges	91
		Critical Facilities	6
		Dykes	4
		PCPs	4
		Roads	164
250 UTRCA	24.56	Buildings	1762
		Bridges	89
		Critical Facilities	3
		Dykes	4
		PCPs	4
		Roads	147

Table 5.9: Final risk index (unit less) for four climate change scenarios plus additional UTRCA scenario, all infrastructure; spatially independent

	100 CC_LB	*100 CC UB*	*250 CC_LB*	*250 CC_UB*	250 UTRCA
Risk Index	5,730,000	9,840,000	3,668,000	5,004,000	3,188,000

Risk in 100 CC_UB scenario is significantly higher than all others. This is in part due to the higher probability of a 100 year flood event occurring compared to a 250 year event. There are more infrastructure element inundated under the 250 CC_UB scenario (due to larger flood extent) but the difference does not compensate for the fact that the 250 year flood event is significantly less likely to occur. The 250 UTRCA scenario is used to represent current risk. The risk in this scenario is less than all other climate change scenarios considered in the case study. The 250 UTRCA risk is lower than the 250 CC_LB scenario which suggests that currently there are areas unprepared to handle additional climate change loads. To target which particular infrastructure contribute most to risk, composition of overall risk index is provided in Table 5.10 for each climate scenario.

Table 5.10: Final risk index (unit less) for four climate change scenarios plus additional UTRCA scenario, infrastructure independent; spatially independent

Infrastructure	*100 CC_LB*	*100 CC_UB*	*250 CC_LB*	*250 CC_UB*	*250 UTRCA*
Barriers	544,700	2,236,600	781,200	1,115,100	632,500
Bridges	1,698,300	2,011,200	791,300	927,500	894,700
Buildings	1,491,400	3,434,600	1,267,400	1,918,300	752,200
Critical Infrastructure	11,800	17,400	7,100	8,500	0
PCPs	124,400	284,700	78,400	304,000	167,700
Roads	1,400	2,200	900	1,000	800

Bridges and buildings appear to contribute most to overall risk measure. Highest risk is in 100 CC_UB scenario to buildings. This, in large part, can be attributed to the overtopping failure of the WLD at downtown Forks location. The dyke protects mainly residential structures which become inundated incurring damage to contents and foundation. Water levels behind the dyke under 100 CC_UB scenario are over 3m at some locations. At this depth, many personal belongings and furniture becomes garbage due to moisture damage. The house structural components are likely to incur damage at these depths that would cause structural failure or require financial investment over the value of the home to return it to pre-flooding condition. PCPs are very expensive infrastructure and each plant contributes a significant amount to overall risk. Risk is higher in 250 CC_UB scenario because the flood extent is very large and inundates critical treatment components. As a result, some PCPs are not able to provide preliminary or secondary treatment, resulting in loss of function and requiring the plants to bypass raw sewage into the Thames River. The costs associated with bypass are high and therefore contributes significant portion to PCP risk. Access in 250 CC_UB is restricted which also contributes to high risk in this scenario. Inundated roads appear to minimally contribute to overall risk.

5.4.2. Assumptions in Analyses

In the case study application it was necessary to make assumptions at different stages in the risk assessment process. Many of these assumptions were made as a result of poor data quality or data insufficiency, to best support the methodology. These assumptions are of high importance for interpretation of the study results.

[1] Infrastructure elements considered in this study are assumed not to have any flood proofing measures implemented at the time of a flood event. This assumption is made to present a ‘worst case scenario’ approach to flood risk assessment.

[2] Only those infrastructure elements in the floodplains are considered significant. However, infrastructure outside of these areas may also experience direct and indirect

impacts of flooding. For example, sewer backups may result from storm infrastructure under capacity and may cause localized basement flooding or road closures.

[3] Stage-damage curves for building structures are region-specific and current as of 2007. These curves are the most recent curves available for the City of London. As population demographics, infrastructure construction practices and weather patterns change, these curves will require updating to provide the most up-to-date and accurate structural damage estimations.

[4] Buildings of similar type (e.g. 2-story residential) are all assumed to experience similar damage at the same inundation level during a flood event. However, these structures will not react identically in a flood situation. The response of a structure is dependent on factors such as: quality of construction and regular maintenance which play important factor in the structural integrity of a house during a flood event

[5] The stage-damage curves for buildings provided by Flood Damage Estimation Guide (Helsten and Davidge, 2007) do not have a category to represent damages to inundated apartments. Therefore it is assumed apartments perform similarly to 2-story residential structures with no basement.

[6] Structures identified as sheds or garages are assumed to experience no damage. The data pertaining to these structures within the City is limited. Sheds and garages are therefore associated with zero risk.

[7] Where data for a particular piece of infrastructure is missing or incomplete, an estimation is made based on structures with similar properties in the same neighbourhood.

[8] Residential and commercial content damages are assumed to be 30% of a structures total damage in the Flood Damage Estimation Guide (Helsten and Davidge, 2007). This study uses the stage-damage curves provided by the Flood Damage Estimation Guide and therefore adopts the same assumption.

[9] More detailed and specific data (including use of regional surveys) could increase accuracy, reliability and representative risk assessment

[10] Data resolution is not as spatially refined as desired. Refer to Bowering (2011) for discussions of coarse spatial resolution of some data, which limits the reliability of analysis.

[11] Data suppression observed during the interviews. Individual expression was often compromised by work hierarchy. Application of fuzzy reliability methods rely on the variability and perception of individuals for accurate representation and aggregation. Although difficult to coordinate, the author recommends individual interviews for fuzzy-related input.

[12] The study performs static flood risk analysis but the nature of policy, infrastructure and climate is change. Therefore the study would have to be updated accordingly as more current information becomes available; at the same time, improved data could allow for a more detailed risk assessment and the methodology presented could at this time be revised.

[13] Many important infrastructures are not included in the study including: utility grids, drinking water infrastructure, railways, etc. A large component of selection criteria is related to the availability of data. Risk is more representative of true value if all essential municipal infrastructures are considered in assessment.

[14] There are discrepancies between stage-damage curves used in the analysis and the actual home values as provided by MPAC. These differences often result in using the actual home value to represent damage incurred to a building structure and these values are considerably lower than damage as defined in the curves. The result is often building risk index is underestimated relative to other infrastructure in the case study. It also may skew the actual differences in risk between building structures as they will be defined by difference in actual home value as opposed to actual damage incurred.

5.4.3. Risk Tables and Risk Maps

Tables and maps are used to disseminate risk results. Tables are created first and are used to in combination with ArcGIS software to represent risk spatially in risk maps. Both dissemination styles provide valuable risk information and appeal to different types of stakeholders.

Risk Tables

The first output of risk assessment methodology includes risk tables. These tables are used to display numerical risk results used for creating spatial risk maps. Risk indices are presented for each infrastructure type, under each flood scenario. In this way it is possible to compare risk across infrastructure and identify those infrastructure elements which contribute most significantly to risk.

Risk Maps

Risk maps are used for spatial risk representation. ArcGIS is program used to create maps for easy identification of areas of high risk within the City. Maps are produced for each climate case (100 CC_LB; 100 CC_UB; 250 CC_LB; 250 CC_UB) and the additional 250 UTRCA scenario for all infrastructure considered applicable to the case study. Those areas in darker shades represent regions of high risk in the City, regions of lower risk are lighter, and regions unaffected by riverine flooding are lightest as indicated in the map legends. These maps identify areas of focus for climate change adaptation efforts. For more details on risk mapping procedure and spatial flood risk analysis refer to Bowering (2011).

Tables and maps are related to each other and by way of a GIS tool, the risk indices from tables are linked to spatial units (DAs) in the program. Using this link it is possible to graphically display risk indices for each climate scenario across the entire City in a GIS environment. As risk indices change (e.g. with inclusion of new infrastructure), the risk tables are updated in the spreadsheet associated with GIS program. GIS then automatically retrieves this information and redistributes spatial risk in the form of updated risk maps. This provides for minimal computational requirements and simplicity in updating maps when reevaluating risk.

Numerical risk values presented in tables may be more useful for some end users while maps may be more understandable and appropriate for other applications. The maps are directly associated with tables and use of both provides a more comprehensive description of risk.

5.5 Comparative Analyses of Results

This section describes five comparison analyses of climate change flood risk results. The purpose of these comparisons is to indentify differences between lower and upper bounds of climate change risk (CC_LB; CC_UB), changes in risk between the two return regulatory return periods (100-year; 250 year) and determine the contribution of climate change to the increase in flood risk to infrastructure. These comparisons are defined as follows:

Analysis 1: Comparison of 100 year climate scenarios

Change in risk index between 100 CC_LB and 100 CC_UB scenarios

Focus: Areas that experience greatest change in risk between the two climate scenarios (for the same return period)

Purpose: To identify drawbacks of selecting a single climate scenario and identify those areas exposed to additional risk if subscribing to either CC_LB or CC_UB scenario

Analysis 2: Comparison of 250 year climate scenarios

Change in risk index between 250 CC_LB and 250 CC_UB scenarios

Focus: Areas that experience greatest change in risk between the two climate scenarios (for the same return period)

Purpose: To identify drawbacks of selecting a single climate scenario and identify those areas exposed to additional risk if subscribing to either CC_LB or CC_UB scenario

Analysis 3: Comparison between two return periods for lower bound climate scenario

Change in risk index between 100 CC_LB and 250 CC_LB scenarios

Focus: Areas that experience greatest change in risk between the regulatory flood events (for the same climate scenario)

Purpose: To identify susceptibilities of areas if subscribing to a particular return period

Analysis 4: Comparison between two return periods for upper bound climate scenario

Change in risk index between 100 CC_UB and 250 CC_UB scenarios

Focus: Areas that experience greatest change in risk between the regulatory flood events (for the same climate scenario)

Purpose: To identify susceptibilities of areas if subscribing to a particular return period

Analysis 5: Aggregated risk contribution of climate change

Change in risk index between 250 UTRCA (current) and 250 CC_UB scenarios

Focus: Areas that experience greatest change in risk between the two climate scenarios (for the same return period)

Purpose: To identify regions that may presently be unprepared for flood disaster and climate change consequences.

The five analyses cases use the following mathematical relationships to describe the change of risk.

Analysis 1:

$$\text{Change} = [(R_{DA(100CC\_UB)} - R_{DA(100CC\_LB)})/R_{DA(100CC\_LB)}] * 100 \qquad (5.4)$$

Analysis 2:

$$\text{Change} = [(R_{DA(250CC\_UB)} - R_{DA(250CC\_LB)})/R_{DA(250CC\_LB)}] * 100 \qquad (5.5)$$

Analysis 3:

$$\text{Change} = [(R_{DA(250CC\_LB)} - R_{DA(100CC\_LB)})/R_{DA(100CC\_LB)}] * 100 \tag{5.6}$$

Analysis 4:

$$\text{Change} = [(R_{DA(250CC\_UB)} - R_{DA(100CC\_UB)})/R_{DA(100CC\_UB)}] * 100 \tag{5.7}$$

Analysis 5:

$$\text{Change} = [(R_{DA(250CC\_UB)} - R_{DA(250UTRCA)})/R_{DA(250UTRCA)}] * 100 \tag{5.8}$$

Where,

$R_{DA(100CC\_UB)}$ = Risk Index for dissemination area DA, 100 CC_LB scenario;

$R_{DA(100CC\_LB)}$ = Risk Index for dissemination area DA, 100 CC_UB scenario;

$R_{DA(250CC\_LB)}$ = Risk Index for dissemination area DA, 250 CC_LB scenario;

$R_{DA(250CC\_UB)}$ = Risk Index for dissemination area DA, 250 CC_UB scenario;

$R_{DA(250UTRCA)}$ = Risk Index for dissemination area DA, 250 UTRCA scenario.

The following comparisons are used to gauge areas of high risk for further consideration in policy and management decisions. High risk areas are displayed in tables and are identified by their four-digit DA code. To quickly recognize these high risk areas, the second column in the tables provides the reference cell identification. These reference cells provide information to where the particular DA is located spatially in risk maps; use it for quick identification of high risk areas.

Analysis 1: Comparison of 100 year climate scenarios (Table 5.11; Figure 5.19)

Areas of highest change in risk index include:

Cells B3/B4: Along North Thames before confluence with Stoney;

Cell C3: Forks of Thames River;

Cell C3: DA 0706; and

Cells C4/C5: Pottersburg Creek.

Greatest differences between the 100 CC_LB and 100 CC_UB scenarios can be seen in areas that are behind flood protection structures. Broughdale dyke on the North Thames branch of the river experiences much greater inundation depths in the 100 CC_UB scenario than in the CC_LB scenario causing significantly greater damages. Another area of concern is at a culvert located on Pottersburg Creek designed to convey water from Pottersburg Creek to South Thames River. In the 100 CC_LB scenario, this culvert conveys the water much more effectively than in the 100 CC_UB scenario. In the 100 CC_UB scenario the floodwaters are much deeper and the culvert acts like a dam, backing up floodwaters onto nearby properties. The West London Dyke at the Forks location is not overtopped in the 100 CC_LB scenario, but it does become overtopped in 100 CC_UB scenario. This greatly increases flooded extent and increases number of structures flooded; mostly residential properties and an elementary school.

Table 5.11: Risk Index comparison 100 CC_LB and 100 CC_UB scenarios

*DA**	*Cells*	*Percent Change in Risk***
0032	B3	469.7
0313	C3	550.7
0314	C3	2655.4
0315	C3	INFINITE
0323	C3	INFINITE
0324	C3	INFINITE
0325	C3	1240.0
0326	C3	472.3
0329	C3	752.8
0429	C3	582.8

* Note that table only includes ten DAs that exhibit greatest percent change in risk
** Areas with "INFINITE" changes in risk are those areas which under a particular climate scenario experienced no risk and under the other climate scenario, became inundated; effectively infinitely increasing its risk

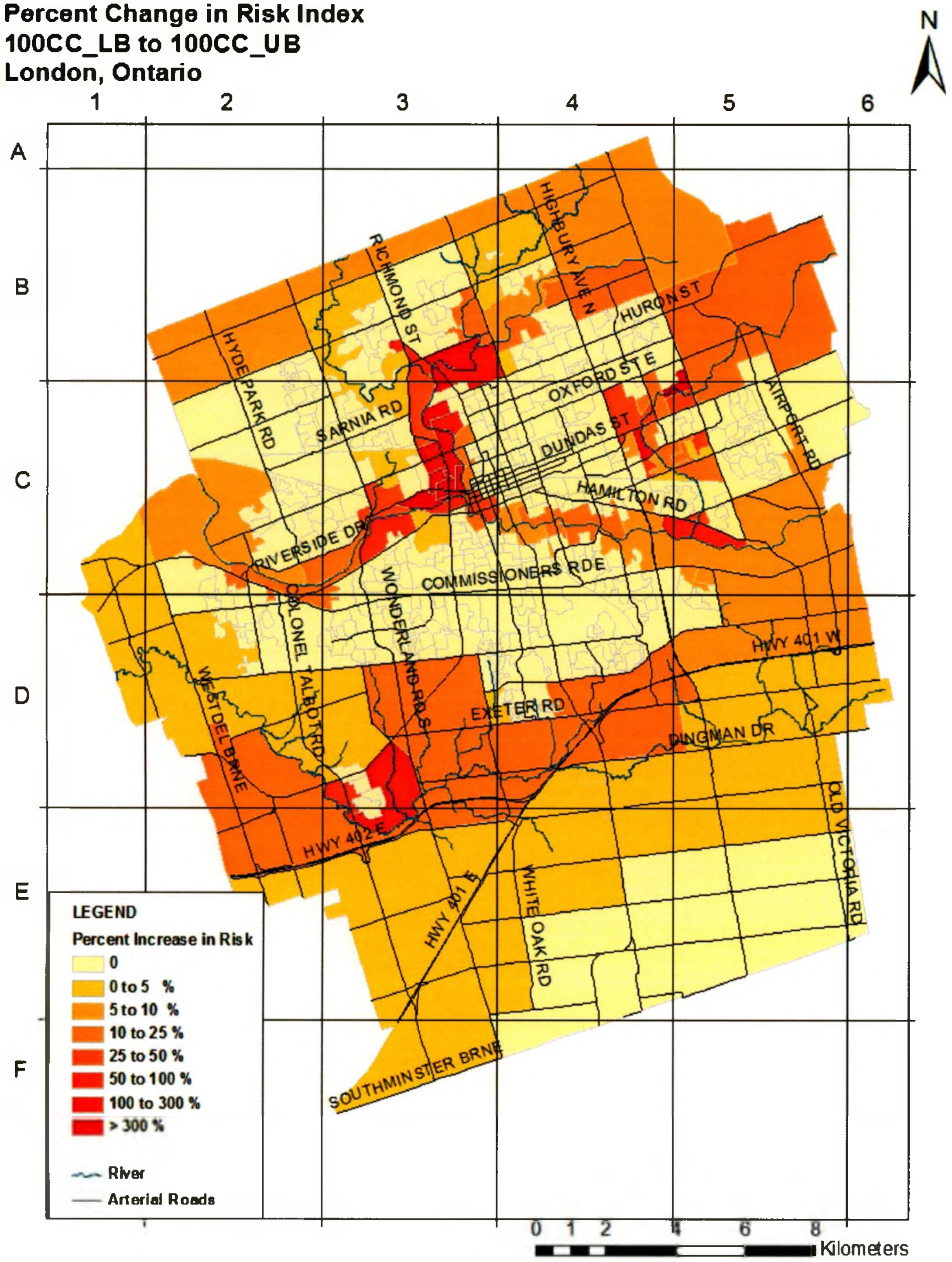


Figure 5.19: Percent change in risk index between 100 CC_LB and 100 CC_UB

Analysis 2: Comparison of 250 year climate scenarios (Table 5.12; Figure 5.20)

Areas of highest change in risk index include:

Cell C4: Vauxhall PCP;

Cell C3: Greenway PCP and North Thames near UWO;

Cell B3: Confluence of Stoney Creek and North Thames, near Fanshawe and Adelaide;

Cell B5: Pottersburg Creek near Airport; and

Cells E3/E4 & D4/D5 Dingman Creek.

The Greenway PCP becomes deeply inundated in the 250 CC_UB scenario and loses a large portion of its functionality, equipment and structural components. The area behind WLD is also inundated to much greater depths in the 250 CC_UB scenario and therefore many residential buildings require complete replacement after a flood event.

Table 5.12: Risk Index comparison 250 CC_LB and 250 CC_UB scenarios

DA	*Cells*	*Percent Change in Risk*
0032	B3	460.5
0035	B3, B4, C3	130.8
0036	B3, C3	201.6
0106	C4	108.6
0328	C3	91.1
0329	C3	121.2
0330	B3, C3	110.7
0541	C3	642.7
0669	B3, B4	222.6
0706	C3	258.5

* Note that table only includes ten DAs that exhibit greatest percent change in risk

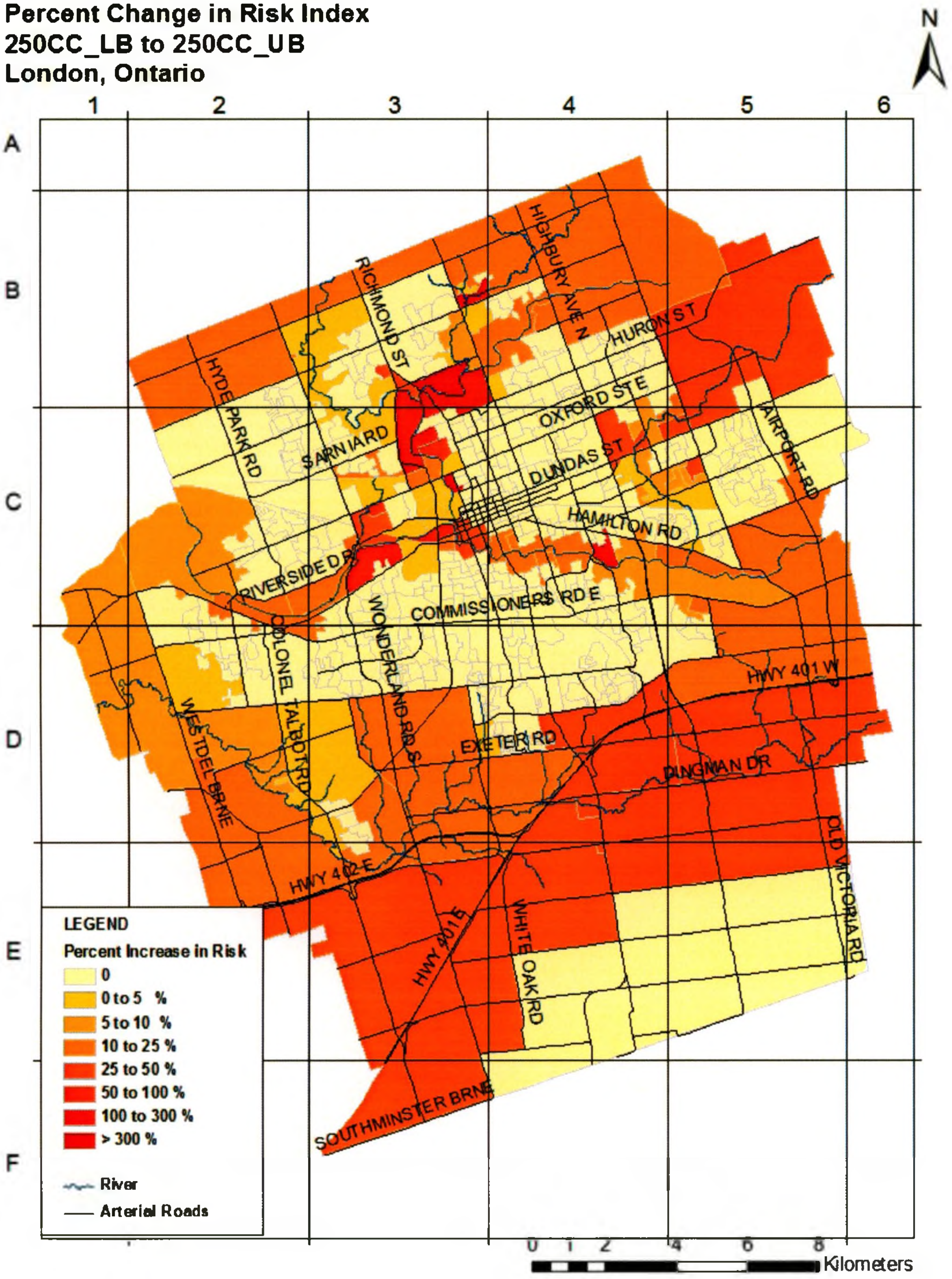


Figure 5.20: Percent change in risk index between 250 CC_LB and 250 CC_UB

Analysis 3: Comparison between lower bounds (Table 5.13; Figure 5.21)

Areas of highest change in risk index include:

Cells C4/C5: Along Pottersburg Creek

Cell C3: Behind the WLD;

Cell B3: Confluence of North Thames and Stoney Creek; and

Cell D3: DA 0466 Dingman Creek near Hwy 402E and Wonderland Rd. S.

Overall, the majority of the percent change from the 100 CC_LB to the 250 CC_LB scenario is a decrease in risk of 25% across the City, indicating that the majority of the flood damage is occurring already under the 100 year flood scenario. The major contribution to additional risk is a result of the WLD being overtopped. In the 100 CC_LB scenario the dyke is performing as designed, however the 250 year event has high enough waters to potentially breach the dyke and flood properties that were protected behind the structure.

Table 5.13: Risk Index comparison 100 CC_LB and 250 CC_LB scenarios

DA	*Cells*	*Percent Change in Risk*
0313	C3	158.5
0314	C3	1001.4
0315	C3	100.0
0323	C3	100.0
0324	C3	100.0
0325	C3	435.7
0326	C3	125.8
0329	C3	241.1
0429	C3	171.9
0660	B5, C4, C5	105.8

* Note that table only includes ten DAs that exhibit greatest percent change in risk

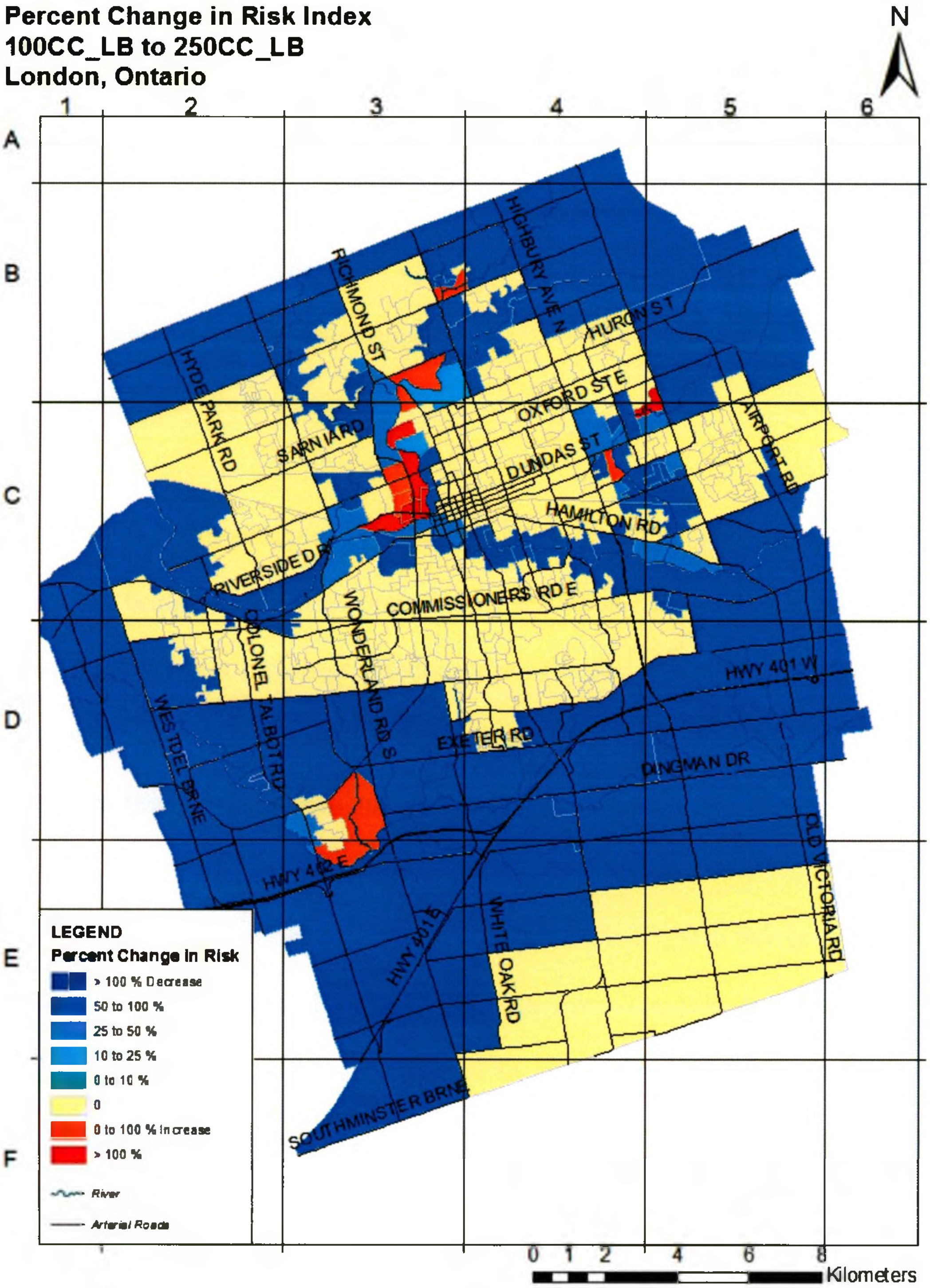


Figure 5.21: Percent change in risk index between 100 CC_LB and 250 CC_LB

Analysis 4: Comparison between upper bounds (Table 5.14; Figure 5.22)

Areas of highest change in risk index include:

Cell B3: DA 0669 on Stoney Creek;

Cell B3: DA 0032 on North Thames;

Cell C3: DA 0541 on North Thames;

Cell C3: DA 0706 along Main Thames; and

Cell D4: DA 0671 on Dingman Creek.

DA 0669 (Cell B3) has bridges, roads and building infrastructure exposed to flooding. Waters reaches bridge decks under both climate scenarios. The 250 CC_UB flood event inundates two apartment buildings previously not flooded in the 100 CC_UB scenario. However, with the rough estimation of apartment damages, they are not enough to compensate for the increased likelihood of the 100 year event.

DA 0032 (Cell C3) has the Richmond Street Bridge (2-BR-03) is at risk of debris damage under both the 100 CC_UB and 250 CC_UB scenarios. The bridge risk factor value is higher under the 100 CC_UB scenario because the difference between the water levels in two scenarios does not compensate for the fact that the 100 year event is more likely to occur. The significant difference in risk can be attributed to the additional flooding of multiple residential properties (up to 13) under the 250 CC_UB scenario.

DA 0541 (Cell C3) is almost triple the risk under the 250 CC_UB scenario than in the 100 CC_UB scenario. The driving factors behind additional risk are three expensive commercial structures inundated under the 250 CC_UB scenario that are not flooded under the 100 CC_UB scenario. Even though the 100 year event is more likely to occur, the risk from additional inundation exceeds the probability of the event occurring.

DA 0706 (Cell C3) risk is largely a result of the inundation depth and extent at Greenway PCP. Ash (waste) piles are inundated under both the 100 CC_UB and 250 CC_UB scenarios; rendering them useless. Under the 100 CC_UB scenario the plant is estimated to be able to maintain partial plant and able to at least provide primary treatment to raw sewage. However, under the 250 CC_UB scenario, the flood extent is much greater and floods most components, requiring complete bypass of the plant for direct discharge into the Thames River. Water quality may become an issue and could have detrimental environmental and health consequences.

DA 0671 (Cell D4) risk is attributed to a culvert on Dingman Creek. Under the 250 CC_UB scenario, the water level approaches (<1m) the top of the culvert invert which can cause debris damage. Water level in the 100 CC_UB scenario does not cross this critical threshold and therefore the risk increase is significant between the two scenarios.

Table 5.14: Risk Index comparison 100 CC_UB and 250 CC_UB scenarios

DA	*Cells*	*Percent Change in Risk*
0032	B3	38.9
0036	B3, C3	-25.1
0071	C5	-36.7
0106	C4	-19.9
0328	C3	-24.1
0329	C3	-11.5
0330	B3, C3	-18.8
0541	C3	178.2
0669	B3, B4	275.3
0706	C3	23.8

* Note that table only includes ten DAs that exhibit greatest percent change in risk

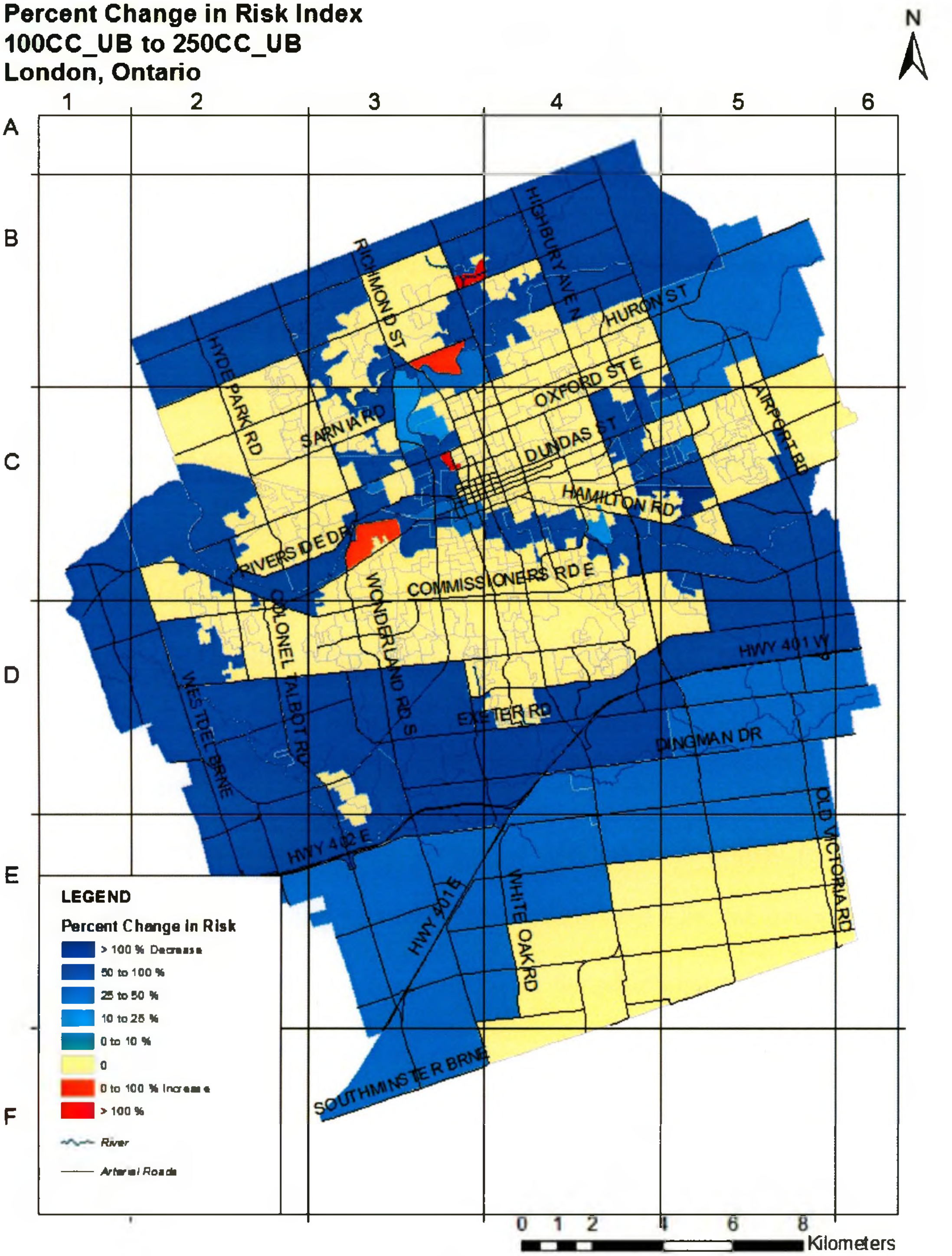


Figure 5.22: Percent change in risk index between 100 CC_UB and 250 CC_UB

Analysis 5: Aggregated risk contribution of climate change (Table 5.14; Figure 5.23)

Areas of highest change in risk index include:

Cells B3/B4: Along North Thames before confluence with Stoney Creek;

Cells C1/D1/D2: Along Dingman Creek, west of Westdel Bourne, south of Oxford;

Cells D5/E3/E4: Along Dingman Creek, south of Highway 402 and 401; and

Cells B5/C4: Along Pottersburg Creek, north of Trafalgar to the airport.

It is important to note the 250 CC_UB scenario and 250 UTRCA case, were constructed using different methods. For a detailed description of creating 250 UTRCA case, please refer to Bowering (2011). For this reason, the risk results and comparison analysis may not be as accurate as for other climate scenarios. The purpose of the UTRCA case is to provide an estimation of current risk under a 250-year flood event and compare it to the 250 CC_UB scenario. The intention is to provide a rough estimation of the contribution of climate change to risk and identify areas that may be most critical to consider in formulating climate change policy and adaptation. Across the City, the overall risk index increases by approximately 74%. This emphasizes the additional risk contribution that climate change is making to the City.

Table 5.15: Risk Index comparison 250 UTRCA and 250 CC_UB scenarios

DA	*Cells*	*Percent Change in Risk***
0032	B3	754.4
0064	C4	2006.5
0066	C4	1467.6
0068	C4, C5	597.2
0069	C4, C5	19452.3
0070	C5	INFINITE
0092	C4, C5	825.1
0589	C4	930.6
0660	B5, C4, C5	691.5
0669	B3, B4	1027.3

* Note that table only includes ten DAs that exhibit greatest percent change in risk
** Areas with "INFINITE" changes in risk are those areas which under a particular climate scenario experienced no risk and under the other climate scenario, became inundated; effectively infinitely increasing its risk

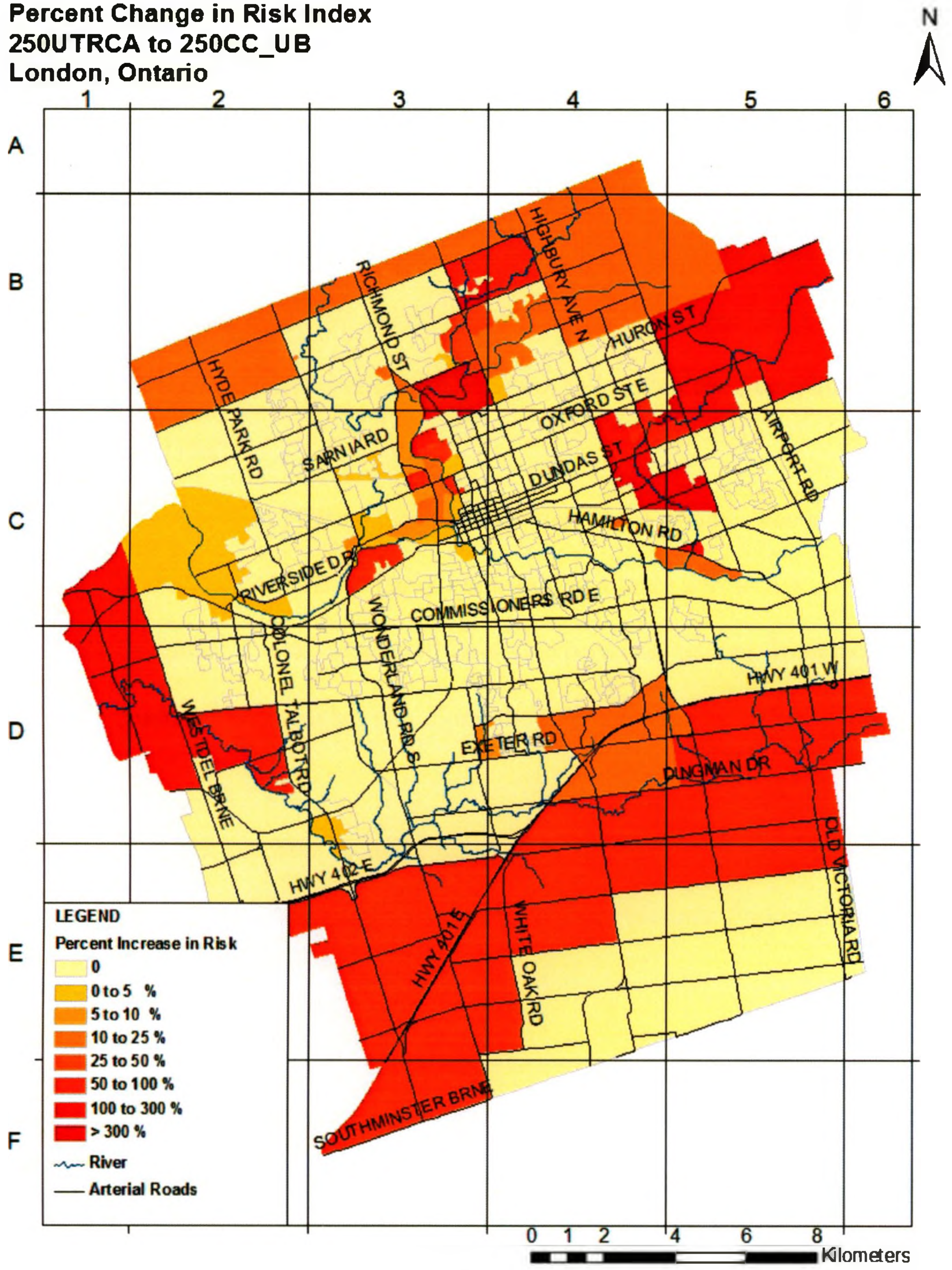


Figure 5.23: Percent change in risk index between 250 UTRCA and 250 CC_UB

Increases in risk may be attributed to a few key areas including:

(1) The damming of Pottersburg Creek in the 250 CC_UB scenario that causes floodwaters to backup into residential neighbourhoods. The entire Pottersburg Creek region experiences increase in risk as these waters inundate the lower lying areas nearby, increasing the extent of flooding. Two schools in the neighbourhood behind the dam are flooded in 250 CC_UB scenario that currently do not fall within the floodplain as defined by UTRCA.

(2) The Adelaide PCP on the North Branch of the Thames becomes inundated in the 250 CC_UB scenario, contributing a large part to risk.

(3) Dingman Creek inundated areas experience deeper inundation levels contributing to higher risk along the entire tributary.

Unfortunately, it is not possible to make comparison between 100-year climate change scenarios and the current 100 year floodplain regulation because floodplain data is not available.

The following Table 5.16 provides an overview of the results of the five comparison analyses. It is interesting to see that in analysis three and four the damage is actually larger in the 250-year return period scenarios - as compared to the 100-year scenarios - but the risk is less. Damages in the 250-year climate scenarios is expected to be higher because there is greater flood extent and depth in these scenarios than there is in the 100-year scenarios. However, risk considers the probability of a flood hazard occurring, therefore risk in the 100-year scenarios is greater. This is because the 100-year event is 2.5 times more likely to occur than the 250-year event. The increase in probability compensates for the difference in damages and therefore the 100-year events are higher risk events.

Table 5.16: Differences in results between climate scenarios

Scenario	Difference in Area (km^2)	Difference in Damage	Difference in Risk
Analysis 1	2.84	106%	106%
Analysis 2	1.92	46%	46%
Analysis 3	3.00	89%	-25%
Analysis 4	2.08	33%	-47%
Analysis 5	3.31	75%	75%

Useful insight into areas of high infrastructure and climate risk is provided in the risk tables and maps. However there are other factors which should be combined with infrastructure risk in order to inform climate change adaptation policy.

5.6 Social and Environmental Vulnerability

Social and environmental factors can increase the susceptibility of a region to incurring damages from a disaster; this in turn affects a regions risk.

Social vulnerability is based on the concept that a population exposed to flooding is susceptible to suffering physical, emotional or psychological distress. The degree to which an individual may experience these intangible damages is influenced by their tolerance and coping capabilities in stressful situations. An individual's behavioural response during a disastrous event may be the product of various experiences and perceptions. This makes vulnerability assessments situationally dependent and challenging to predict for a flood event. However, certain demographics and individuals exhibiting particular characteristics are predisposed to higher levels of vulnerability. Populations with high levels of poverty, minorities, elderly and disabled persons are considered more susceptible during natural disasters. These characteristics are associated with disadvantages during natural disasters such as limited access to resources, physical shortcomings, communication barriers and limited mobility. A more comprehensive list (adapted from Peck et al. 2007) of potential social vulnerability indicators is contained in Appendix D. Populations are not static, people move homes and change cities making the precise demographics of an area difficult to predict at any particular time. This research uses data from Population Census released by Statistics Canada for population over 65+ years of age as an indicator of vulnerable peoples to determine the effects that social vulnerability may have on risk.

Identifying vulnerable populations can aid emergency management and increase the effectiveness of disaster response and recovery actions. These areas can be targeted for social resiliency improvement programs and specific adaptation strategies.

Environmental vulnerability is the susceptibility of sensitive natural areas to flood effects. Wetlands and bogs are diverse natural habitats that support a variety of wildlife, some of which are biologically sensitive to changes in the environment. Flooding these areas can modify wetland composition, destroy habitat, deposit sediments and introduce pollutants and toxins into water, soils and wildlife. These areas are environmentally significant and take time and assistance to recover after flood event. In this case study the area of wetland in each DA is used to represent environmental susceptibility to flooding in an effort to determine any influence it has on risk.

5.7 Multi-objective Analysis

In water resources management it is often necessary to select a single solution (or in this case identify the single area of highest risk) to guide politicians and develop appropriate action. Water resources management problems are often complex and rely on solutions that have to be evaluated according to multiple objectives.

Multi-objective (MO) analysis is a methodology for assessing trade-offs between alternatives subject to more than one objective (Simonovic, 2009). This approach is useful for problems where objectives are very different and measured in various terms. It is extremely challenging to specify all objectives in a problem on a common scale with similar values. Some objectives are not easily expressed in monetary terms or otherwise easily quantifiable and comparable ways; this is where MO analysis is useful. As described in Simonovic (2009), the MO programming problem is characterized by a vector of r objective functions:

$$Z(x) = [Z_1(x), Z_2(x), \dots, Z_r(x)] \tag{5.9}$$

Subject to:

$x \in X$

where X is a feasible region:

$$X = \{x: x \in R^n, g_i(x) \leq 0, x_j \geq 0 \forall i, j\} \tag{5.10}$$

and where

R = set of real numbers,

$g_i(x)$ = set of constraints

x = set of decision variables

The MO analysis approach is particularly useful in complex situations especially in cases that all objectives are difficult to quantify in the same units (for example monetary). MO Compromise Programming is one of the tools that can successfully deal with a multi-objective analysis problem and involve multiple stakeholders. Determining a single optimal solution in these cases is not possible. The best compromise solution is sought instead that meets the preferences of stakeholders involved in the decision making process. Long-term planning often involves addressing different economic, social, environmental, political and other concerns.

This research uses a computer software program, COMPRO (Simonovic, 2009) to integrate climate change caused flood risk to infrastructure with various social and environmental objectives under various potential preference structures of decision makers. The purpose of the Compromise Programming method is to reduce the number of alternatives by systematically eliminating those alternatives that are dominated by others. The results should identify priority areas according to broader set of objectives.

Alternatives in this case study are the fifty DAs that have highest infrastructure risk value under the 100 CC_UB scenario. These areas are of particular interest and MO Compromise Programming is used to determine the effects of additional objectives important in risk evaluation. Additional objectives in this case study include social and environmental factors.

Upon ranking the DAs using the Compromise Programming, it is possible to identify a list of priority areas (alternatives) that meet various objectives (infrastructure, social, environmental) and reflect preferences of various decision makers.

For this case study, the purpose is to determine those areas subject to highest risk and vulnerability. Therefore the selected set of objectives includes:

Maximization of infrastructure risk

Maximization of elderly population

Maximization of the area of exposed wetland

Input from decision makers is required to introduce value judgments into the solution process (Simonovic, 2009) and define the relative importance of the objectives based on the preferences of decision makers. The following preference structures are considered in five trials to provide examples of potential decision maker preferences:

(a) Equal importance of all objectives
(b) Municipal engineer (high importance of infrastructure risk)
(c) Emergency management personnel
(d) High importance of environmental flood impacts
(e) High importance of social impacts of flooding

Those preference options are presumed to be reflected by the following weights (Table 5.17):

Table 5.17: Normalized weighting parameters for potential decision makers

	Infrastructure, α_1	Social, α_2	Environmental, α_3
(a)	0.333	0.333	0.333
(b)	0.50	0.40	0.10
(c)	0.30	0.65	0.05
(d)	0.10	0.40	0.50
(e)	0.15	0.60	0.25

Five trials (1 through 5) are completed for three objectives $\{\alpha_1, \alpha_2, \alpha_3\}$ and three values of the Compromise Programming method parameter $\{p_1, p_2, p_3\}$ (Simonovic, 2009) to assess each of the preference structures. Results and discussion related to the multi-objective Compromise Programming analyses are presented in the remainder of this chapter.

The top 50 DAs with highest risk index (subject to the 100 CC_UB scenario) are considered for Compromise Programming analyses. Data pertaining to infrastructure risk is collected from multiple sources mentioned in previous chapters and is represented by the risk index value for fifty DAs under the 100 CC_UB scenario. Social vulnerability objective is defined by the number of elderly persons (aged 65 and over) in each of the fifty DAs obtained from Statistics Canada's Population Census 2006. Environmental susceptibility objective is defined by the total area (m^2) of wetland in each of the fifty DAs represented in GIS spatial files as provided by Serge A. Sauer map library at UWO.

With the exception of DA 0315 (excluded due to lack of available social data), input parameters for highest risk DAs for all five trials are provided in Appendix E. An example of the input for five of the fifty DAs is included below.

Table 5.18: Example input for the COMPRO Compromise Programming software

Criterion	Infrastructure	Social	Environmental
Weight	XXX	XXX	XXX
Alternatives			
0710	2779882	150	5093
0727	3208648	70	159915
0746	6339082	220	0
0837	2605754	60	102909
0859	3020046	35	41634

Parameter p 1 2 1000

Results are presented for the top five ranked DAs in each of the trials. A parameter $p = 2$ is used to analyze results as the best estimate for first approximation of the best compromise solution (as described in Simonovic, 2009 p. 557); full extent of results is presented in Appendix E.

Trial 1: Preference scheme (a)

The preference scheme (a) could capture an indifferent decision maker - someone who weights all criteria equally {0.333.0.333,0.333} as per Table 5.17. The top five ranked DAs and their distance metric values (see Simonovic, 2009, section 10.3.1) are presented in Table 5.19.

Table 5.19: COMPRO ranking results for preference scheme (a)

Criterion	Infrastructure	Social	Environmental
Weight	0.333	0.333	0.333

Parameter p 2

Distance Metric Value [and Rank]

0035	4.054E-01 [1]
0727	4.343E-01 [2]
0890	4.480E-01 [3]
0696	4.558E-01 [4]
0837	4.573E-01 [5]

Trial 2: Preference scheme (b) may represent a municipal engineer - someone who places an emphasis on the value of infrastructure risk index {0.50, 0.40,0.10} as per Table 5.17. The top five ranked DAs and their distance metric values are presented in Table 5.20.

Table 5.20: COMPRO ranking results for preference scheme (b)

Criterion	Infrastructure	Social	Environmental
Weight	0.50	0.40	0.10
Parameter p	2		
Distance Metric Value [and Rank]			
0035	2.952E-01 [1]		
0313	4.355E-01 [2]		
0325	4.394E-01 [3]		
0036	4.480E-01 [4]		
0890	4.481E-01 [5]		

Trail 3: Preference scheme (c)

The preference scheme (c) may represent an emergency manager - someone who places an emphasis on social susceptibilities, but is also interested in infrastructure risk index value (for administering assistance during disasters) {0.30, 0.65,0.05} as per Table 5.17. The top five ranked DAs and their distance metric values are presented in Table 5.21.

Table 5.21: COMPRO ranking results for preference scheme (c)

Criterion	Infrastructure	Social	Environmental
Weight	0.30	0.65	0.05
Parameter p	2		
Distance Metric Value [and Rank]			
0696	2.982E-01 [1]		
0327	3.002E-01 [2]		
0032	3.037E-01 [3]		
0890	3.446E-01 [4]		
0706	3.746E-01 [5]		

Trail 4: Preference scheme (d)

The preference scheme (d) may represent an environmentalist - someone who places an emphasis on the vulnerability of ecosystems in the event of a disaster {0.10, 0.40,0.50} as per Table 5.17. The top five ranked DAs and their distance metric values are presented in Table 5.22.

Table 5.22: COMPRO ranking results for preference scheme (d)

Criterion	Infrastructure	Social	Environmental
Weight	0.10	0.40	0.50
Parameter p	2		
Distance Metric Value [and Rank]			
0727	3.531E-01 [1]		
0837	4.052E-01 [2]		
0327	5.096E-01 [3]		
0032	5.104E-01 [4]		
0696	5.121E-01 [5]		

Trial 5: Preference scheme (e)

The preference scheme (e) may represent a social worker - someone who places an emphasis on the vulnerability of people and the environment $\{0.15, 0.60, 0.25\}$ as per Table 5.17. The top five ranked DAs and their distance metric values are presented in Table 5.23.

Table 5.23: COMPRO ranking results for preference scheme (e)

Criterion	Infrastructure	Social	Environmental
Weight	0.15	0.60	0.25
Parameter p	2		
Distance Metric Value [and Rank]			
0327	2.905E-01 [1]		
0032	2.935E-01 [2]		
0696	3.001E-01 [3]		
0890	3.532E-01 [4]		
0706	3.757E-01 [5]		

The best compromise solution and the most robust solution may be the same alternative (Simonovic, 2009). However, this is not necessarily the case. The best compromise solution may be determined using Compromise Programming technique based on a priori articulation of stakeholder preferences. The most robust solution can be described as the alternative which is least sensitive to the changes in decision maker preferences. The most robust solution is more significant in the situation where there are a large number of stakeholders involved and reaching preference consensus among them is almost impossible. This solution may also satisfy decision makers who are not comfortable in expressing a particular preference structure. In the five trials that were completed DAs 0327 (Cell C3) and 0696 (Cell C3) may be considered the best compromise alternative (i.e. the DA with the highest risk) and DA 0706 (Cell C3) may potentially be considered the most robust alternative (Table 5.24). To identify more specifically where these DAs are, please refer to Appendix F for an enlarged image of cell C3.

Table 5.24: Rank for selected DAs from five trials of different decision maker preferences for MO compromise programming

DA	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**
0327	[8]	[11]	[2]	[3]	[1]
0696	[4]	[8]	[1]	[5]	[3]
0706	[6]	[6]	[5]	[7]	[5]

Results point to DA 0327 and 0696 as best compromise solutions because of the areas relatively high infrastructure risk and high population of vulnerable people. These two DAs share similar characteristics in all three factors (infrastructure, social, environmental) and they consistently score high ranks under multiple decision maker preferences. Infrastructure risk in these DAs can be attributed to inundated roads, bridges and buildings. DA 0327 is North of the downtown London core in a more historical part of the city generally characterized by many older homes, presumably inhabited by more senior people who have been residing there for many years. DA 0696 is at the confluence of Mud Creek and Main Thames with a similar profile to DA 0327. These DAs may be fairly high risk under multiple preferences, but its ranking fluctuates which suggests that it may be moderately sensitive to decision maker preferences.

DA 0706 appears to be one of the most robust alternatives; it consistently obtained a fairly similar rank for all weighting schemes. This behavior suggests that this DA is not very sensitive to decision maker preferences. Areas which exhibit these qualities are good to consider in making decisions as they are relatively stable units that may not always be highest risk, but are consistent. DA 0706 is located on the South side of Main Thames at the confluence with Mud Creek. This location is subject to high infrastructure risk due in large part to Greenway PCP and also has relatively high social vulnerability value. However, DA 0706 does not consistently rank very high overall of the forty-nine DAs considered in compromise programming. This implies that although this DA is least sensitive to changes in the decision maker weights, other alternatives (DAs) should also be considered in interpreting results and defining areas of high risk.

Environmental susceptibility did not play a large factor in modifying risk because most DAs in the MO analysis did not contain environmentally susceptible areas (wetlands). In decision maker preference scheme (d), DA 0727 has rank [1] because it has very high area of wetlands. However, this DA fails to consistently rank within even the top ten DAs under other preference schemes and fluctuates greatly with decision maker weighting so might not necessarily be the best location to direct risk-reduction measures unless they pertain specifically to the environment.

The important observation in this analysis is that in general, risk to DAs changes with addition of other criteria. Social and environmental implications can influence risk and should not be neglected when considering water resources management, policy and emergency preparedness. Areas of high risk to infrastructure are undoubtedly important to identify but must be evaluated in the context of social and environmental conditions as well.

CHAPTER 6

CONCLUSIONS

Results of the climate change-caused flood risk analyses provide preliminary insight into vulnerability of municipal infrastructure to climate change. A combined qualitative and quantitative risk approach can capture multiple types of risk. Areas of high risk are flagged for additional study which may include residential surveys related to flood proofing and emergency preparedness measures. Emergency management and disaster preparedness is especially important for the high risk areas. Identification of safe, travelable roads and critical emergency routes will aide emergency management personnel in the event of a flood disaster. These measures can save lives, reduce damage and improve recovery efforts. As additional data becomes available, the flood risk assessment requires updating to continue identifying high risk areas.

Land use planning is an integral part of flood damage reduction. High damage in flood-prone areas can be ascribed to dense built network of vulnerable infrastructure in these floodplain regions. Climate change may bring physical hazard of flooding to areas which have not previously been exposed. Areas in the floodplain delineated by climate change scenarios, but not within current 250 floodplain regulations, may be especially unprepared for high magnitude flood events that climate change imposes. It is important to strike a balance between increasing development and floodplain management (Sandink and Simonovic, 2009). The City of London may consider revising floodplain management policy to include climate change and provisions for high risk areas under the 100 CC_UB floodplain as it demonstrated to be the most critical climate scenario.

Results of the case study in this research can provide insight into flood risk and management for the City of London. The results of municipal risk assessment can provide useful recommendations in the areas of (i) engineering; (ii) operations; and (iii) policy and regulations.

A drawback to risk assessments of this nature is they often consider time frames which extend beyond the next political election and in some cases, beyond the lifetime of most individuals (Auld and MacIver 2006b). Climate change requires adoption into policy, engineering design and regulations. Flood risk should be considered in the context of direct and indirect damages. Potential social and environmental susceptibility is important to consider in the context of regional risk and emergency management as both of these factors can modify risk.

Future work should consider the effects of flood on agricultural land, climate change risk to municipal sewer infrastructure and the effects of multiple simultaneous disastrous events. Risk management does not end with identification of high risk areas. It requires policy modification, prioritization, emergency planning and continual updating to account for new data. This study demonstrates the importance of initiating collaboration between academia, climate change scientists and local politicians.

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Appendix A

Stage-Damage Curves

The following figures are stage-damage curves used in the City of London case study to determine values of EF. A few notes to consider in using the curves:

- Commercial and residential structure curves presented include the value of building contents, which were factored out separately for the analysis in this research
- For commercial and residential damages, mean value curves are used unless the structure is an apartment or has a pool, in which case the high curves are used
- Commercial and residential structure curves obtained from Glengowan Report (Marshall, 1983); study on local damages due to flooding
- Other infrastructure stage-damage curves derived from local reports, budgets and interviews with technical experts; estimated values that do not include content damages unless otherwise specified
- Bridges and culverts consider a ratio h* instead of direct stage value to represent the level at which a bridge incurs damage (1m below the low chord of the bridge deck) as follows:

$$h^* = \left(\frac{WE - LCE}{S}\right)$$

where,

h^*	is stage ratio (dml)
WE	is water elevation (masl)
LCE	is low chord elevation of bottom of bridge deck (msal)
S	is thickness of bridge deck (m)

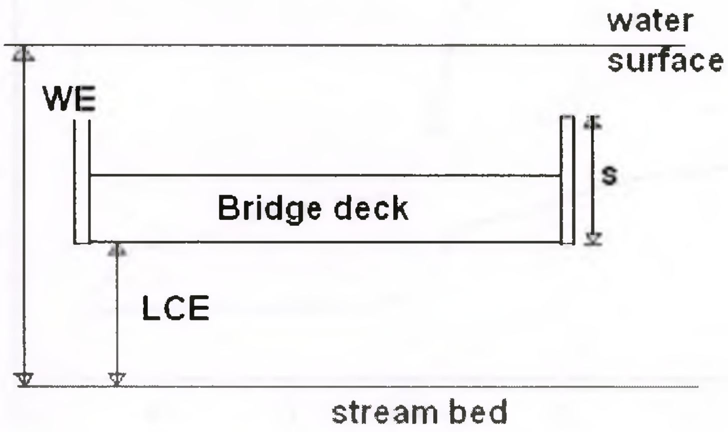

Figure A.1: Description of terms used to describe stage ratio for bridges

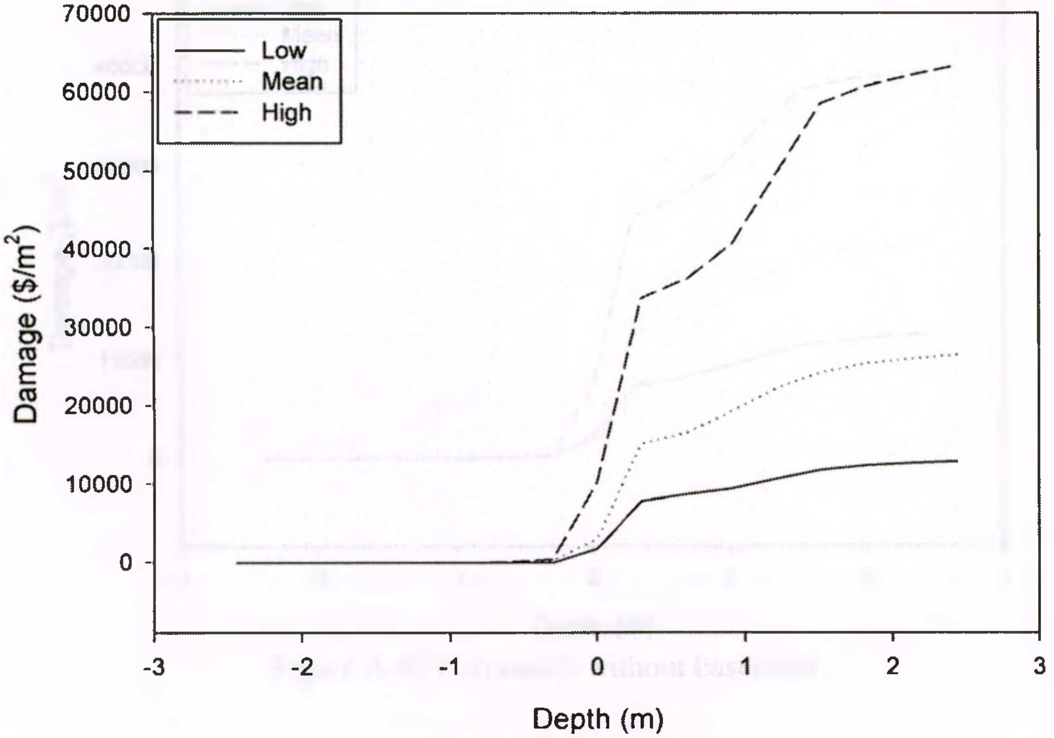

Figure A.2: Single storey without basement

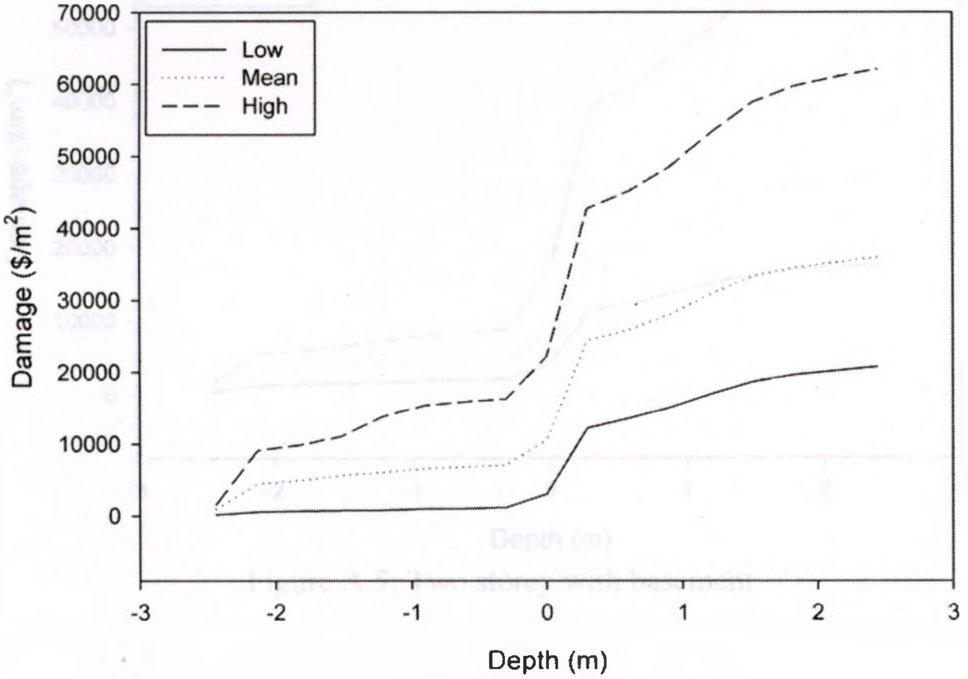

Figure A.3: Single story with basement

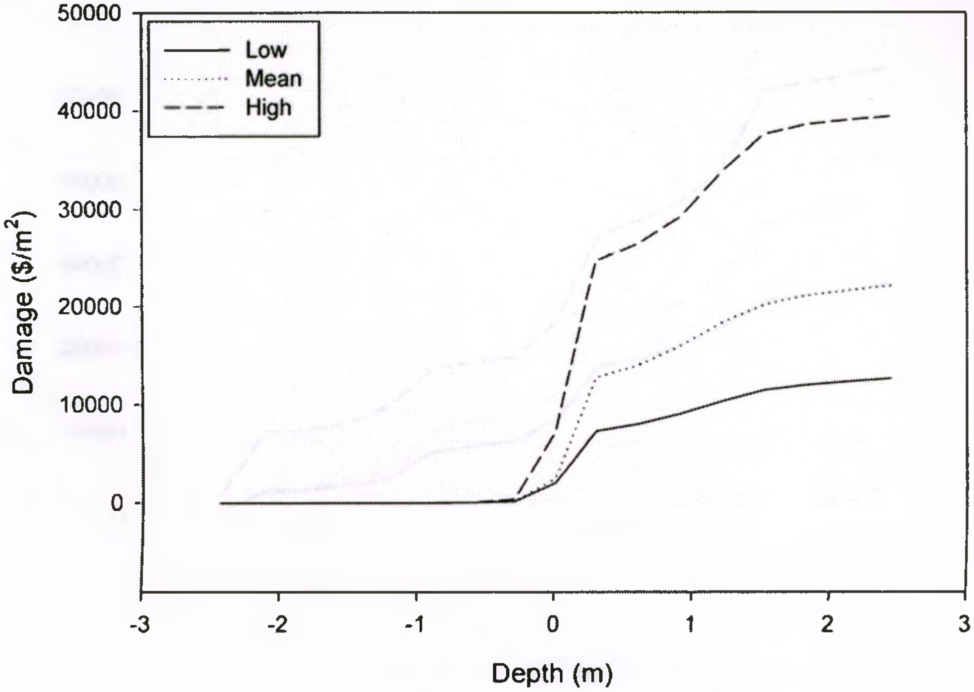

Figure A.4: Two storey without basement

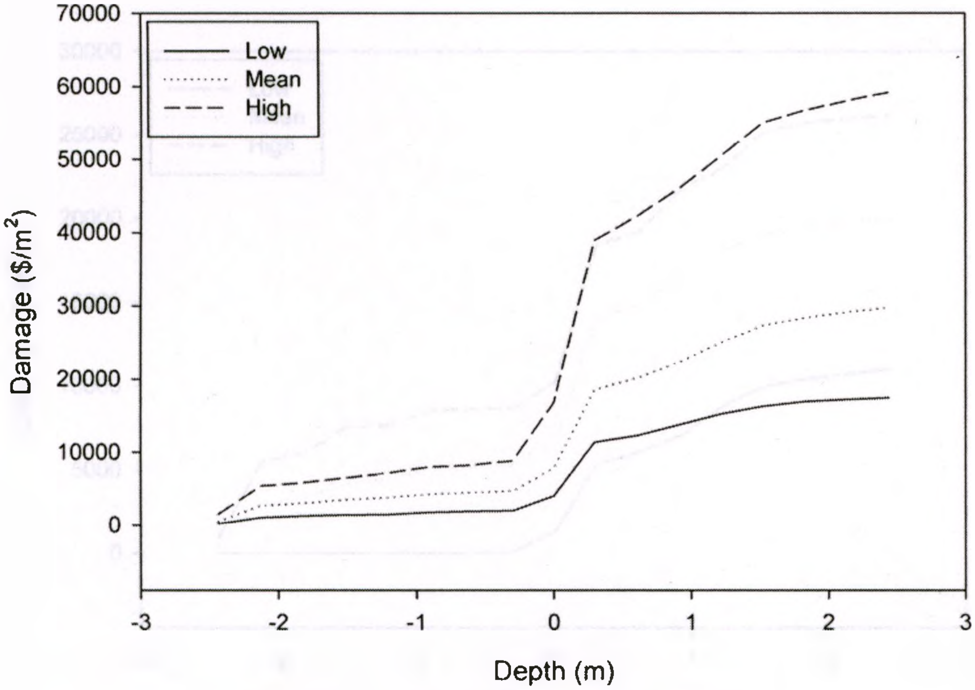

Figure A.5: Two storey with basement

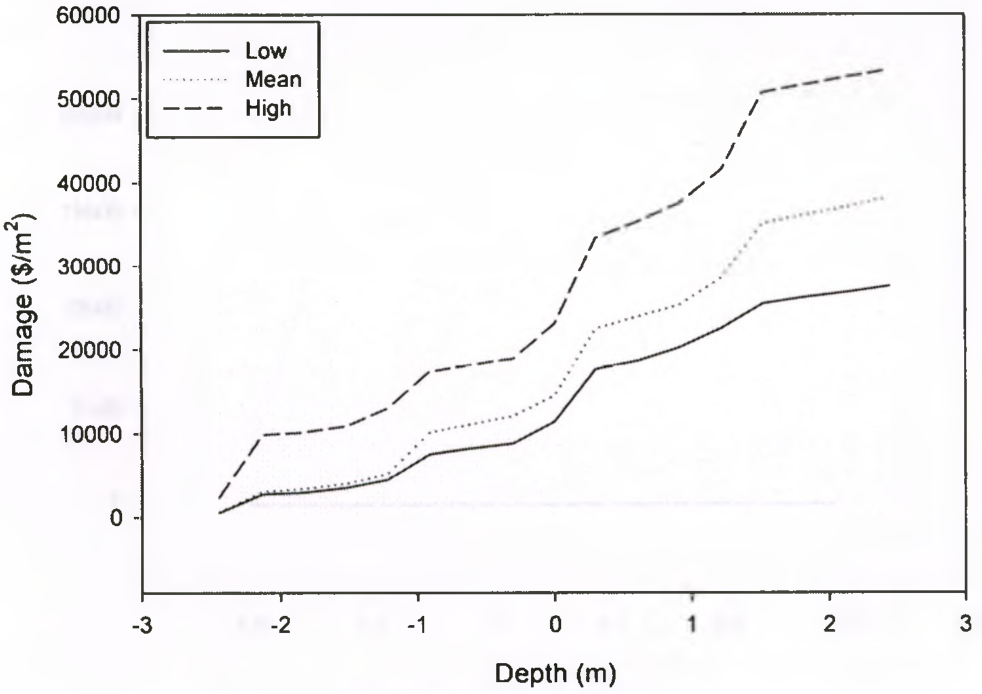

Figure A.6: Split level

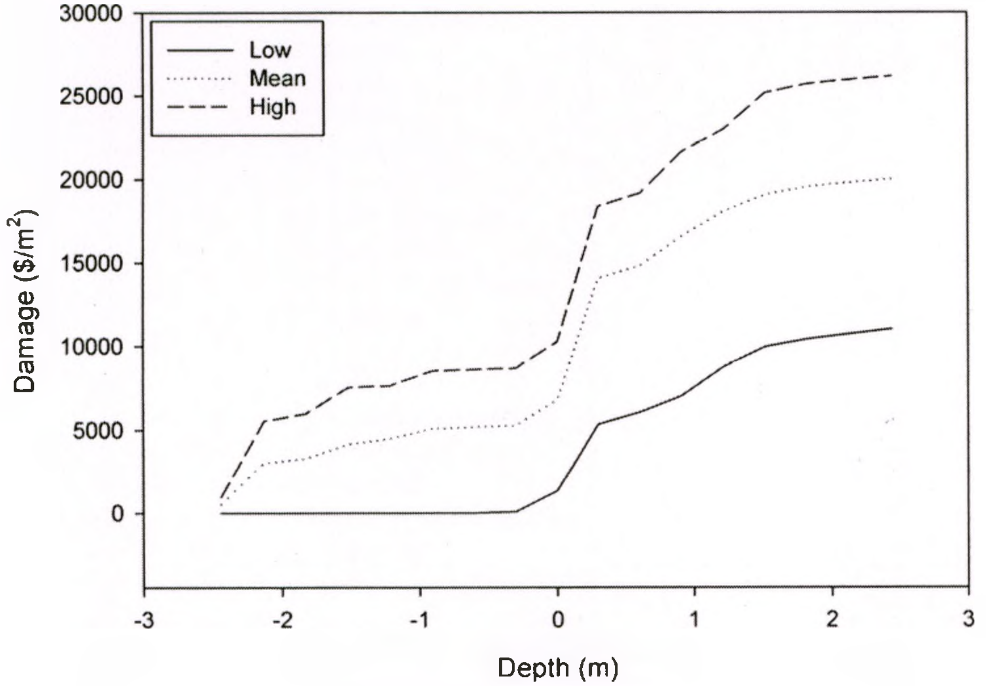

Figure A.7: Townhouse

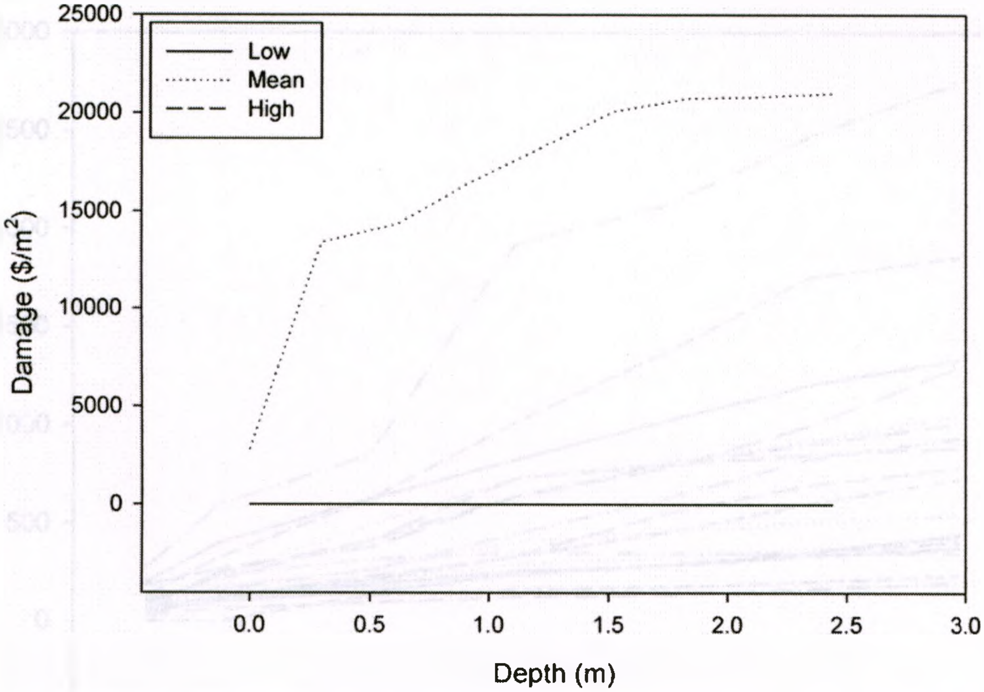

Figure A.8: Mobile homes

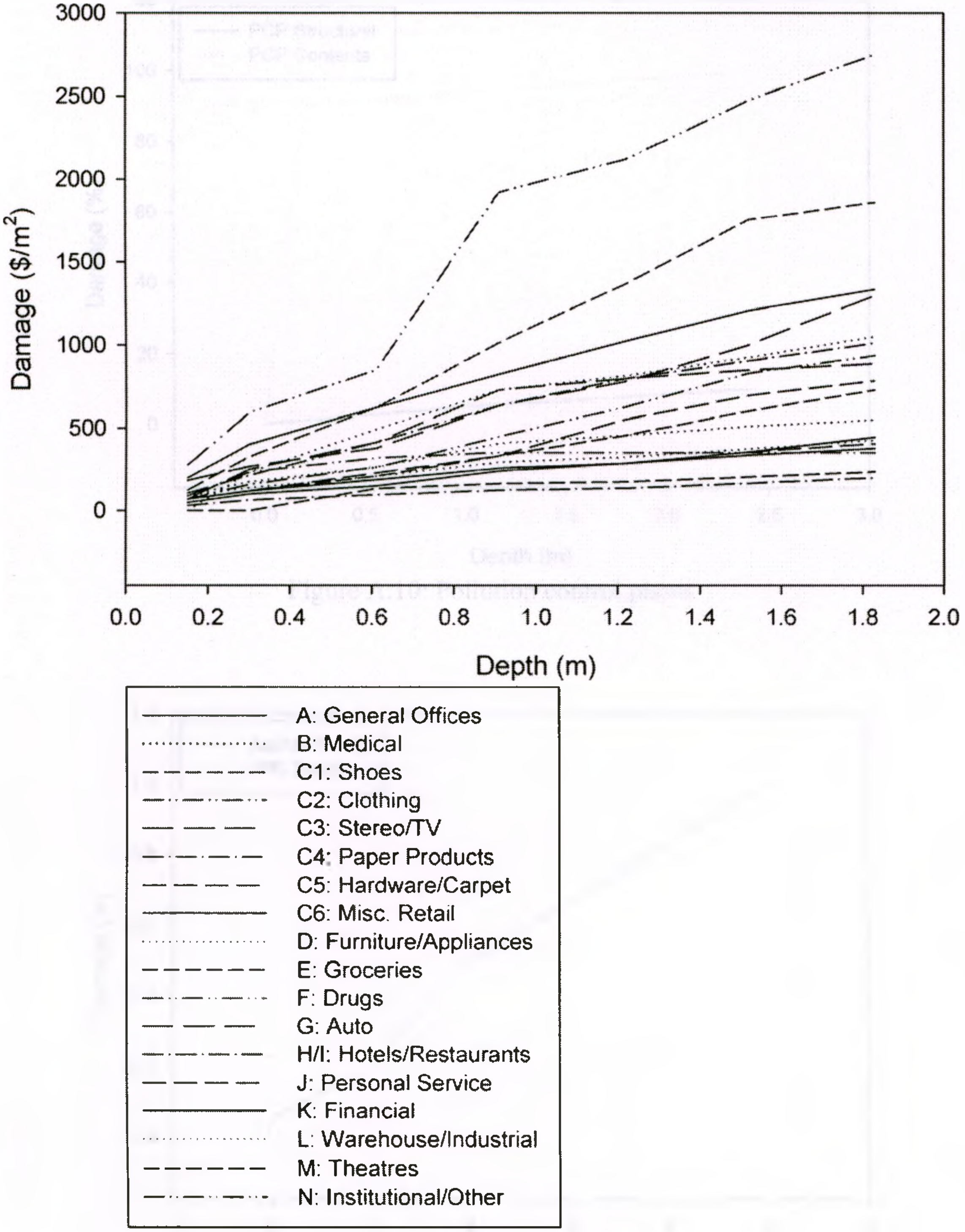

Figure A.9: Commercial buildings

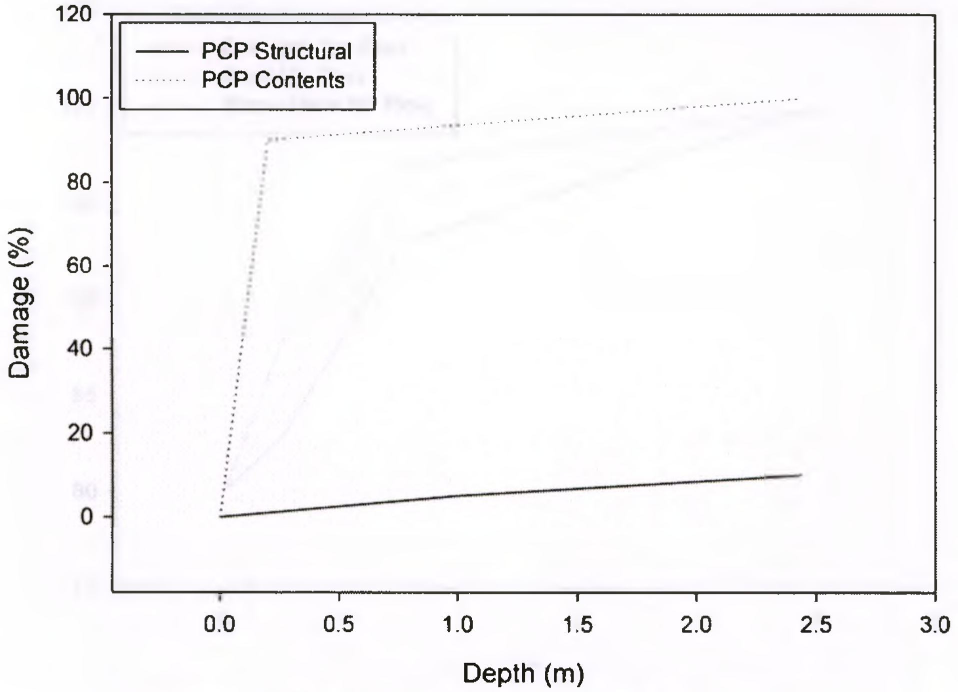

Figure A.10: Pollution control plants

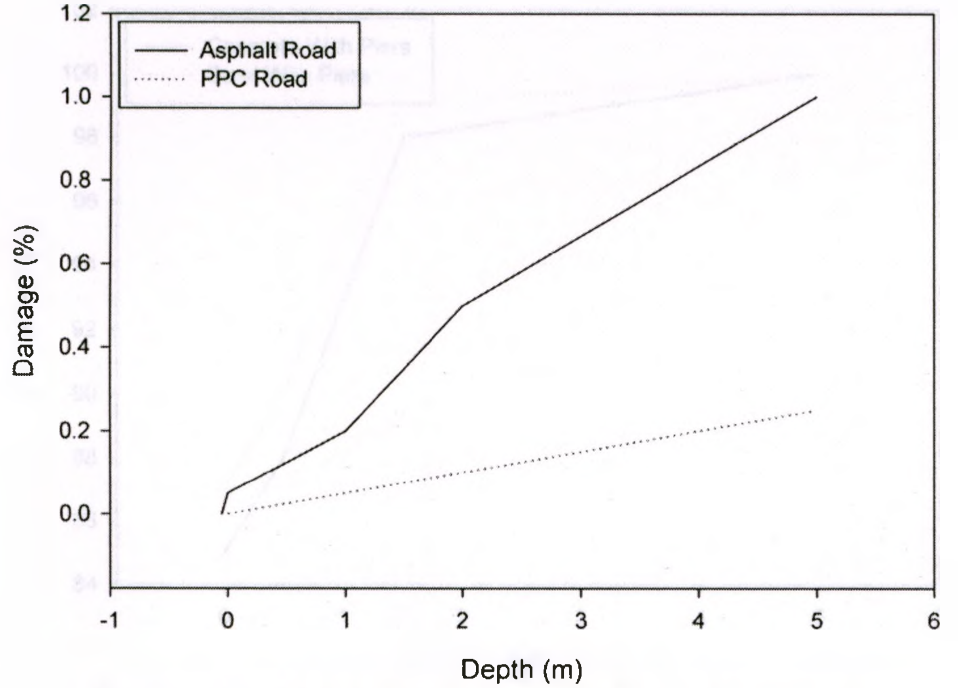

Figure A.11: Roads

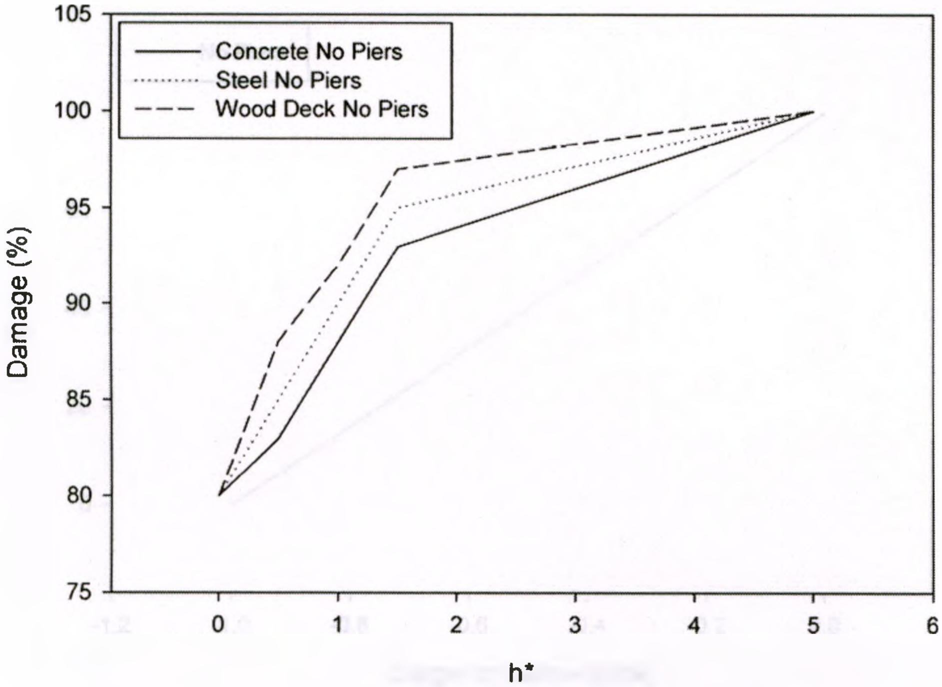

Figure A.12: Bridges no piers; water level at or above deck

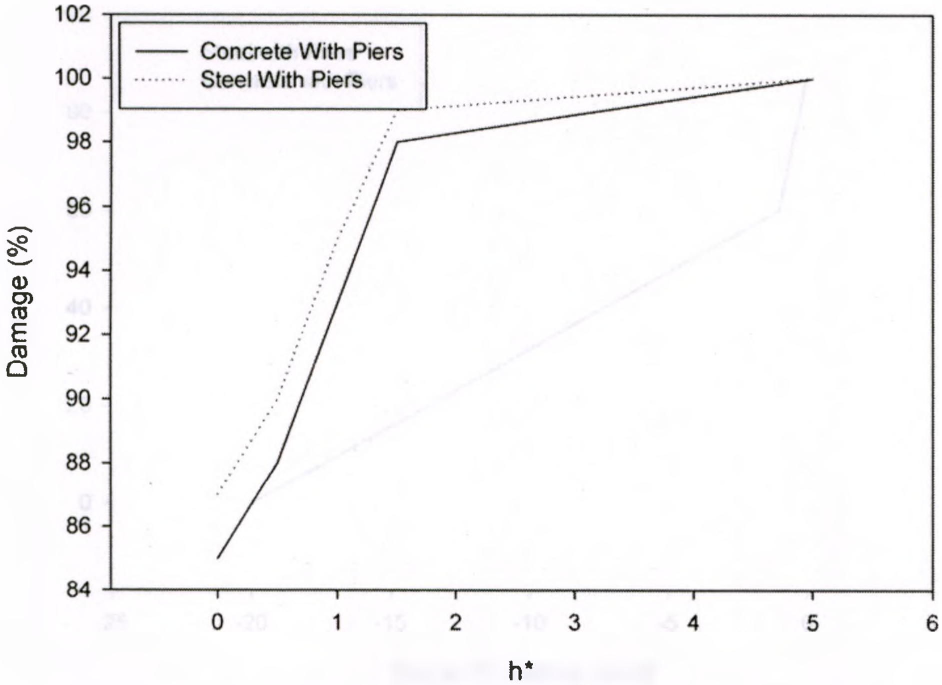

Figure A.13: Bridges with piers; water level at or above deck

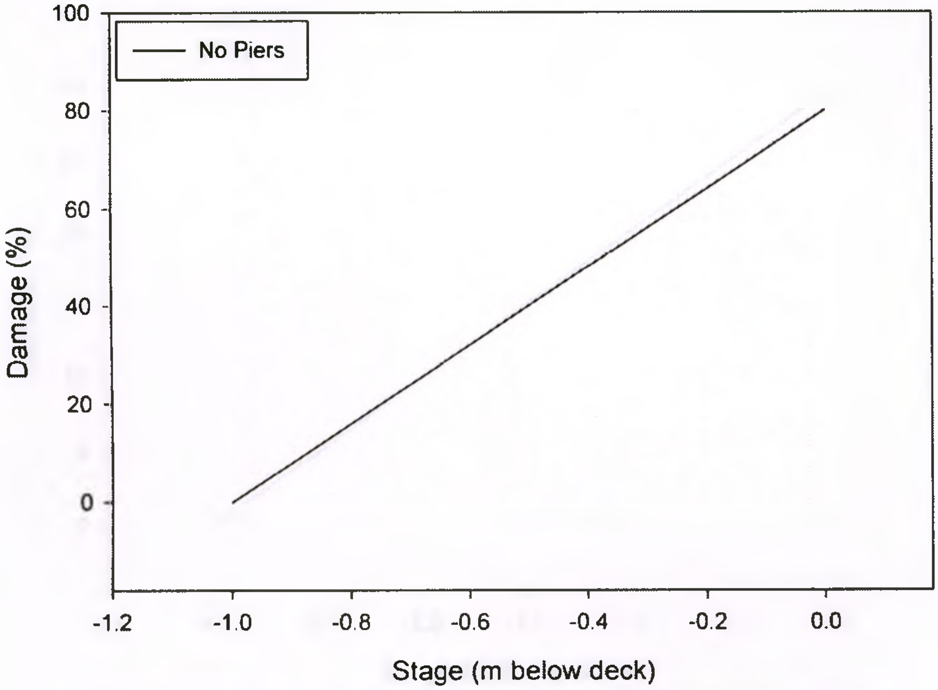

Figure A.14: Bridges without piers; water level below deck

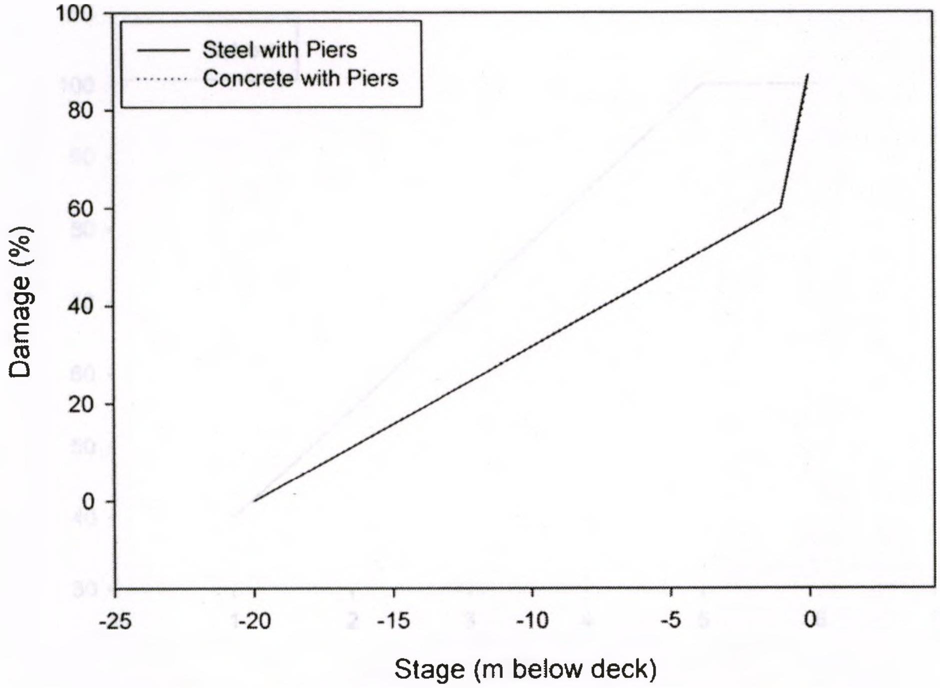

Figure A.15: Bridges with piers; water level below deck

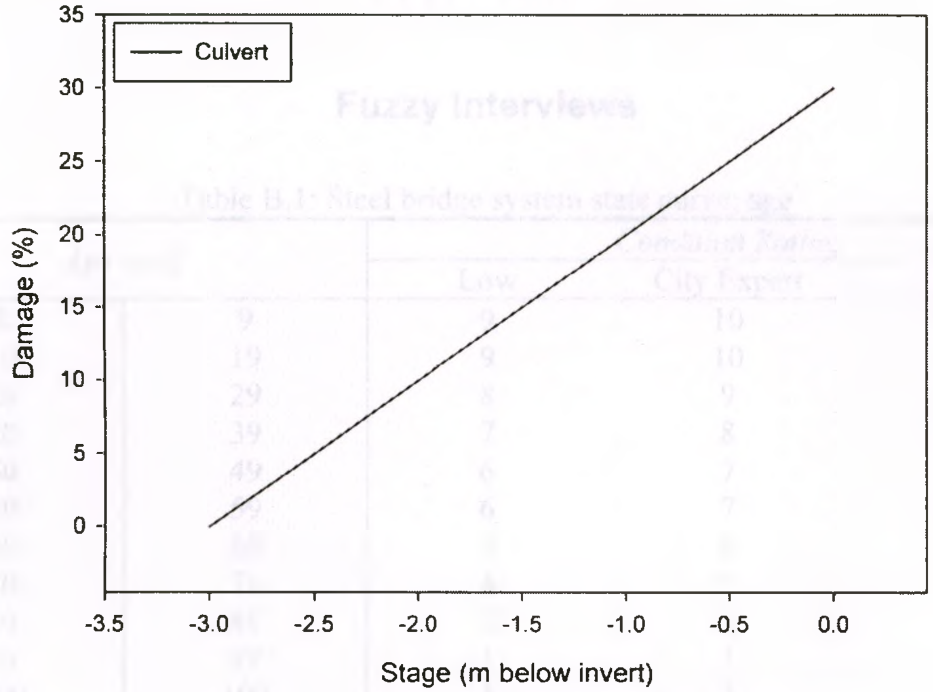

Figure A.16: Culvert; water level below invert

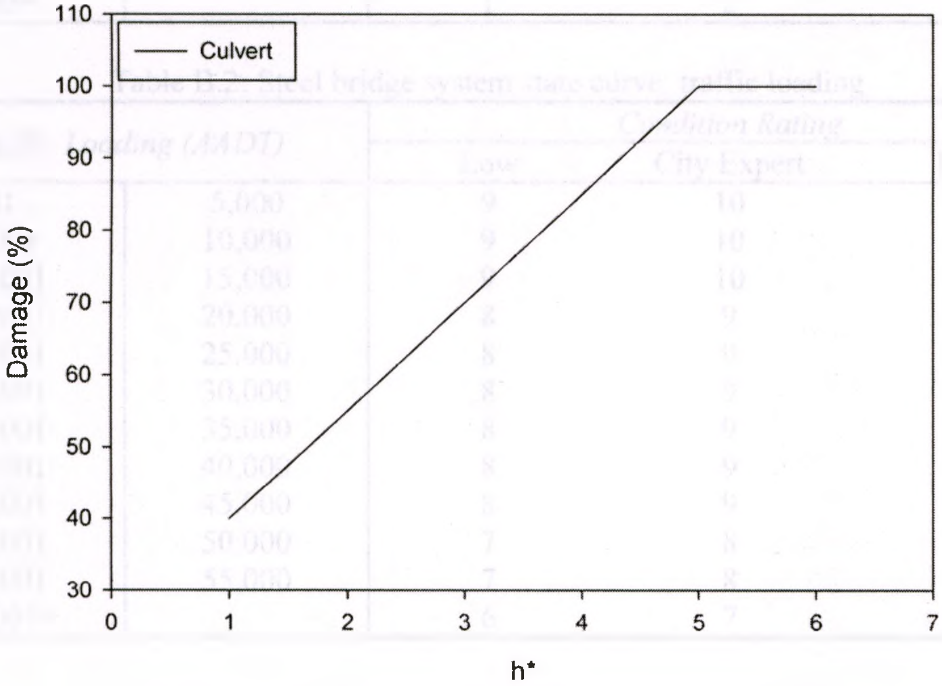

Figure A.17: Culvert; water level at or above invert

Appendix B

Fuzzy Interviews

Table B.1: Steel bridge system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	9	10	10
10	19	9	10	10
20	29	8	9	10
30	39	7	8	9
40	49	6	7	8
50	59	6	7	8
60	69	5	6	7
70	79	4	5	6
80	89	4	5	6
90	99	3	4	5
100	109	3	4	5
110	119	2	3	4
120	129	2	3	4
130	139	1	2	3
140+		1	2	3

Table B.2: Steel bridge system state curve; traffic loading

Traffic Loading (AADT)		*Condition Rating*		
		Low	City Expert	High
0	5,000	9	10	10
5,001	10,000	9	10	10
10,001	15,000	9	10	10
15,001	20,000	8	9	10
20,001	25,000	8	9	10
25,001	30,000	8	9	10
30,001	35,000	8	9	10
35,001	40,000	8	9	10
40,001	45,000	8	9	10
45,001	50,000	7	8	9
50,001	55,000	7	8	9
55,001+		6	7	8

Table B.3: Concrete bridge system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	9	10	10
10	19	9	10	10
20	29	9	10	10
30	39	8	9	10
40	49	8	9	10
50	59	7	8	9
60	69	7	8	9
70	79	6	7	8
80	89	5	6	7
90	99	5	6	7
100	109	4	5	6
110	119	3	4	5
120	129	3	4	5
130	139	2	3	4
140+		2	3	4

Table B.4: Concrete bridge system state curve; traffic loading

Traffic Loading (AADT)		*Condition Rating*		
		Low	City Expert	High
0	5,000	9	10	10
5,001	10,000	9	10	10
10,001	15,000	9	10	10
15,001	20,000	9	10	10
20,001	25,000	9	10	10
25,001	30,000	8	9	10
30,001	35,000	8	9	10
35,001	40,000	8	9	10
40,001	45,000	7	8	9
45,001	50,000	7	8	9
50,001	55,000	6	7	8
55,001+		6	7	8

Table B.5: Wood bridge system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	8	9	10
10	19	7	8	9
20	29	6	7	8
30	39	3	4	5
40	49	3	4	5
50	59	2	3	4
60	69	2	3	4
70	79	0	0	1
80	89	0	0	1
90	99	0	0	1
100	109	0	0	1
110	119	0	0	1
120	129	0	0	1
130	139	0	0	1
140+		0	0	1

Table B.6: Wood bridge system state curve; traffic loading

Traffic Loading (AADT)		*Condition Rating*		
		Low	City Expert	High
0	5,000	8	9	10
5,001	10,000	7	8	9
10,001	15,000	7	8	9
15,001	20,000	4	5	6
20,001	25,000	4	5	6
25,001	30,000	2	3	4
30,001	35,000	2	3	4
35,001	40,000	0	1	2
40,001	45,000	0	1	2
45,001	50,000	0	1	2
50,001	55,000	0	1	2
55,001+		0	1	2

Table B.7: Culvert system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	9	10	10
10	19	9	10	10
20	29	9	10	10
30	39	8	9	10
40	49	7	8	9
50	59	7	8	9
60	69	5	6	7
70	79	5	6	7
80	89	4	5	6
90	99	4	5	6
100	109	1	2	3
110	119	1	2	3
120	129	1	2	3
130	139	1	2	3
140+		1	2	3

Table B.8: Culvert system state curve; traffic loading

Traffic Loading (AADT)		*Condition Rating*		
		Low	City Expert	High
0	5,000	9	10	10
5,001	10,000	7	8	9
10,001	15,000	7	8	9
15,001	20,000	6	7	8
20,001	25,000	6	7	8
25,001	30,000	5	6	7
30,001	35,000	5	6	7
35,001	40,000	4	5	6
40,001	45,000	3	4	5
45,001	50,000	2	3	4
50,001	55,000	1	2	3
55,001+		0	1	2

Table B.9: Weighting factors for parameters affecting bridge condition

Condition Parameters	*Weighting Factor*
Age	7
Traffic Loading	8

Table B.10: PCP system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	9	10	10
10	19	9	10	10
20	29	9	10	10
30	39	9	10	10
40	49	9	10	10
50	59	8	9	10
60	69	8	9	10
70	79	8	9	10
80	89	8	9	10
90	99	7	8	9
100	109	7	8	9
110	119	7	8	9
120	129	6	7	8
130	139	6	7	8
140+		5	6	7

Table B.11: PCP system state curve; maintenance

Maintenance (years between inspections)	*Condition Rating*		
	Low	City Expert	High
<1	9	10	10
1	9	10	10
2	7	8	9
3	6	7	8
4	5	6	7
5	2	3	4
6	2	3	4
7	0	1	2
8	0	1	2
9	0	1	2
10	0	1	2
>10	0	1	2

Table B.12: PCP system state curve; material

Material	*Condition Rating*		
	Low	City Expert	High
Wood		n/a	
Brick	5	6	7
Concrete	9	10	10
Glass	7	8	9

Table B.13: Weighting factors for parameters affecting PCP condition

Condition Parameters	*Weighting Factor*
Age	5
Maintenance	10
Material	8

Table B.14: Critical facilities system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	9	10	10
10	19	9	10	10
20	29	9	10	10
30	39	8	9	10
40	49	8	9	10
50	59	7	8	9
60	69	7	8	9
70	79	6	7	8
80	89	6	7	8
90	99	5	6	7
100	109	5	6	7
110	119	5	6	7
120	129	4	5	6
130	139	3	4	5
140+		n/a		

Table B.15: Critical Facilities system state curve; maintenance

Maintenance (years between inspections)	*Condition Rating*		
	Low	City Expert	High
<1	9	10	10
1	9	10	10
2	8	9	10
3	7	8	9
4	5	6	7
5	3	4	5
6	3	4	5
7	2	3	4
8	0	1	2
9	0	1	2
10	0	1	2
>10	n/a		

Table B.16: Critical Facilities system state curve; material

Material	*Condition Rating*		
	Low	City Expert	High
Wood		n/a	
Brick	5	6	7
Concrete	9	10	10
Glass	7	8	9

Table B. 17: Weighting factors for parameters affecting critical infrastructure condition

Condition Parameters	*Weighting Factor*
Age	5
Maintenance	10
Material	8

Table B.18: Non-critical buildings system state curve; age

Age (yrs)		*Condition Rating*		
		Low	City Expert	High
0	9	9	10	10
10	19	9	10	10
20	29	8	9	10
30	39	8	9	10
40	49	7	8	9
50	59	7	8	9
60	69	6	7	8
70	79	5	6	7
80	89	4	5	6
90	99	3	4	5
100	109	2	3	4
110	119	1	2	3
120	129	1	2	3
130	139	0	1	2
140+		0	1	2

Appendix C

Comprehensive Tables of Risk

Table C.1: Change in risk -Case 1

250 UTRCA vs. 250 CC_UB				
DAUID	Cell Index			% Increase
35390014	B3	B4		29.9
35390032	B3			754.4
35390033	B3			0.1
35390034	B3			28.1
35390035	B3	B4	C3	327.3
35390036	B3	C3		553.2
35390063	C4			451.7
35390064	C4			2006.5
35390066	C4			1467.6
35390067	C4	C5		585.0
35390068	C4	C5		597.2
35390069	C4	C5		19452.3
35390070	C5			INFINITE
35390092	C4	C5		825.1
35390095	C4	C5		23.0
35390096	C5			205.4
35390129	C3	C4		0.6
35390166	D3	D4		7.3
35390172	D4	D5		16.2
35390312	C3			0.9
35390313	C3			5.9
35390314	C3			11.0
35390315	C3			22.6
35390323	C3			51.8
35390324	C3			7.4
35390325	C3			22.9
35390326	C3			22.9
35390327	C3			2.7
35390328	C3			96.8
35390329	C3			121.2
35390330	B3	C3		6.1
35390333	C3			3.9
35390374	B3			23.7
35390399	C2			1.2

35390403	C2						1.2
35390404	C1	C2					1.2
DAUID	Cell Index						% Increase
35390419	C3						5.6
35390429	C3						7.5
35390440	C2						4.5
35390459	D2						93.8
35390541	C3						71.8
35390547	C3						0.1
35390563	C4						22.0
35390589	C4						930.6
35390590	C4						291.4
35390660	B5	C4	C5				691.5
35390661	C4	C5					97.1
35390666	C4						346.6
35390668	B3	B4					56.4
35390669	B3	B4					1027.3
35390675	B3						21.3
35390677	B3	B4					3.2
35390682	B4	C4					56.5
35390696	C3						1.6
35390705	C2						3.4
35390706	C3						70.8
35390709	B3	B4					17.9
35390710	B4						20.0
35390727	A4	B2	B3	B4	B5		19.1
35390745	C1	C2	D1	D2			110.2
35390747	D4	E2	E3	E4	F3	F4	54.6
35390837	D4	D5	D6	E4	E5	E6	83.2
35390859	B4	B5	C5				138.6

Table C.2: Change in risk - Case 2

100 CC_LB vs. 100 CC_UB				
DAUID	Cell Index			% Increase
35390014	B3	B4		1.9
35390018	B3			0.0
35390032	B3			469.7
35390033	B3			19.2
35390034	B3			14.6
35390035	B3	B4	C3	208.4
35390036	B3	C3		313.9

35390063	C4	5.8
35390064	C4	210.9
35390066	C4	29.0
35390067	C4 C5	2.9
35390068	C4 C5	12.2
35390069	C4 C5	14.1
35390070	C5	3.3
35390071	C5	30.4
35390092	C4 C5	14.2
35390095	C4 C5	53.4
35390096	C5	42.6
35390099	C4 C5	0.0
35390102	C4	8.5
35390103	C4	7.9
35390106	C4	23.6
35390110	C4	14.1
35390119	C4	16.7
35390120	C4	9.2
35390121	C3 C4	8.0
35390122	C3 C4	8.0
35390129	C3 C4	10.3
35390166	D3 D4	0.3
35390172	D4 D5	10.0
35390200	C4	13.1
35390201	C4	0.0
35390202	C4	12.1
35390203	C4	9.2
35390311	C3	0.0
35390312	C3	69.0
35390313	C3	550.7
35390314	C3	2655.4
35390315	C3	INFINITE
35390323	C3	INFINITE
35390324	C3	INFINITE
35390325	C3	1240.0
35390326	C3	472.3
35390327	C3	11.1
35390328	C3	102.0
35390329	C3	752.8
35390330	B3 C3	31.2
35390333	C3	0.0
35390368	B3 C3	0.7
35390374	B3	63.6

35390399	C2	7.1
35390403	C2	7.2
35390404	C1 C2	7.3
35390415	C2 C3	24.9
35390419	C3	28.6
35390429	C3	582.8
35390430	C3	2.1
35390437	C2 C3 D2 D3	15.3
35390440	C2	8.1
35390450	D2	0.5
35390459	D2	3.1
35390460	D2 D3	2.6
35390463	D3 E3	64.9
35390466	D3 E3	242.5
35390541	C3	24.0
35390547	C3	19.4
35390550	C3 C4	30.5
35390563	C4	0.0
35390589	C4	11.7
35390590	C4	37.3
35390660	B5 C4 C5	412.5
35390661	C4 C5	25.5
35390666	C4	9.8
35390668	B3 B4	0.0
35390669	B3 B4	2.4
35390671	D4	0.0
35390672	C3	0.7
35390675	B3	15.3
35390677	B3 B4	0.0
35390682	B4 C4	20.1
35390685	C4	7.5
35390696	C3	37.4
35390698	B2 B3 C3	1.2
35390702	C4	7.9
35390704	B3 C3	0.7
35390705	C2	10.0
35390706	C3	72.3
35390708	B3	1.2
35390709	B3 B4	10.0
35390710	B4	10.4
35390727	A4 B2 B3 B4 B5	8.9
35390728	B2 B3	1.0
35390745	C1 C2 D1 D2	2.1

35390746	D2 D3 D4 E2 E3 E4	16.7
35390747	D4 E2 E3 E4 F3 F4	2.9
35390837	D4 D5 D6 E4 E5 E6	2.1
35390838	C5 C6 D4 D5 D6	6.7
35390843	C4 C5	7.4
35390844	C5	6.8
35390859	B4 B5 C5	11.4
35390889	C3	0.9
35390890	C3	0.7

Table C.3: Change in risk - Case 3

250 CC_LB vs. 250 CC_UB		
DAUID	Cell Index	% Increase
35390014	B3 B4	4.4
35390018	B3	1.9
35390032	B3	460.5
35390033	B3	2.6
35390034	B3	6.7
35390035	B3 B4 C3	130.8
35390036	B3 C3	201.6
35390063	C4	3.9
35390064	C4	4.4
35390066	C4	5.5
35390067	C4 C5	0.0
35390068	C4 C5	7.3
35390069	C4 C5	6.1
35390070	C5	8.0
35390071	C5	49.9
35390092	C4 C5	2.3
35390095	C4 C5	14.1
35390096	C5	0.8
35390102	C4	7.5
35390103	C4	8.0
35390106	C4	108.6
35390110	C4	15.1
35390119	C4	17.4
35390120	C4	16.7
35390121	C3 C4	15.2
35390122	C3 C4	14.6

35390129	C3	C4			46.7
35390166	D3	D4			0.3
35390172	D4	D5			28.8
35390200	C4				14.6
35390201	C4				0.0
35390202	C4				16.3
35390203	C4				16.7
35390311	C3				17.2
35390312	C3				51.4
35390313	C3				3.0
35390314	C3				0.1
35390315	C3				0.1
35390323	C3				18.4
35390324	C3				3.6
35390325	C3				1.8
35390326	C3				17.0
35390327	C3				2.5
35390328	C3				91.1
35390329	C3				121.2
35390330	B3	C3			110.7
35390333	C3				20.7
35390368	B3	C3			1.0
35390374	B3				28.1
35390399	C2				7.1
35390403	C2				7.2
35390404	C1	C2			7.2
35390415	C2	C3			22.1
35390419	C3				13.7
35390429	C3				3.7
35390430	C3				54.1
35390437	C2	C3	D2	D3	14.6
35390440	C2				10.2
35390450	D2				0.6
35390459	D2				6.5
35390460	D2	D3			0.9
35390463	D3	E3			0.5
35390466	D3	E3			15.3
35390541	C3				642.7
35390547	C3				2.7
35390550	C3	C4			36.8
35390563	C4				0.0
35390589	C4				9.8
35390590	C4				26.8

35390660	B5 C4 C5	15.4
35390661	C4 C5	32.3
35390666	C4	0.5
35390668	B3 B4	11.3
35390669	B3 B4	222.6
35390671	D4	0.0
35390672	C3	1.1
35390675	B3	10.2
35390677	B3 B4	3.2
35390682	B4 C4	5.3
35390685	C4	8.5
35390696	C3	25.3
35390698	B2 B3 C3	1.1
35390702	C4	8.0
35390704	B3 C3	1.0
35390705	C2	15.2
35390706	C3	258.5
35390708	B3	1.1
35390709	B3 B4	10.5
35390710	B4	10.8
35390727	A4 B2 B3 B4 B5	10.4
35390728	B2 B3	1.0
35390745	C1 C2 D1 D2	7.7
35390746	D2 D3 D4 E2 E3 E4	19.0
35390747	D4 E2 E3 E4 F3 F4	47.1
35390837	D4 D5 D6 E4 E5 E6	31.9
35390838	C5 C6 D4 D5 D6	11.6
35390843	C4 C5	9.6
35390844	C5	21.0
35390859	B4 B5 C5	28.8
35390889	C3	0.3
35390890	C3	0.2

Table C.4: Change in risk - Case 4

100 CC_LB vs. 250 CC_LB		
DAUID	Cell Index	% Change
35390014	B3 B4	-58.6
35390018	B3	-59.7
35390032	B3	41.2

35390033	B3	-51.7
35390034	B3	-53.4
35390035	B3 B4 C3	-18.5
35390036	B3 C3	2.8
35390063	C4	-57.7
35390064	C4	25.1
35390066	C4	-48.4
35390067	C4 C5	-58.9
35390068	C4 C5	-54.8
35390069	C4 C5	-54.1
35390070	C5	-58.4
35390071	C5	-45.0
35390092	C4 C5	-54.2
35390095	C4 C5	-37.3
35390096	C5	-41.2
35390099	C4 C5	-60.0
35390102	C4	-56.6
35390103	C4	-56.9
35390106	C4	-52.5
35390110	C4	-54.3
35390119	C4	-53.3
35390120	C4	-56.3
35390121	C3 C4	-56.8
35390122	C3 C4	-56.8
35390129	C3 C4	-55.9
35390166	D3 D4	-59.8
35390172	D4 D5	-59.2
35390200	C4	-54.7
35390201	C4	0.0
35390202	C4	-55.1
35390203	C4	-56.3
35390312	C3	-34.6
35390313	C3	158.5
35390314	C3	1001.4
35390315	C3	100.0
35390323	C3	100.0
35390324	C3	100.0
35390325	C3	435.7
35390326	C3	125.8
35390327	C3	-55.6
35390328	C3	-19.7
35390329	C3	241.1
35390330	B3 C3	-49.5

35390368	B3	C3				-59.6
35390374	B3					-40.9
35390399	C2					-57.6
35390403	C2					-57.5
35390404	C1	C2				-57.5
35390415	C2	C3				-50.9
35390419	C3					-48.8
35390429	C3					171.9
35390430	C3					-59.2
35390437	C2	C3	D2	D3		-54.4
35390440	C2					-57.7
35390450	D2					-59.7
35390459	D2					-57.2
35390460	D2	D3				-57.3
35390463	D3	E3				-34.0
35390466	D3	E3				43.9
35390541	C3					-53.5
35390547	C3					-52.6
35390550	C3	C4				-48.6
35390589	C4					-54.6
35390590	C4					-46.0
35390660	B5	C4	C5			105.8
35390661	C4	C5				-49.2
35390666	C4					-56.1
35390668	B3	B4				-58.0
35390669	B3	B4				19.1
35390672	C3					-59.7
35390675	B3					-55.5
35390677	B3	B4				-60.0
35390682	B4	C4				-51.9
35390685	C4					-57.0
35390696	C3					-46.2
35390698	B2	B3	C3			-58.1
35390702	C4					-56.9
35390704	B3	C3				-59.6
35390705	C2					-56.4
35390706	C3					-40.5
35390708	B3					-58.1
35390709	B3	B4				-57.6
35390710	B4					-57.6
35390727	A4	B2	B3	B4	B5	-57.6
35390728	B2	B3				-58.3
35390745	C1	C2	D1	D2		-58.2

35390746	D2	D3	D4	E2	E3	E4	-56.1
35390747	D4	E2	E3	E4	F3	F4	-56.9
35390837	D4	D5	D6	E4	E5	E6	-58.5
35390838	C5	C6	D4	D5	D6		-57.3
35390843	C4	C5					-57.0
35390844	C5						-57.3
35390859	B4	B5	C5				-55.3
35390889	C3						-59.6
35390890	C3						-59.7

Table C.5: Change in risk - Case 5

100 CC_UB vs. 250 CC_UB							
DAUID	Cell Index						% Change
35390014	B3	B4					-57.5
35390018	B3						-59.0
35390032	B3						38.9
35390033	B3						-58.5
35390034	B3						-56.6
35390035	B3	B4	C3				-39.0
35390036	B3	C3					-25.1
35390063	C4						-58.5
35390064	C4						-58.0
35390066	C4						-57.8
35390067	C4	C5					-60.0
35390068	C4	C5					-56.8
35390069	C4	C5					-57.4
35390070	C5						-56.5
35390071	C5						-36.7
35390092	C4	C5					-59.0
35390095	C4	C5					-53.3
35390096	C5						-58.4
35390099	C4	C5					-60.8
35390102	C4						-57.0
35390103	C4						-56.8
35390106	C4						-19.9
35390110	C4						-54.0
35390119	C4						-53.0
35390120	C4						-53.3

35390121	C3	C4			-53.9
35390122	C3	C4			-54.2
35390129	C3	C4			-41.3
35390166	D3	D4			-59.7
35390172	D4	D5			-52.2
35390200	C4				-54.2
35390202	C4				-53.5
35390203	C4				-53.3
35390311	C3				-53.1
35390312	C3				-41.5
35390313	C3				-59.1
35390314	C3				-60.0
35390315	C3				-60.0
35390323	C3				-53.3
35390324	C3				-58.6
35390325	C3				-59.3
35390326	C3				-53.8
35390327	C3				-59.0
35390328	C3				-24.1
35390329	C3				-11.5
35390330	B3	C3			-18.8
35390333	C3				-51.7
35390368	B3	C3			-59.5
35390374	B3				-53.7
35390399	C2				-57.6
35390403	C2				-57.6
35390404	C1	C2			-57.6
35390415	C2	C3			-52.0
35390419	C3				-54.7
35390429	C3				-58.7
35390430	C3				-38.4
35390437	C2	C3	D2	D3	-54.7
35390440	C2				-56.9
35390450	D2				-59.7
35390459	D2				-55.8
35390460	D2	D3			-58.0
35390463	D3	E3			-59.8
35390466	D3	E3			-51.6
35390541	C3				178.2
35390547	C3				-59.2
35390550	C3	C4			-46.1
35390589	C4				-55.4
35390590	C4				-50.2

35390660	B5 C4 C5	-53.6
35390661	C4 C5	-46.4
35390666	C4	-59.8
35390668	B3 B4	-53.2
35390669	B3 B4	275.3
35390672	C3	-59.6
35390675	B3	-57.5
35390677	B3 B4	-58.7
35390682	B4 C4	-57.9
35390685	C4	-56.6
35390696	C3	-51.0
35390698	B2 B3 C3	-58.2
35390702	C4	-56.8
35390704	B3 C3	-59.5
35390705	C2	-54.3
35390706	C3	23.8
35390708	B3	-58.2
35390709	B3 B4	-57.4
35390710	B4	-57.5
35390727	A4 B2 B3 B4 B5	-57.0
35390728	B2 B3	-58.3
35390745	C1 C2 D1 D2	-55.9
35390746	D2 D3 D4 E2 E3 E4	-55.2
35390747	D4 E2 E3 E4 F3 F4	-38.4
35390837	D4 D5 D6 E4 E5 E6	-46.3
35390838	C5 C6 D4 D5 D6	-55.3
35390843	C4 C5	-56.2
35390844	C5	-51.6
35390859	B4 B5 C5	-48.3
35390889	C3	-59.9
35390890	C3	-60.0

Appendix D

Social Vulnerability Indicators

Table D.1: Social vulnerability indicators and justification for their selection (adapted from Peck et al., 2007).

Category	Theme	Indicator	Description	Justification
Social vulnerability	Age	Population under 20 years of age	# people under 20yrs old	Physically weak; susceptible to health related problems; limited mobility; difficulties in decision making and disaster response; dependent
		Population over 65 years of age	# people over 65yrs old	Physically weak; limited mobility; reluctant to leave home; less informed; less aid; susceptibility to health related problems
	Differential access to resources	Female population	# females	Physically disadvantaged; slower recovery; increased stress and emotion
		Population of single-parent households	# of single parent headed households	Differential access to resources; longer recovery; high stress
		Population whose primary mode of transportation is not by vehicle	# people who rely on transportation other than a vehicle to get to work	May lack transportation during an evacuation or emergency
		Low income households	# households considered low income	Differential access to resources; financial instabilities
	Household structure	Population living alone	# people residing by themselves	Less informed; less support
		Full households	# households with 6 or more persons	More likely poor; limited resources; disadvantaged
	Social	Population of	# people	Less informed; less

	status	renters	renting a house	disaster preparedness; less cleanup after a disaster
		Mobility status	# people who have recently moved	Less familiar with area and potential risks; less familiar with emergency response; less prepared for disaster; less contacts
		Population who have not graduated high school	# people without a high school diploma	Communication issues; difficulties in assessing and recovering from disasters
		Regions of low community participation	# people involved in unpaid community activities	Higher stress; slower recovery; less willingness to help others
	Ethnicity	Population whose official lang. is neither English nor French	# people who do not have sound understanding of Canada's official languages	Language/communication barriers may prevent appropriate response
		Population of visible minorities	# people who are visibly a minority	Communication barriers; slower recovery time
	Economics	Employed workforce working from home	# people who regularly work from home	Home and career damages; added stress; loss of job during disaster; greater losses
		Direct workforce in agriculture	# people directly involved in agricultural activities	Usually poorer; direct affect on personal life and career

* Many of these indicators may be represented by data provided by Statistics Canada Population Census

Appendix E

COMPRO Input

Table E.1: Input into COMPRO program for all Trials

Criterion	Infrastructure	Social	Environmental
Weight	XXX	XXX	XXX
Alternatives			
0014	2611861	190	0
0032	3698051	350	0
0034	5147229	160	0
0035	117535880	125	0
0036	6.283377E+07	45	0
0063	3254266	100	0
0064	26782508	160	0
0067	5495059	55	0
0068	7236272	75	0
0069	7605745	110	0
0070	2741474	125	0
0092	4.309224E+07	60	0
0106	3429251	75	0
0110	3012497	65	0
0129	5572088	35	0
0200	4483413	45	0
0202	4642637	30	0
0312	7490202	60	0
0313	57138696	75	0
0314	18516292	55	0
0323	4861292	60	0
0324	12971145	65	0
0325	60784188	60	0
0326	37502684	60	0
0327	3768602	375	0
0374	4036128	80	0
0415	11393806	190	0
0429	3.445188E+07	40	0
0437	17052098	90	0
0541	4123720	15	0
0547	3587155	105	0
0550	13736212	50	0
0589	4352012	95	0
0590	6788304	20	0
0660	6505678	85	0
0666	7205255	70	0
0675	2904458	220	0

Criterion Alternatives	Infrastructure	Social	Environmental
0677	1.849586E+07	125	0
0696	11203213	320	0
0705	2228278	150	0
0706	19942952	225	0
0709	4570231	175	0
0710	2779882	150	5093
0727	3208648	70	159915
0746	6339082	220	0
0837	2605754	60	102909
0859	3020046	35	41634
0889	15353329	30	0
0890	22469042	245	0

Parameter p 1 2 1000

* XXX designates parameters which are modified for each trial

Table E.2: Trial 1 - Results

Distance Metric Value [and Rank]

DA	$p = 1$	$p = 2$	$p = 1000$
0014	8.360E-01 [16]	5.003E-01 [19]	0.000E+00 [1]
0032	6.849E-01 [4]	4.685E-01 [10]	0.000E+00 [2]
0034	8.564E-01 [21]	5.058E-01 [21]	0.000E+00 [3]
0035	5.642E-01 [1]	4.054E-01 [1]	0.000E+00 [4]
0036	7.962E-01 [12]	4.786E-01 [12]	0.000E+00 [5]
0063	9.174E-01 [31]	5.334E-01 [32]	0.000E+00 [6]
0064	7.940E-01 [11]	4.681E-01 [9]	0.000E+00 [7]
0067	9.526E-01 [44]	5.506E-01 [44]	0.000E+00 [8]
0068	9.290E-01 [35]	5.379E-01 [35]	0.000E+00 [9]
0069	8.956E-01 [27]	5.213E-01 [27]	0.000E+00 [10]
0070	8.958E-01 [28]	5.237E-01 [28]	0.000E+00 [11]
0092	8.394E-01 [17]	4.919E-01 [16]	0.000E+00 [12]
0106	9.400E-01 [39]	5.445E-01 [39]	0.000E+00 [13]
0110	9.505E-01 [43]	5.500E-01 [43]	0.000E+00 [14]
0129	9.708E-01 [46]	5.607E-01 [46]	0.000E+00 [15]
0200	9.647E-01 [45]	5.574E-01 [45]	0.000E+00 [16]
0202	9.782E-01 [47]	5.648E-01 [47]	0.000E+00 [17]
0312	9.422E-01 [40]	5.448E-01 [40]	0.000E+00 [18]
0313	7.849E-01 [9]	4.672E-01 [7]	0.000E+00 [19]
0314	9.150E-01 [30]	5.294E-01 [29]	0.000E+00 [20]
0323	9.498E-01 [42]	5.492E-01 [42]	0.000E+00 [21]
0324	9.217E-01 [33]	5.332E-01 [31]	0.000E+00 [22]
0325	7.883E-01 [10]	4.719E-01 [11]	0.000E+00 [23]

0326	8.555E-01 [20]	4.992E-01 [18]	0.000E+00 [24]
0327	6.616E-01 [3]	4.678E-01 [8]	0.000E+00 [25]
0374	9.337E-01 [37]	5.411E-01 [38]	0.000E+00 [26]
0415	8.107E-01 [15]	4.839E-01 [13]	0.000E+00 [27]
0429	8.828E-01 [24]	5.143E-01 [23]	0.000E+00 [28]
0437	8.868E-01 [25]	5.144E-01 [24]	0.000E+00 [29]
0541	9.935E-01 [49]	5.736E-01 [49]	0.000E+00 [30]
0547	9.118E-01 [29]	5.306E-01 [30]	0.000E+00 [31]
0550	9.334E-01 [36]	5.396E-01 [36]	0.000E+00 [32]
0589	9.189E-01 [32]	5.337E-01 [33]	0.000E+00 [33]
0590	9.812E-01 [48]	5.666E-01 [48]	0.000E+00 [34]
0660	9.219E-01 [34]	5.345E-01 [34]	0.000E+00 [35]
0666	9.338E-01 [38]	5.404E-01 [37]	0.000E+00 [36]
0675	8.074E-01 [14]	4.910E-01 [15]	0.000E+00 [37]
0677	8.503E-01 [19]	4.962E-01 [17]	0.000E+00 [38]
0696	6.910E-01 [5]	4.558E-01 [4]	0.000E+00 [39]
0705	8.741E-01 [23]	5.149E-01 [25]	0.000E+00 [40]
0706	7.536E-01 [8]	4.578E-01 [6]	0.000E+00 [41]
0709	8.442E-01 [18]	5.015E-01 [20]	0.000E+00 [42]
0710	8.619E-01 [22]	5.070E-01 [22]	0.000E+00 [43]
0727	6.123E-01 [2]	4.343E-01 [2]	0.000E+00 [44]
0746	7.975E-01 [13]	4.843E-01 [14]	0.000E+00 [45]
0837	7.420E-01 [7]	4.573E-01 [5]	0.000E+00 [46]
0859	8.915E-01 [26]	5.186E-01 [26]	0.000E+00 [47]
0889	9.472E-01 [41]	5.476E-01 [41]	0.000E+00 [48]
0890	7.278E-01 [6]	4.480E-01 [3]	0.000E+00 [49]

Table E.3: Trial 2 - Results

Distance Metric Value [and Rank]

DA	$p = 1$	$p = 2$	$p = 1000$
0014	8.039E-01 [16]	5.483E-01 [20]	4.983E-01 [47]
0032	6.214E-01 [3]	5.044E-01 [12]	4.936E-01 [37]
0034	8.262E-01 [19]	5.519E-01 [21]	4.873E-01 [28]
0035	3.778E-01 [1]	2.952E-01 [1]	0.000E+00 [1]
0036	7.039E-01 [9]	4.480E-01 [4]	0.000E+00 [2]
0063	9.011E-01 [31]	5.907E-01 [32]	4.956E-01 [40]
0064	7.324E-01 [10]	4.711E-01 [7]	0.000E+00 [3]
0067	9.414E-01 [43]	6.103E-01 [42]	4.858E-01 [27]
0068	9.116E-01 [35]	5.915E-01 [33]	4.783E-01 [21]
0069	8.711E-01 [25]	5.691E-01 [25]	4.767E-01 [19]
0070	8.756E-01 [26]	5.787E-01 [27]	4.978E-01 [46]
0092	7.728E-01 [14]	4.865E-01 [9]	0.000E+00 [4]
0106	9.281E-01 [40]	6.049E-01 [39]	4.948E-01 [39]
0110	9.410E-01 [42]	6.126E-01 [43]	4.966E-01 [42]
0129	9.633E-01 [46]	6.232E-01 [45]	4.855E-01 [26]

0200	9.569E-01 [45]	6.203E-01 [44]	4.902E-01 [32]
0202	9.729E-01 [47]	6.297E-01 [48]	4.895E-01 [30]
0312	9.272E-01 [39]	6.002E-01 [37]	4.772E-01 [20]
0313	6.952E-01 [7]	4.355E-01 [2]	0.000E+00 [5]
0314	8.849E-01 [28]	5.664E-01 [23]	0.000E+00 [6]
0323	9.386E-01 [41]	6.093E-01 [40]	4.886E-01 [29]
0324	8.979E-01 [30]	5.781E-01 [26]	0.000E+00 [7]
0325	6.961E-01 [8]	4.394E-01 [3]	0.000E+00 [8]
0326	7.970E-01 [15]	5.029E-01 [10]	0.000E+00 [9]
0327	5.933E-01 [2]	5.034E-01 [11]	4.933E-01 [36]
0374	9.199E-01 [37]	5.997E-01 [36]	4.922E-01 [35]
0415	7.658E-01 [12]	5.139E-01 [13]	0.000E+00 [10]
0429	8.325E-01 [20]	5.276E-01 [16]	0.000E+00 [11]
0437	8.524E-01 [24]	5.478E-01 [19]	0.000E+00 [12]
0541	9.918E-01 [49]	6.418E-01 [49]	4.918E-01 [34]
0547	8.941E-01 [29]	5.866E-01 [29]	4.941E-01 [38]
0550	9.112E-01 [34]	5.857E-01 [28]	0.000E+00 [13]
0589	9.019E-01 [32]	5.896E-01 [31]	4.908E-01 [33]
0590	9.747E-01 [48]	6.294E-01 [47]	4.802E-01 [23]
0660	9.037E-01 [33]	5.879E-01 [30]	4.815E-01 [24]
0666	9.173E-01 [36]	5.948E-01 [35]	4.784E-01 [22]
0675	7.693E-01 [13]	5.355E-01 [17]	4.971E-01 [44]
0677	8.072E-01 [17]	5.211E-01 [14]	0.000E+00 [14]
0696	6.222E-01 [4]	4.757E-01 [8]	0.000E+00 [15]
0705	8.500E-01 [23]	5.679E-01 [24]	5.000E-01 [49]
0706	6.899E-01 [6]	4.657E-01 [6]	0.000E+00 [16]
0709	8.121E-01 [18]	5.471E-01 [18]	4.898E-01 [31]
0710	8.444E-01 [22]	5.652E-01 [22]	4.976E-01 [45]
0727	8.346E-01 [21]	6.005E-01 [38]	4.957E-01 [41]
0746	7.544E-01 [11]	5.217E-01 [15]	4.822E-01 [25]
0837	8.840E-01 [27]	6.100E-01 [41]	4.984E-01 [48]
0859	9.483E-01 [44]	6.283E-01 [46]	4.966E-01 [43]
0889	9.264E-01 [38]	5.944E-01 [34]	0.000E+00 [17]
0890	6.567E-01 [5]	4.481E-01 [5]	0.000E+00 [18]

Table E.4: Trial 3 - Results

Distance Metric Value [and Rank]

DA	$p = 1$	$p = 2$	$p = 1000$
0014	6.830E-01 [11]	4.511E-01 [9]	0.000E+00 [1]
0032	3.913E-01 [2]	3.037E-01 [3]	0.000E+00 [2]
0034	7.306E-01 [13]	4.886E-01 [13]	0.000E+00 [3]
0035	5.014E-01 [4]	4.541E-01 [10]	0.000E+00 [4]
0036	7.882E-01 [19]	6.146E-01 [29]	5.958E-01 [41]
0063	8.439E-01 [26]	5.809E-01 [22]	4.965E-01 [20]
0064	6.743E-01 [10]	4.571E-01 [11]	0.000E+00 [5]

0067	9.193E-01 [42]	6.491E-01 [42]	5.778E-01 [38]
0068	8.786E-01 [32]	6.150E-01 [30]	5.417E-01 [25]
0069	8.145E-01 [22]	5.597E-01 [18]	4.785E-01 [18]
0070	8.001E-01 [20]	5.436E-01 [17]	0.000E+00 [6]
0092	8.124E-01 [21]	6.029E-01 [26]	5.687E-01 [32]
0106	8.885E-01 [37]	6.197E-01 [31]	5.417E-01 [26]
0110	9.077E-01 [40]	6.361E-01 [36]	5.597E-01 [30]
0129	9.552E-01 [46]	6.813E-01 [45]	6.139E-01 [44]
0200	9.400E-01 [44]	6.664E-01 [43]	5.958E-01 [42]
0202	9.666E-01 [47]	6.905E-01 [47]	6.229E-01 [46]
0312	9.051E-01 [38]	6.387E-01 [37]	5.687E-01 [33]
0313	7.488E-01 [14]	5.662E-01 [19]	5.417E-01 [27]
0314	8.854E-01 [34]	6.346E-01 [35]	5.778E-01 [39]
0323	9.119E-01 [41]	6.418E-01 [38]	5.687E-01 [34]
0324	8.818E-01 [33]	6.243E-01 [33]	5.597E-01 [31]
0325	7.664E-01 [18]	5.897E-01 [24]	5.687E-01 [35]
0326	8.270E-01 [24]	6.077E-01 [27]	5.687E-01 [36]
0327	3.460E-01 [1]	3.002E-01 [2]	0.000E+00 [7]
0374	8.779E-01 [31]	6.111E-01 [28]	5.326E-01 [24]
0415	6.602E-01 [9]	4.363E-01 [8]	0.000E+00 [8]
0429	8.710E-01 [30]	6.443E-01 [40]	6.049E-01 [43]
0437	8.260E-01 [23]	5.793E-01 [21]	5.146E-01 [22]
0541	9.951E-01 [49]	7.156E-01 [49]	6.500E-01 [49]
0547	8.340E-01 [25]	5.728E-01 [20]	4.875E-01 [19]
0550	9.069E-01 [39]	6.479E-01 [41]	5.868E-01 [40]
0589	8.500E-01 [28]	5.872E-01 [23]	5.056E-01 [21]
0590	9.791E-01 [48]	7.045E-01 [48]	6.410E-01 [48]
0660	8.625E-01 [29]	6.001E-01 [25]	5.236E-01 [23]
0666	8.877E-01 [36]	6.230E-01 [32]	5.507E-01 [28]
0675	6.281E-01 [8]	.120E-01 [7]	0.000E+00 [9]
0677	7.591E-01 [17]	5.222E-01 [16]	0.000E+00 [10]
0696	4.260E-01 [3]	2.982E-01 [1]	0.000E+00 [11]
0705	7.562E-01 [16]	5.075E-01 [15]	0.000E+00 [12]
0706	5.747E-01 [6]	3.746E-01 [5]	0.000E+00 [13]
0709	7.050E-01 [12]	4.683E-01 [12]	0.000E+00 [14]
0710	7.532E-01 [15]	5.065E-01 [14]	0.000E+00 [15]
0727	8.481E-01 [27]	6.259E-01 [34]	5.507E-01 [29]
0746	6.192E-01 [7]	4.056E-01 [6]	0.000E+00 [16]
0837	8.856E-01 [35]	6.428E-01 [39]	5.687E-01 [37]
0859	9.488E-01 [45]	6.834E-01 [46]	6.139E-01 [45]
0889	9.388E-01 [43]	6.791E-01 [44]	6.229E-01 [47]
0890	5.321E-01 [5]	.446E-01 [4]	0.000E+00 [17]

Table E.5: Trial 4 - Results

Distance Metric Value [and Rank]

DA	$p = 1$	$p = 2$	$p = 1000$
0014	8.052E-01 [12]	5.497E-01 [12]	5.000E-01 [5]
0032	6.265E-01 [3]	5.104E-01 [4]	5.000E-01 [6]
0034	8.364E-01 [16]	5.626E-01 [16]	5.000E-01 [7]
0035	7.778E-01 [10]	5.720E-01 [18]	5.000E-01 [8]
0036	9.141E-01 [28]	6.218E-01 [41]	5.000E-01 [9]
0063	9.047E-01 [26]	5.943E-01 [23]	5.000E-01 [10]
0064	8.176E-01 [13]	5.597E-01 [15]	5.000E-01 [11]
0067	9.527E-01 [43]	6.212E-01 [40]	5.000E-01 [12]
0068	9.290E-01 [33]	6.085E-01 [29]	5.000E-01 [13]
0069	8.898E-01 [22]	5.880E-01 [21]	5.000E-01 [14]
0070	8.773E-01 [20]	5.806E-01 [20]	5.000E-01 [15]
0092	9.146E-01 [29]	6.137E-01 [33]	5.000E-01 [16]
0106	9.323E-01 [34]	6.090E-01 [30]	5.000E-01 [17]
0110	9.438E-01 [38]	6.152E-01 [36]	5.000E-01 [18]
0129	9.749E-01 [46]	6.341E-01 [45]	5.000E-01 [19]
0200	9.647E-01 [44]	6.277E-01 [44]	5.000E-01 [20]
0202	9.812E-01 [47]	6.376E-01 [47]	5.000E-01 [21]
0312	9.454E-01 [40]	6.177E-01 [37]	5.000E-01 [22]
0313	8.857E-01 [21]	6.032E-01 [27]	5.000E-01 [23]
0314	9.414E-01 [37]	6.195E-01 [39]	5.000E-01 [24]
0323	9.477E-01 [41]	6.181E-01 [38]	5.000E-01 [25]
0324	9.351E-01 [36]	6.139E-01 [34]	5.000E-01 [26]
0325	8.992E-01 [24]	6.123E-01 [32]	5.000E-01 [27]
0326	9.194E-01 [31]	6.143E-01 [35]	5.000E-01 [28]
0327	5.987E-01 [2]	5.096E-01 [3]	5.000E-01 [29]
0374	9.262E-01 [32]	6.059E-01 [28]	5.000E-01 [30]
0415	7.976E-01 [11]	5.484E-01 [11]	5.000E-01 [31]
0429	9.443E-01 [39]	6.275E-01 [43]	5.000E-01 [32]
0437	9.038E-01 [25]	5.982E-01 [25]	5.000E-01 [33]
0541	9.984E-01 [49]	6.478E-01 [49]	5.000E-01 [34]
0547	8.988E-01 [23]	5.914E-01 [22]	5.000E-01 [35]
0550	9.511E-01 [42]	6.233E-01 [42]	5.000E-01 [36]
0589	9.093E-01 [27]	5.970E-01 [24]	5.000E-01 [37]
0590	9.905E-01 [48]	6.441E-01 [48]	5.000E-01 [38]
0660	9.185E-01 [30]	6.026E-01 [26]	5.000E-01 [39]
0666	9.346E-01 [35]	6.116E-01 [31]	5.000E-01 [40]
0675	7.716E-01 [9]	5.381E-01 [10]	5.000E-01 [41]
0677	8.637E-01 [19]	5.784E-01 [19]	5.000E-01 [42]
0696	6.533E-01 [5]	5.121E-01 [5]	5.000E-01 [43]
0705	8.500E-01 [18]	5.679E-01 [17]	5.000E-01 [44]
0706	7.513E-01 [7]	5.338E-01 [7]	5.000E-01 [45]
0709	8.202E-01 [14]	5.559E-01 [14]	5.000E-01 [46]
0710	8.336E-01 [15]	5.538E-01 [13]	4.841E-01 [4]
0727	4.380E-01 [1]	3.531E-01 [1]	0.000E+00 [1]
0746	7.687E-01 [8]	5.376E-01 [8]	5.000E-01 [47]

0837	6.279E-01 [4]	4.052E-01 [2]	0.000E+00 [2]
0859	8.469E-01 [17]	5.379E-01 [9]	0.000E+00 [3]
0889	9.720E-01 [45]	6.362E-01 [46]	5.000E-01 [48]
0890	7.269E-01 [6]	5.269E-01 [6]	5.000E-01 [49]

Table E.6: Trial 5 - Results

Distance Metric Value [and Rank]

DA	$p = 1$	$p = 2$	$p = 1000$
0014	7.078E-01 [11]	4.242E-01 [9]	0.000E+00 [1]
0032	4.398E-01 [2]	2.935E-01 [2]	0.000E+00 [2]
0034	7.545E-01 [14]	4.607E-01 [12]	0.000E+00 [3]
0035	6.667E-01 [9]	4.859E-01 [15]	0.000E+00 [4]
0036	8.712E-01 [27]	6.083E-01 [40]	5.500E-01 [41]
0063	8.570E-01 [25]	5.428E-01 [21]	0.000E+00 [5]
0064	7.264E-01 [12]	4.526E-01 [11]	0.000E+00 [6]
0067	9.291E-01 [43]	6.068E-01 [39]	5.333E-01 [38]
0068	8.935E-01 [32]	5.771E-01 [28]	5.000E-01 [25]
0069	8.347E-01 [21]	5.273E-01 [18]	0.000E+00 [7]
0070	8.160E-01 [19]	5.083E-01 [17]	0.000E+00 [8]
0092	8.718E-01 [28]	5.895E-01 [32]	5.250E-01 [32]
0106	8.984E-01 [33]	5.784E-01 [29]	5.000E-01 [26]
0110	9.156E-01 [38]	5.930E-01 [35]	5.167E-01 [30]
0129	9.623E-01 [46]	6.363E-01 [45]	5.667E-01 [44]
0200	9.471E-01 [44]	6.218E-01 [44]	5.500E-01 [42]
0202	9.719E-01 [47]	6.440E-01 [47]	5.750E-01 [46]
0312	9.182E-01 [40]	5.988E-01 [36]	5.250E-01 [33]
0313	8.286E-01 [20]	5.645E-01 [26]	5.000E-01 [27]
0314	9.121E-01 [37]	6.029E-01 [38]	5.333E-01 [39]
0323	9.216E-01 [41]	5.997E-01 [37]	5.250E-01 [34]
0324	9.027E-01 [36]	5.899E-01 [33]	5.167E-01 [31]
0325	8.488E-01 [23]	5.862E-01 [31]	5.250E-01 [35]
0326	8.791E-01 [30]	5.907E-01 [34]	5.250E-01 [36]
0327	3.980E-01 [1]	2.905E-01 [1]	0.000E+00 [9]
0374	8.893E-01 [31]	5.710E-01 [27]	4.917E-01 [24]
0415	6.964E-01 [10]	4.203E-01 [8]	0.000E+00 [10]
0429	9.164E-01 [39]	6.212E-01 [43]	5.583E-01 [43]
0437	8.557E-01 [24]	5.525E-01 [23]	4.750E-01 [22]
0541	9.975E-01 [49]	6.665E-01 [49]	6.000E-01 [49]
0547	8.482E-01 [22]	5.357E-01 [20]	0.000E+00 [11]
0550	9.267E-01 [42]	6.117E-01 [41]	5.417E-01 [40]
0589	8.639E-01 [26]	5.495E-01 [22]	0.000E+00 [12]
0590	9.857E-01 [48]	6.583E-01 [48]	5.917E-01 [48]
0660	8.778E-01 [29]	5.630E-01 [25]	4.833E-01 [23]
0666	9.019E-01 [35]	5.844E-01 [30]	5.083E-01 [28]
0675	6.575E-01 [8]	3.892E-01 [7]	0.000E+00 [13]

0677	7.955E-01 [18]	5.027E-01 [16]	0.000E+00 [14]
0696	4.800E-01 [3]	3.001E-01 [3]	0.000E+00 [15]
0705	7.750E-01 [17]	4.750E-01 [14]	0.000E+00 [16]
0706	6.270E-01 [5]	3.757E-01 [5]	0.000E+00 [17]
0709	7.303E-01 [13]	4.418E-01 [10]	0.000E+00 [18]
0710	7.663E-01 [16]	4.706E-01 [13]	0.000E+00 [19]
0727	6.571E-01 [7]	5.296E-01 [19]	5.083E-01 [29]
0746	6.530E-01 [6]	3.875E-01 [6]	0.000E+00 [20]
0837	7.636E-01 [15]	5.531E-01 [24]	5.250E-01 [37]
0859	9.005E-01 [34]	6.144E-01 [42]	5.667E-01 [45]
0889	9.579E-01 [45]	6.409E-01 [46]	5.750E-01 [47]
0890	5.903E-01 [4]	3.532E-01 [4]	0.000E+00 [21]

Appendix F

Cell C3

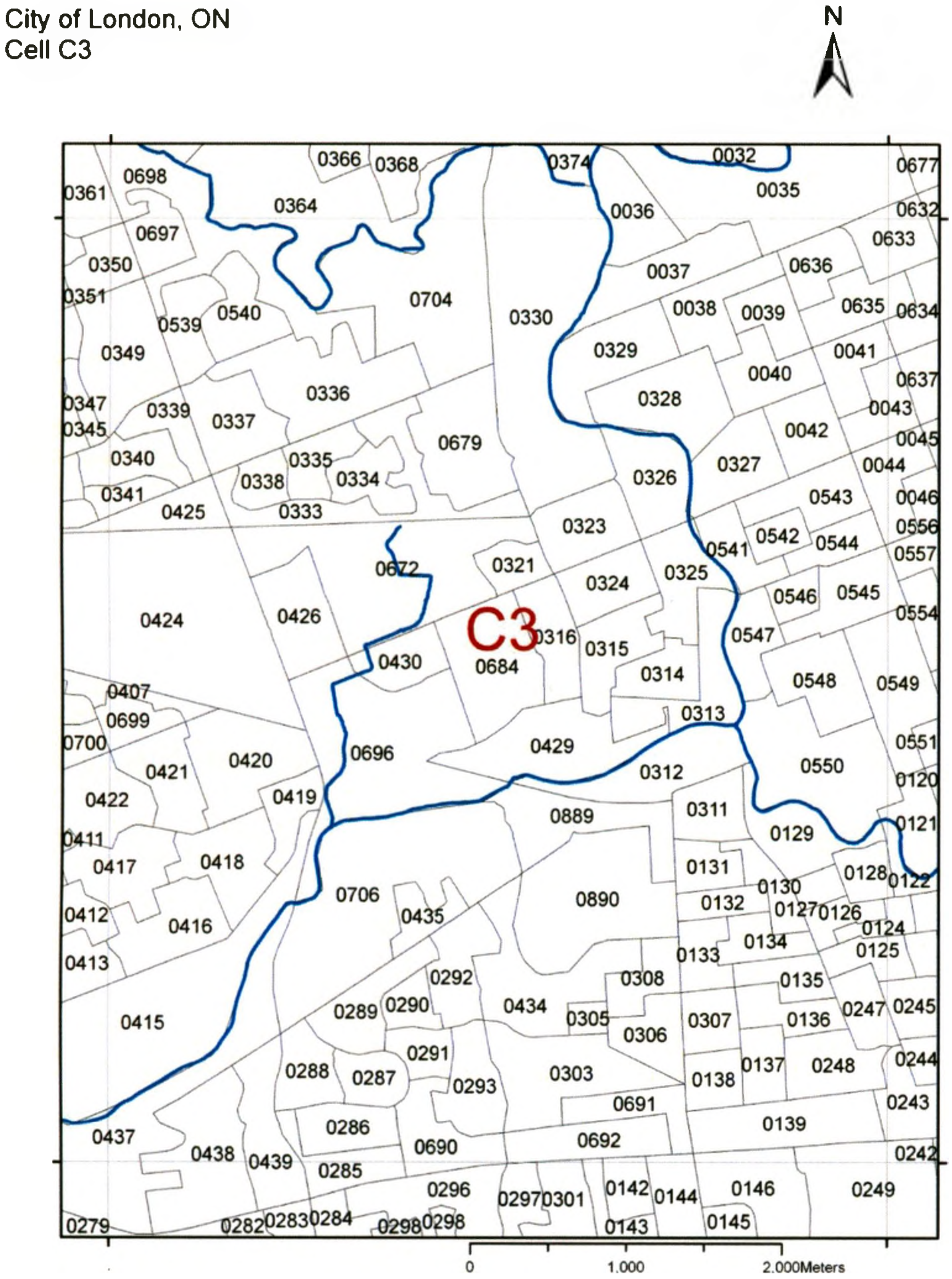

Figure F.1: Enlargement of reference cell C3 in GIS for quick identification of critical DAs in the City of London; downtown Forks location