THE UNIVERSITY OF WESTERN ONTARIO
DEPARTMENT OF CIVIL AND
ENVIRONMENTAL ENGINEERING

Water Resources Research Report

City of London: Vulnerability of Infrastructure to Climate Change
Final Report

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The City of London:
Vulnerability of Infrastructure to Climate Change

Final Report

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Executive Summary

The Earth's climate is changing and these changes are documented to have a serious impact on municipal infrastructure. Current infrastructure is designed and constructed based on standards and codes developed decades ago. These standards and codes include historic climate and design storms which are no longer representative of the current climate. With the changes in climate patterns, infrastructure may no longer have the capacity to handle new climate loads. Thus, a region must adapt its policies and procedures to consider climate change and mitigate risks to municipal infrastructure. Climate modeling suggests that the City of London can expect to experience more frequent severe precipitation events in the future as a consequence of climate change. Flooding is therefore a natural hazard event of significance to this region and as such the City commissioned this study to assess the vulnerability of London's public infrastructure to changing climate conditions.

From a hazards perspective, vulnerability assessments provide insights into responses necessary to prevent loss of life, damages, or in worst cases disasters. From a climate change perspective, capturing the differential elements of vulnerability is a prerequisite for developing adaptation policies that will promote equitable and sustainable development.

Risk is defined in this study as the intersection of a hazard (flooding) with vulnerability. The risk measure enables conclusions and recommendations to be made regarding the reliability of the infrastructure network within the city to adapt to the changing climate conditions.

The study results are meant to identify and prioritize areas of high risk or interest within the city which are recommended for further investigation. These recommendations are meant to aid in policy development as it relates to municipal infrastructure and the future.

The risk used in the study concerns only infrastructure elements. No social data has been aggregated with the structures. Therefore the recommendations are based on risk solely due to the interaction of each structure with the flood event.

Climate, hydraulic and hydrologic analyses were used as input to assess the risk of municipal infrastructure. The risk assessment considers both a quantitative and qualitative approach of assessing risk. Fuzzy set theory was used to address uncertainties associated with the subjective nature of criteria in quantitative analysis. Interviews held with City of London experts created the framework for membership functions used to address perceptions of risk and variability of the condition (or state) of municipal infrastructure as part of the qualitative risk assessment procedure. Quantitative and qualitative results were combined into risk indices. These indices are used to identify regions of high risk.

Infrastructure considered in this study include: critical facilities (schools, hospitals, fire stations), barriers (dams, dykes), Pollution Control Plants (PCPs), buildings (residential, commercial, industrial, institutional), roads (arterial, primary), and bridges (footbridges, culverts). Two climate change scenarios were considered representing lower and upper bounds of potential climate changes. The current regulatory floodplain developed by the Upper Thames River Conservation Authority (UTRCA) was also considered as an additional scenario representing the historical climate conditions.

The integrated risk assessment procedure developed for this project includes:

1. selection of climate models and scenarios,
2. climate modeling using Weather Generator to simulate meteorological data,
3. hydrologic modeling using Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) to transform meteorological data into runoff and generate streamflows,
4. hydraulic modeling using Hydrologic Engineering Center – River Analysis System (HEC-RAS) to map floodplains for each climate scenario,
5. data collection on local infrastructure,
6. infrastructure risk assessment to climate change to produce flood risk tables and maps, and
7. identification of recommendations for climate change adaptation.

Climate Modeling

Currently, one of the best ways to study the effects of climate change is to use Global Circulation Models (GCM). These models are the current state of the art in climate science. Their aim is to describe the functioning of the climate system through the use of physics, fluid mechanics, chemistry, as well as other sciences.

A traditional way of studying the impacts of climatic change for small areas involves downscaling the outputs from GCM (temporally and spatially) from which user and location specific impacts are derived.

In this study the weather generator approach was used for downscaling the global information to local scale. This approach takes as input historical climate information, as well as information from the GCM, and generates climatic information for an arbitrary long period of time for the local weather station. Climate change scenarios are the output of GCM. They do not predict the future but simply offer possibilities of what may happen in the future following a particular course of action.

Two climate scenarios, named the *climate change lower bound scenario* (CC_LB) and the *climate change upper bound scenario* (CC_UB), were derived from the historical data and inputs from the global climate models (GCMs). The choice of the GCMs was made on the basis that the first scenario represents the lower boundary of potential climate change impacts and the second represents the upper boundary of potential climate change. The selection of two GCMs was made from a wide range of available models and their runs. Selection of the range of potential climate change through the use of two scenarios compensate for the existing level of uncertainty present in global modeling of climate change at the watershed scale. It is important to point out that both climate scenarios are equally likely as well as the range of climatic conditions between the two.

The two climate scenarios developed for use in this study are based on locally observed data for the period 1964-2006.

Hydrologic Modeling

The US Army Corps of Engineers (USACE) Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS**)** was used to transform two climate scenarios of meteorological conditions into corresponding runoff. HEC-HMS is a precipitation-runoff model that includes a large set of mix-and-match methods to simulate river basin, channel and water control structures.

The modified meteorological records produced by the climate modeling were used as input into the HEC-HMS to simulate the direct runoff due to precipitation events and translate the runoff into the stream flow. The final model includes 72 sub-basins, 45 reaches, 49 junctions, and 3 reservoirs. The HEC-HMS model outputs stream flow data that is used directly as input for hydraulic modeling.

Hydraulic Modeling

Stream flow generated by the hydrologic model was used in conjunction with the Digital Terrain Models (DTMs) and channel characteristics as input into the Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic modeling program to generate water surface profiles. The extent and depth of these floods are represented in Geographic Information System (GIS) environment and are the foundation for the quantitative risk assessment.

Both the 100-yr and 250-yr return periods were selected for use in this study as they are the basis for the current regulatory floodplains enforced by the City of London and the Upper Thames River Conservation Authority. This study therefore considers the five scenarios:

1. 100 yr CC_LB;
2. 100 yr CC_UB;
3. 250 yr CC_LB;
4. 250 yr CC_UB; and
5. 250 UTRCA.

The fifth scenario represents the current floodlines generated by the Upper Thames River Conservation Authority (UTRCA) which are included in the City of London Official Plan. The extent of the floodlines was provided by UTRCA and the data is available for the 250-yr return period only.

Local Infrastructure

The study considers transportation infrastructure (including bridges, culverts and arterial roads), buildings (residential, commercial and industrial), and critical facilities, defined in this study as the buildings which provide essential or emergency services (fire stations, Emergency Management Services (EMS), police stations, hospitals, schools and pollution control plants), flood protection structures, sanitary and storm networks and the drinking water distribution network. Each of these infrastructure elements has a different failure mechanism under flood loading.

A summary of the type and quantities of data being considered for the infrastructure within the study is presented in the following table.

Infrastructure	Quantity
Bridges & Culverts	216
Arterial Roads	520km
Buildings	>3,000*
Sanitary/Storm Pipe Network	> 1,300km
Pollution Control Plants	6
Stormwater Management Facilities	100

*within the floodplain area under consideration

The study team conducted interviews with experts across the infrastructure categories at the City of London to better understand each system and gather input for the risk analysis. The departments and divisions involved in this process included:

- Risk Management Division,
- Wastewater and Drainage Engineering,
- Planning and Development – Building,
- Transportation Planning and Design,
- Water Operations Division,
- Water Engineering Division,
- Pollution Control Operations,
- Environmental Programs and Customer Relations, and

- Corporate Security and Emergency Management Division.

The study team also interviewed experts from the UTRCA and at the University of Western Ontario.

Risk Assessment
The risk assessment methodology produces an integrated risk index for each infrastructure element considered in the study. This risk index allows for the comparison among various locations that may be flooded and is presented in tabular and spatial (maps) forms.

Risk is commonly defined as the product between a hazard and vulnerability when used in the context of flooding (Apel, 2008). This study measures vulnerability which is defined by Engineers Canada in the context of engineering infrastructure and climate change as "the shortfall in the ability of public infrastructure to absorb the negative effects, and benefit from the positive effects, of changes in the climate conditions used to design and operate infrastructure" (Engineers Canada, 2007).

The Risk Index R is calculated for each infrastructure element and incorporates quantitative and qualitative data to address both objective and subjective types of uncertainty.

The risk index is tabulated for each infrastructure element for each of the five scenarios. These values are then combined and displayed spatially using GIS in the form of risk maps. Risk is portrayed geographically by Dissemination Areas (DA) classification consistent with Statistics Canada method of representing data. There are 527 DA within the City of London. Each DA is identified by its unique 4-digit code. Statistics Canada defines DA as "a small, relatively stable geographic unit comprised of one or more adjacent dissemination blocks". The DA are divided with populations usually 400 to 700 persons while respecting the boundaries of the larger census subdivisions and census tracts (Statistics Canada, 2001). They remain relatively stable over time and they are considered small enough to remain significant in municipal decision making.

Results
The vulnerability of the City of London Infrastructure to flooding is presented in the form of maps and tables. A map was produced for each climate scenario: 100-yr CC_LB, 100-yr CC_UB, 250-yr CC_LB, 250-yr CC_UB) and the 250 UTRCA scenario. The resolution of these maps is 4 m^2. Risk index is calculated for each Dissemination Area with areas of high risk represented by darker shades of colour. Risk levels are indicated in the legend of each map. The Risk Index has been normalized for ease of comparison across the infrastructure category. More detail is presented in risk tables associated to each scenario with highest level of risk indicated by a 1 and zero risk represented by a 0. It is intended that these risk maps be used in conjunction with risk tables provided to aid in urban planning, emergency management and decision making.

Each scenario has at least a single DA for which the risk index value is one. Generally, as flooding intensity increases, damages also increase, but the risk index does not always do the same. As risk is a product of probability of the hazard event and potential damages it causes, there are occurrences where high probability of a flood event has a greater influence on risk index than the increase in damages. Thus, it is possible for an event of lower intensity to achieve higher risk indices as observed in this project.

Infrastructure for which risk indices are calculated include: bridges, arterial roads, pollution control plants (PCP), critical facilities, dykes, and buildings (non-critical facilities). Pipe network and outlets are overlaid with city risk maps but are not represented by a risk index as indicated by the tables.
Five analyses were conducted in the study to gain insight into the risk to infrastructure due to the climate change-caused flooding:

Case 1: Contribution of climate change;
Change in risk index between 250 UTRCA scenario and 250 CC_UB scenario
Case 2: Comparison of 100 year climate change events;
Change in risk index between 100 CC_LB scenario and 100 CC_UB scenario
Case 3: Comparison of 250 year climate change events;
Change in risk index between 250 CC_LB scenario and 250 CC_UB scenario
Case 4: Comparison between lower bound scenarios;
Change in risk index between 100 CC_LB scenario and 250 CC_LB scenario
Case 5: Comparison between upper bound scenarios;
Change in risk index between 100 CC_UB scenario and 250 CC_UB scenario.

The development of risk assessment methodology, presented in this report, required some assumptions implemented at different stages of the risk assessment process. They are of high importance for the interpretation of the study results.

Discussion of Results
The main findings of the study are as follows:
- Pollution control plants (PCPs) are high risk infrastructure
- Critical areas of the high risk include: area behind Broughdale dyke along the North Thames; area behind West London Dyke near the downtown Forks; Pottersburg Creek southwest of Trafalgar Street and Clarke Road; and DA 35390706 (Cell C3) that contains Greenway PCP.

- The most critical climate change scenario is the 100 year Climate Change Upper Bound (CC_UB) scenario and it is recommended for use in climate change adaptation policy development and decision making

This study is limited to the assessment of climate change-caused flood risk to infrastructure. However, it is important to consider social implications of climate change-caused flooding and make infrastructure-related decisions in the context of local residents. Regions identified in this study to be of high risk should be subject of a more detailed municipal assessment study that will include (a) more reliable data and (b) integrate infrastructure risk with economic, social and environmental implications of flooding.

Preliminary Recommendations

The results of the study provide insight in the climate change-caused flood risk to municipal infrastructure. Various recommendations are provided to assist the City of London in developing a viable climate change adaptation policy. Recommendations are classified into three major themes: (i) engineering; (ii) operational; (iii) policy and regulatory. Although they have been classified, there are recommendations that may cross these themes.

Engineering

Recommendation E1 - The region behind the Broughdale dyke is at high risk. Possible alternatives to mitigate this risk include: raising the height of the dyke; extending the dyke east to prevent encroaching floodwaters; floodproofing structures behind the dyke; temporary sandbagging efforts to increase the height of the dyke in the case of a flood event; regular maintenance and inspection. It is recommended that the area behind the dyke that may be affected be prepared for the possibility of dyke failure. This should be included in emergency plan and preparedness for this area.

Recommendation E2 - The area behind the West London dyke is at high risk. The recent repair of the dyke will contribute to its safety but will not prevent the protection from climate change-caused flooding. It is recommended that the repair of remaining sections of the dyke be completed together with: floodproofing structures behind the dyke; development of the detailed emergency management plan for temporary sandbagging efforts to increase the height of the dyke in the case of a flood event; and regular maintenance and inspection. It is recommended that the detailed emergency management planning is in place for the area behind the dyke that may be affected by the possible dyke failure.

Recommendation E3 - The CN rail embankment in Pottersburg Creek (southwest of Trafalgar St. and Clarke Rd.) backs up floodwaters and behaves like a dam. This phenomenon does not occur to such an extent in the 250 UTRCA scenario and this contributes to the great difference in risk to areas upstream of the culvert. Infrastructure not inundated in the 250 UTRCA scenario becomes inundated in the 250-yr climate change scenarios, creating the large difference in risk for DAs upstream. This is an area of high concern and a more detailed hydrologic and hydraulic study is suggested for this location. Culvert modifications and alternatives may need to be considered to mitigate the high risk of flooding. It is recommended that this region considers the use of 100 CC_UB scenario for floodplain management, decision making and regulations to capture the high risk nature of this area.

Recommendation E4 - The City would benefit from improved data collection, data documentation and data dissemination procedures. All infrastructure data should be kept in a database with consistent format and documentation procedures.

Recommendation E5 - Increasing the number of flow monitoring stations across the City may provide better input into risk assessment and provide real-time data related to flood hazard. This has potential to allow sufficient time to disseminate flood warnings and prepare for disaster management.

Recommendation E6 - Due to the variability and inconsistency in bank slopes and over-water infrastructure, it is recommended that the City resurveys the bridges and bank slopes within the City boundaries; the City should consider updating their topographic information. This would improve hydraulic calculations, floodplain accuracy and provide a more representative risk assessment.

Recommendation E7 - It is recommended that the City continue to expand the infrastructure considered in the risk analysis. Infrastructure selection for this study is driven by data availability and quality. As more detailed data becomes available the City is recommended to continue efforts to extend the risk analysis to include other infrastructure types such as public utilities, sanitary sewer networks and storm sewer networks.

Recommendation E8 - The flood scenarios considered in this risk assessment are all static events, that is, they are a snapshot of the flood at a moment in time. The City would benefit from a dynamic simulation model and risk assessment procedure to help capture the dynamic nature of flood events. Overland flow modeling would change the nature of the flood and provide additional flood impacts. There may be regions outside of the floodplain that flood as well which would require extensive overland flow analysis. This could contribute to a more complete flood model and risk assessment.

Operational

Recommendation O1 - Pollution Control Plants (PCPs) would benefit from a detailed emergency plan with regards to the critical flood scenarios in this study. In the event of a flood Greenway, Adelaide, Vauxhall and Pottersburg PCP may have limited access. There should be preparatory procedures in place to maintain safety (or potentially evacuation) at the plant. Access may also be restricted in the recovery phase of flooding due to unfavorable road conditions and should be considered in recovery plan. To maintain functioning capacity during a flood event it is recommended that all four of the aforementioned PCPs raise or make mobile their essential operational equipment. In the event of a flood these equipment will experience less damage and be able to maintain partial functionality. Any of these PCPs in the recovery stages of a flood may not be able to run at full capacity. It would be beneficial to have a flood recovery plan outlining procedures to manage and maintain the plant during this stage.

Recommendation O2 - Bridges with piers are greatly affected by scour during flood situations; it is the single most important parameter for bridge failure during high water events. Thus, it is recommended that bridges with piers be closely monitored on a regular basis for signs of scour and pier degradation; with particular emphasis on monitoring before and after a flood event of both 100 and 250 year magnitude.

Recommendation O3 - The City is advised to maintain detailed historical records of damages during high water events for all critical facilities and city-owned infrastructure. Damages to building structure, foundation, equipment, contents and lost profits can be used to improve flood damage estimates and modify flood risk assessment.

Recommendation O4 - Four schools are affected in the flood scenarios; Prince Charles Public School, Princess Anne French Immersion Public School, St. Pius X Separate School and Jeanne Sauve French Immersion Public School. These schools should have very detailed protocol and procedure in case of a flood event. These schools would benefit from a program and training in emergency response for all staff and students. It is important that there is organization and preparedness in the response to natural hazards to avoid confusion and chaos.

Recommendation O5 - Monitoring and regular inspection of the Broughdale and the West London dykes will have to be strengthen due to the fact that they will be overtopped by the climate change-caused floods.

Policy

Recommendation P1 - The City is recommended to fund additional studies related to the response of bridges and pollution control plants at high risk to better understand their response to flooding and potential risk-reducing measures.

Recommendation P2 - Infrastructure may also be affected by other climate change factors including temperature extremes and shifts in freeze/thaw cycles, among others. The City is recommended to investigate these other climate change factors that may affect the region and further impact municipal infrastructure.

Recommendation P3 - This study did not directly consider sanitary and storm network infrastructure in risk assessment but it is recommended that those areas considered at high risk which also contain a dense network of sanitary and storm infrastructure should be investigated. The additional pipe infrastructure may result in even higher risk to these areas and these pipe networks should be regularly inspected.

Recommendation P4 - It is advised that the City considers both the risk to municipal infrastructure and social vulnerability when addressing climate change adaptation and planning strategies. Although the purpose of this study is to assess the effects of flooding on municipal infrastructure, it is important to mention that physical structures are not the only element at risk during a flood event. Natural disasters have very significant social impacts as well. It is the combination of both infrastructure and social risk that could change the magnitude and spatial distribution of risk. When intersected with high infrastructure risk regions, these are areas of particular concern and both infrastructure and social risks require attention. One of these cases includes the Coves. Although this region was classified at risk, the region does not appear to experience one of the highest risks. However, the region is dominated by trailer homes, most of which require complete reconstruction after any of the flood scenarios considered in this study. These trailer homes may not be worth as much as residential structures in other flooded areas, therefore the region will show lower risk. However the people living in the Coves may be especially vulnerable. The entire community may be inundated and recovery can be especially difficult for those with limited access to resources. This is why it is important to consider social risk in combination with infrastructure risk before making any critical decisions based on this study's analysis.

Recommendation P5 - This study indicates that there is a need to consider future regulations and possible change of the regulatory floodplain to include impacts of climate change. An economic analysis is recommended to assess the consequences of changing regulations and perform the cost-benefit analysis using the results of this study – to find out the cost of risk reduction.

Recommendation P6 - The final recommendation is to initiate the process of change of the infrastructure design criteria to include climate change impacts. Risk increase identified in this study points out that the future infrastructure will have to be designed to withstand the potential impacts of climate change. This recommendation should complement the recommendation P3.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i

1.0 INTRODUCTION 1
1.1 Background 1
1.2 Objective 1
1.3 Methodology 1
1.4 Reporting 2
1.5 Acknowledgements 2

2.0 INTRODUCTION OF RISK ASSESSMENT METHODOLOGY TO CLIMATE CHANGE 3
2.1 Climate Change Scenarios 3
2.2 Weather Generator 5
2.3 Hydrologic Modeling 5
2.4 Hydraulic Modeling 5

3.0 INFRASTRUCTURE AT RISK 6
3.1 Floodlines 6
3.2 Infrastructure 12
3.2.1 Transportation 12
3.2.2 Bridges and Culverts 14
3.2.3 Critical Facilities 14
3.2.4 Storm Water 15
3.2.5 Water Distribution Network 15
3.2.6 Flood Control Structures 15
3.2.7 Buildings 16

4.0 RISK ASSESSMENT METHODOLOGY 17
4.1 Risk Index 17
4.2 Example Calculation of Risk Index 23
4.3 Application of Risk Assessment Methodology to the Study Area 24

5.0 RESULTS 27
5.1 Assumptions 27
5.2 Results 27
5.3 Discussion of Results 28

6.0 PRELIMINARY RECOMMENDATIONS 52

7.0 REFERENCES 54

8.0 LIST OF PREVIOUS REPORTS IN THE SERIES 55

APPENDIX A: STUDY REPORTS A1-A5

APPENDIX B: COMPREHENSIVE LIST OF INFRASTRUCTURE B1

APPENDIX C: DISSEMINATION AREAS GRID MAPS C1-C37

APPENDIX D:RISK MAPS AND TABLES D1-D43

APPENDIX E: STAGE DAMAGE CURVES E1-E6

APPENDIX F:FUZZY MEMBERSHIP FUNCTION CURVES F1-F7

APPENDIX G:INDIRECT DAMAGES G1

APPENDIX H:LIST OF CONSUMER PRICE INDICES H1

APPENDIX I: DETAILED LIST OF DATA COLLECTED I1-I12

APPENDIX J:GIS COMPUTATIONAL FILES AND SPREADSHEETS (CD) J1

LIST OF FIGURES

Figure 1: Infrastructure Risk Assessment to Climate Change Project Procedure 3
Figure 2: Upper Thames Watershed 6
Figure 3: Extent of 100 CC_LB floodplain 7
Figure 4: Extent of 100 CC_UB floodplain 8
Figure 5: Extent of 250 CC_LB floodplain 9
Figure 6: Extent of 250 CC_UB floodplain 10
Figure 7: Extent of 250 UTRCA floodplain 11
Figure 8: Infrastructure Included in Risk Assessment (not including buildings) 13
Figure 9: Dissemination Areas for London Ontario with reference grid 18
Figure 10: Membership Functions of System-State and Acceptable Level of Performance 21
Figure 11: River sub-watersheds used for data processing (from Background Report 1) 25
Figure 12: Percent change in risk between 250 UTRCA and 250 CC_UB scenarios 31
Figure 13: Inundation of Adelaide PCP under 250 UTRCA and 250 CC_UB scenarios 32
Figure 14: Inundation of Greenway PCP under 250 UTRCA and 250 CC_UB scenarios 32
Figure 15: Damming of water behind culvert on Pottersburg Creek; 250 UTRCA and 250 CC_UB scenarios 33
Figure 16: Inundation of building structures and roads along Pottersburg Creek; 250 UTRCA and 250 CC_UB scenarios 33
Figure 17: Inundation of building structures along Pottersburg Creek; 250 UTRCA and 250 CC_UB scenarios 34
Figure 18: Inundation of critical transportation routes; 250 UTRCA and 250 CC_UB scenarios 34
Figure 19: Percent change between 100 year climate change events 37
Figure 20: Stormwater Pipe Network under the 100 CC_UB scenario 38
Figure 21: Percent change in risk between 250 CC_LB and 250 CC_UB scenarios 42
Figure 22: Vauxhall PCP inundation; 250 CC_LB and 250 CC_UB scenarios 43
Figure 23: Inundation of Greenway PCP under 250 CC_LB and 250 CC_UB scenarios 43
Figure 24: Inundation of schools; 250 CC_LB and 250 CC_UB scenarios 44
Figure 25: Change in risk between 100 CC_LB and 250 CC_LB scenarios 46
Figure 26: Inundation at Pottersburg Creek; 100 CC_LB and 250 CC_LB scenarios 47
Figure 27: Inundation behind the West London Dyke - 100 CC_LB and 250 CC_LB scenarios 47
Figure 28: Change in risk index value between 100 CC_UB and 250 CC_UB scenarios 50

LIST OF TABLES

Table 1: Table of Workshop participants (adapted from Sandink and Simonovic, 2009) 2
Table 2: Flood Scenarios used in Risk Assessment 6
Table 3: Infrastructure Summary 12
Table 4: Change in risk -Case 1 29
Table 5: Change in risk - Case 2 35
Table 6: Change in risk - Case 3 39
Table 7: Change in risk - Case 4 44
Table 8: Change in risk - Case 5 48

1.0 Introduction

1.1 Background

Municipal infrastructure is essential to the functioning of modern-day society. Residents depend on a city's infrastructure for health, psychological and social wellbeing in their daily lives. Some of these dependencies include: shelter from the elements; water plants and pipe networks to deliver clean water and take waste away; roads and bridges for transportation routes to and from places of work; electricity for appliances; and barriers to protect flood-prone areas.

The Earth's climate is changing and these changes are documented to have a serious impact on municipal infrastructure. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) established by Engineers Canada conducted in 2008 an assessment of the vulnerability of Canadian Public Infrastructure to changing climatic conditions. The major conclusion of the assessment was that failures of public infrastructure due to climate change will become common across Canada. Consequently, public infrastructure vulnerability should be identified as one of four priority areas to be reviewed as part of the first National Engineering Assessment. In addition, the previous studies in the Upper Thames River basin reported that the flood risk will increase as a result of climate change (Cunderlik and Simonovic, 2007; Prodanovic and Simonovic, 2009; Simonovic 2010).

Current infrastructure is designed and constructed based on standards and codes developed decades ago. These standards and codes include historic climate and design storms which are no longer representative of the current climate. With the changes in climate patterns, infrastructure may no longer have the capacity to handle new climate loads. Thus, a region must adapt its policies and procedures to consider climate change and mitigate risks to municipal infrastructure. Climate modeling suggests that the City of London can expect to experience more frequent severe precipitation events in the future as a consequence of climate change. Flooding is therefore a natural hazard event of significance to this region and as such the City commissioned this study to assess the vulnerability of London's public infrastructure to changing climate conditions.

Background studies include "Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions" conducted at the University of Western Ontario between 2003 and 2007 for the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). The CFCAS study conducted an extensive climate change impact assessment for the Upper Thames River Basin and the results identified flooding as the most significant climate change impact for the basin.

1.2 Objective

The main objective of the study is to provide an engineering assessment of the vulnerability of London's public infrastructure to climate change-caused flooding conditions.

1.3 Methodology

This study develops and implements a risk assessment methodology that has been motivated by the PIEVC Protocol. The main objective of the Protocol is a qualitative assessment of the impacts of climate change on individual infrastructure components. PIEVC takes a very specific, data intensive approach to risk assessment.

The key steps of the procedure are:

1. Inventory of infrastructure components;
2. Data gathering and sufficiency;
3. Qualitative vulnerability assessment;
4. Quantitative vulnerability assessment; and
5. Prioritization of the infrastructure components based on the level of risk.

Floodplains and flood risk maps are useful in determining where to begin new housing developments, locate a business, and maintain critical infrastructure. Knowledge of flood risk helps decision makers in providing building permits, planning future developments, allocating financial resources for infrastructure rehabilitation and maintenance, development of infrastructure construction and operation guidelines, coordination of effective emergency response strategies, and general policy development and decision making.

The risk assessment results in a step-by-step process for the quantification and analysis of risk to infrastructure elements. The infrastructure elements are then prioritized based on their risk to facilitate in policy planning and decisions.

Risk is defined in this study as the intersection of a hazard (flooding) with vulnerability. The risk measure enables conclusions and recommendations to be made regarding the reliability of the infrastructure network within the city to adapt to the changing climate conditions.

The study results show the spatial distribution of risk across the City as a combination of all infrastructure elements, as well as the risk disseminated into infrastructure categories. The maps and tables with the study results are discussed and expanded upon within the conclusions in this report. The study results are meant to identify and prioritize areas of high risk or interest within the city which are recommended for further investigation. These recommendations are meant to aid in policy development as it relates to municipal infrastructure and the future.

The risk used in the study concerns only infrastructure elements. No social data has been aggregated with the structures. Therefore the recommendations are based on risk solely due to the interaction of each structure with the flood event.

1.4 Reporting

Five interim reports were presented to the City:

1. Status Report 1 – Project Definition Report
2. Status Report 2 – Prioritization of Infrastructure Climate Relationships
3. Status Report 3 – Stakeholder Workshop 1
4. Background Report 1 – Climate and Hydrologic Modelling
5. Background Report 2 – Hydraulic Modelling and Floodplain Mapping

The Table of Contents of these reports is reproduced in Appendix A.

In addition, the first workshop was conducted on September 17, 2009. The objective of the workshop was to confirm the scope of the study, inform stakeholders of the details of the project and develop a list of critical infrastructure elements to be considered for analysis. The list of attendants to the workshop follows:

Table 1: Table of Workshop participants (adapted from Sandink and Simonovic, 2009)

Name (Last, First)	**Position/Organization**
Abernethy, Scott	Ontario Ministry of the Environment
Alperin, Luis	Delcan
Baechler, Joni	Councillor, City of London
Bergsma, Bonnie	Parks Planning and Design, City of London
Branscombe, Nancy	Councillor, City of London
Brick, Jeff	Upper Thames River Conservation Authority
Bryant, Judy	Councillor, City of London
Burgess, Lois	Division Manager, Engineering Review, City of London
Copeland, Tom	Division Manager, Wastewater and Drainage Engineering, City of London
Donnelly, Patrick	Urban Watershed Program Manager, City of London
Haklander, Billy	Stormwater Management Unit, City of London
Krichker, Berta	Stormwater Management Unit, City of London
Listar, Ivan	Transportation and Roadside Operations, City of London
Lucas, John	Division Manager, Transportation Engineering, City of London
McNally, Pat	General Manager of Environmental and Engineering Services and City Engineer, City of London
Milanovic, Shawna	Stormwater Management Unit, City of London
Skimming, Jamie	Environmental Programs and Solid Waste, City of London
Snowsell, Mark	Upper Thames River Conservation Authority
Standish, Ron	Director, Wastewater and Environment, City of London
Wills, Jason	Risk Management, City of London

A second workshop is scheduled for the second week of December 2010 with the aim of presenting the results of the study and discussing the preliminary recommendations. This report is a draft version of the final report that will be presented to the City after the second workshop is completed.

A final report will be prepared taking into account City's comments and the feedback received at the second workshop. It is estimated that the final report will be available by early February 2011.

1.5 Acknowledgements

The project team would like to thank the following persons and organizations for their support in making this project possible:

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Environment Canada, Statistics Canada, MPAC, City of Toronto and the Upper Thames River Conservation Authority (UTRCA) for their assistance and providing pertinent data.

Professors from the department of Civil and Environmental Engineering at the University of Western Ontario consulted for their expertise during the duration of the study.

2.0 Introduction of Risk Assessment Methodology to Climate Change

The focus of this section of the report is on the engineering input for flood risk assessment. A very detailed presentation of the input methodology is available in the two background reports provided to the City.

The integrated risk assessment procedure developed for this project includes:

1. selection of climate models and scenarios,
2. climate modeling using Weather Generator to simulate meteorological data,
3. hydrologic modeling using Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) to transform meteorological data into runoff and generate streamflows,
4. hydraulic modeling using Hydrologic Engineering Center – River Analysis System (HEC-RAS) to map floodplains for each climate scenario,
5. data collection on local infrastructure,
6. infrastructure risk assessment to climate change to produce flood risk tables and maps, and
7. identification of recommendations for climate change adaptation.

Figure 1 provides a visual representation of the study's procedure. There is a vertical interconnectivity between all the steps in methodology. Output from each step is used as input into the next step.

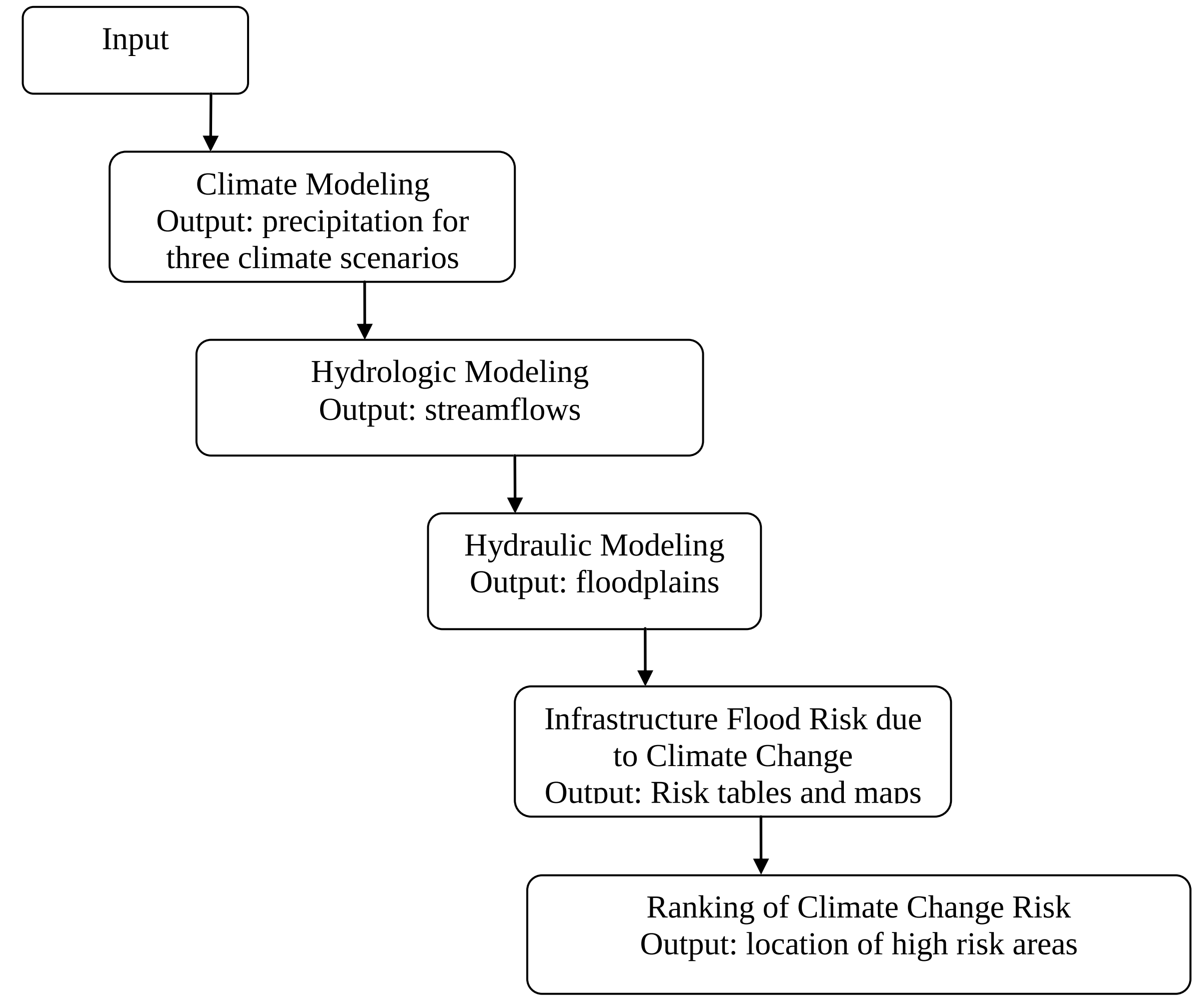

Figure 1: Infrastructure Risk Assessment to Climate Change Project Procedure

2.1 Climate Change Scenarios

Currently, one of the best ways to study the effects of climate change is to use Global Circulation Models (GCM). These models are the current state of the art in climate science. Their aim is to describe the functioning of the climate system through the use of physics, fluid mechanics, chemistry, as well as other sciences. All GCM discretise the planet and its atmosphere into a large number of three dimensional cells to which relevant equations are applied.

Two different types of equations are used in GCM - those describing fundamental governing physical laws, and those that are termed empirical (based on observed phenomena that are only partially understood). The former are representations of fundamental equations of motion, laws of thermodynamics, conservation of mass and energy, etc, and are well known; the latter, however, are those phenomena that are observed, but for which sound theory does not exist yet. For most studies that are concerned with the response of a smaller area (such as a city) to a changed climatic signal, the GCM are inappropriate because they have spatial and temporal scales that are incompatible with those of a city. One way around this is to still use the global input, but downscale its results appropriately for the area under consideration.

A traditional way of studying the impacts of climatic change for small areas involves downscaling the outputs from GCM (temporally and spatially) from which user and location specific impacts are derived. A number of studies have implemented such methodologies, and thus estimated local impacts of climatic change (Coulibaly and Dibike, 2004; Palmer et al., 2004; Southam et al., 1999).

The use of GCM results with downscaling methods involves a number of uncertainties inherent to this approach. First, the GCM have temporal scales that are sometimes incompatible with temporal scales of interest at the local level. The GCM are only able to produce monthly outputs with a higher degree of accuracy. This is insufficient for the use at local level where often the interest is in changes in frequency of occurrence of short-duration high-intensity events. Temporal downscaling of monthly global output must therefore be employed, and shorter duration events be estimated, thus compounding uncertainty. Second, spatial scales of GCM are also incompatible with spatial scales at the local level. The GCM typically have grid cells of 100 km by 100 km, significantly larger than most watersheds (for example, City of London, Ontario covers an area of about 420 km^2). Coarse resolution of GCM is inadequate for the representation of many physical processes of interest at the local scales (including extreme rainfall).

In this study the weather generator approach was used for downscaling the global information to local scale. This approach takes as input historical climate information, as well as information from the GCM, and generates climatic information for an arbitrary long period of time for the local weather station. The main GCM output used as input into the weather generator includes the change fields to modify historic data in accordance to a particular climate change scenario.

Climate change scenarios are the output of GCM. They do not predict the future but simply offer possibilities of what may happen in the future following a particular course of action (i.e., rapid urbanization). Currently, one of the best ways to study the effects of climate change is to use GCM. These models are the current state of the art in climate science. Their aim is to describe the functioning of the climate system through the use of physics, fluid mechanics, chemistry, as well as other sciences. All GCM discretise the planet and its atmosphere into a large number of three dimensional cells (Kolbert, 2006, p. 100) to which relevant equations are applied.

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Two climate scenarios, named the *climate change lower bound scenario* (CC_LB) and the *climate change upper bound scenario* (CC_UB), were derived from the historical data and inputs from the global climate models (GCMs). The choice of the GCMs was made on the basis that the first scenario represents the lower boundary of potential climate change impacts and the second represents the upper boundary of potential climate change. The selection of two GCMs was made from a wide range of available models and their runs. Careful analyses of the GCM outputs lead to the selection of two models that will capture the potential range of climate change impacts on the watershed. Selection of the range of potential climate change through the use of two scenarios compensate for the existing level of uncertainty present in global modeling of climate change at the watershed scale. It is noted in the literature that the GCM offer various predictions of future climate as a consequence of (i) the selected global model, (ii) the selected global model simulation scenario, and (iii) the spatial and temporal resolution of the selected global model.

Lower and upper bound climate scenarios produced by a weather generator use the information provided by the outputs of two GCM, as well as the locally observed data. The generated climate scenarios therefore use all available climatic data (local and global) to provide a range of future climatic conditions. It is important to point out that both climate scenarios are equally likely as well as the range of climatic conditions between the two. Integration of the local and global data is achieved by the modification of observed data using the output of a selected GCM and then processing the modified data by the proposed weather generator.

The two climate scenarios developed for use in this study are based on locally observed data for the period 1964-2006. The climate scenarios, CC_LB and CC_UB, were derived by integrating historical data with the information provided by outputs of CSIROM2kb and CCSRNIES global climate models for the grid cell containing the Upper Thames River basin. The CC_UB climate scenario provides conditions where emphasis is placed on increased temperature and rainfall magnitude over the next century, while the CC_LB climate scenario emphasizes cooler and drier periods.

2.2 Weather Generator

Weather generators are being used as downscaling tools in climate change studies to simulate plausible climate scenarios based on the regional observed data and GCM outputs. Weather generators based on the K-NN algorithm are standard, explicit and simple procedures (Eum and Simonovic, 2009). The K-NN algorithm typically starts with randomly selecting the current day from observed data set and a specified number of days similar in characteristics to the current day. Using resampling procedure, one among the days from the data set with similar statistical characteristics with current day is selected to represent the weather for the next day. The nearest neighbor algorithm (a) uses a simple procedure, and (b) preserves well both, temporal and spatial correlation in multi-region data. This study used the K-NN algorithm developed by Yates et al. (2003) and modified first by Sharif and Burn (2006) and then by Eum and Simonovic (2009). The application of K-NN algorithm is successfully conducted with three variables (precipitation, maximum temperature, and minimum temperature).

2.3 Hydrologic Modeling

In this study, the US Army Corps of Engineers (USACE) Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS**)** was used to transform two climate scenarios of meteorological conditions into corresponding runoff. HEC-HMS is a precipitation-runoff model that includes a large set of mix-and-match methods to simulate river basin, channel and water control structures. It is designed for application to a wide range of geographic areas for solving variety of hydrologic problems (USACE, 2000**).** The model has been applied successfully in numerous studies.

An *event-version of the HMS model* can be used for simulating short rainfall-runoff events and is used in this study for the analysis of high flow events that can cause flooding in the basin. The structure of the event HMS model comprises six components describing main hydro-climatic processes in the river basin.

The modified meteorological records produced by the Weather Generator were used as input into the HEC-HMS to simulate the direct runoff due to precipitation events and translate the runoff into the streamflow. The original model for the Upper Thames River basin that was developed with 34 sub-basins for the purpose of the CFCAS study (Cunderlik and Simonovic, 2007; Prodanovic and Simonovic, 2009; Simonovic 2010) was the starting point. However, the spatial resolution of the original model was insufficient for the detailed climate change risk assessment within the City of London. Hydrologic modeling was the emphasis of the current study and therefore, the previously developed model was expanded by the addition of a large number of sub-basins within the City of London. At the end, the City of London was discretized into 72 sub-basins, 45 reaches, 49 junctions, and 3 reservoirs. The HEC-HMS model outputs streamflow data that is used directly as input for hydraulic modeling.

2.4 Hydraulic Modeling

Stream flow generated by the hydrologic model was used in conjunction with the Digital Terrain Models (DTMs) and channel characteristics as input into the Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic modeling program to generate water surface profiles. The extent and depth of these floods are represented in Geographic Information System (GIS) environment and are the foundation for the quantitative risk assessment.

Both the 100-yr and 250-yr return periods were selected for use in this study as they are the basis for the current regulatory floodplains enforced by the City of London and the Upper Thames River Conservation Authority. This study therefore considers the five scenarios:

1. 100 CC_LB;
2. 100 CC_UB;
3. 250 CC_LB;
4. 250 CC_UB; and
5. 250 UTRCA.

The fifth scenario represents the current floodlines generated by the Upper Thames River Conservation Authority (UTRCA) which are included in the City of London Official Plan. The extent of the floodlines was provided by UTRCA and the data is available for the 250-yr return period only.

3.0 Infrastructure at Risk

The City of London, Ontario is located in Southwestern Ontario, Canada within the Upper Thames River Basin (Figure 2). The City is the 10th largest in Canada, with a population of approximately 352, 000 and an area covering 42, 000 ha. The City is characterized by the Thames River which flows south through the City where the branches meet at a location locally known as The Forks. The river and its major tributaries are shown in Figure 2.

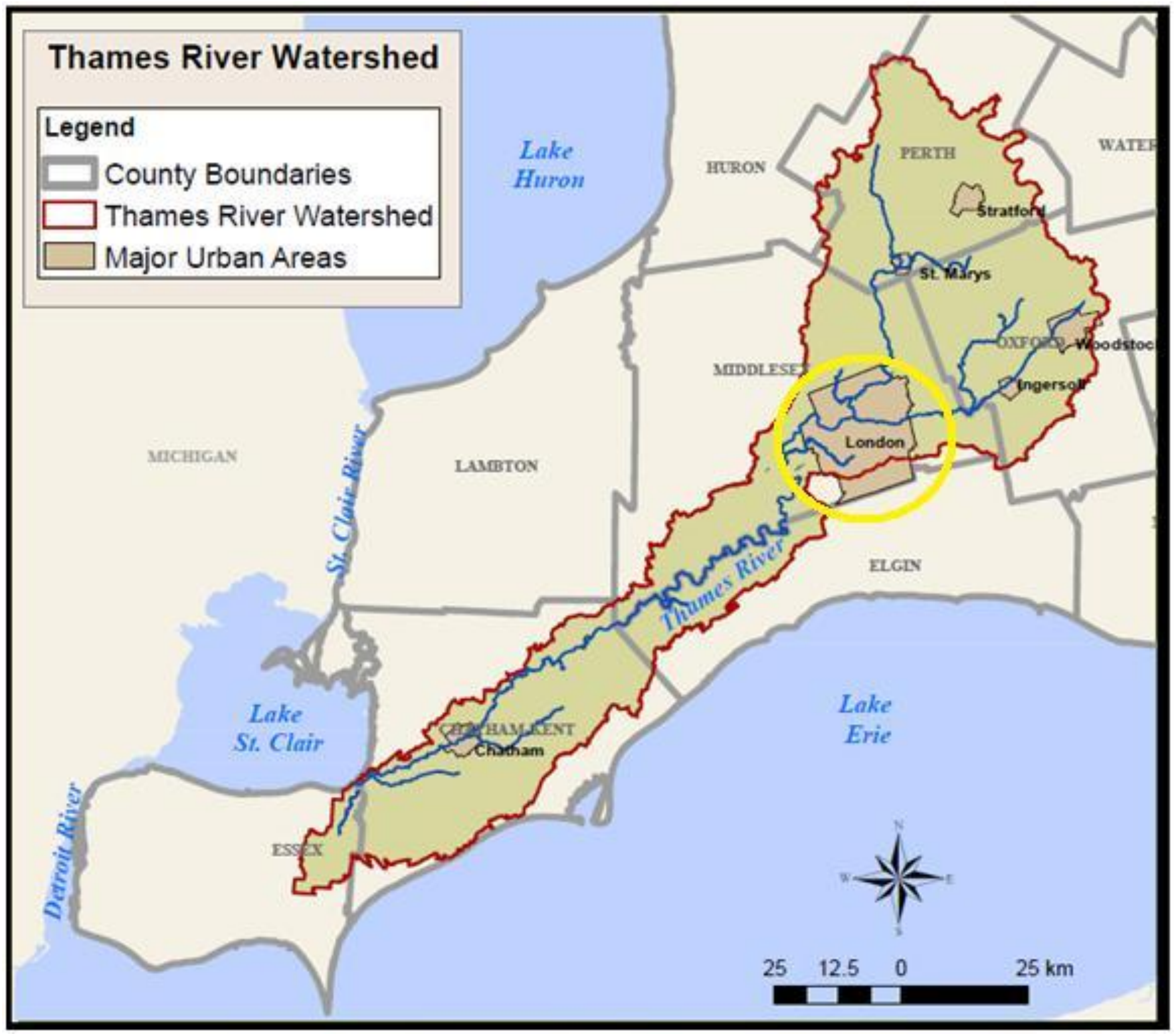

Figure 2: Upper Thames Watershed

3.1 Floodlines

The City has a well documented history of flooding dating back to 1700s with the worst flood event recorded occurring in 1937. This flood was destructive of both life and property; five deaths were recorded and over 1,100 homes experienced significant flood damages (UTRCA, 2010). Fanshawe Dam on the North branch of the Thames is used to control downstream flooding. The City of London has a high density urban core located at the Forks which is largely protected by a series of dykes.

Table 2 shows the five climate scenarios that are run for the risk assessment, and indicates the area that is expected to flood for each event.

Table 2: Flood Scenarios used in Risk Assessment

Scenario	Details
100 CC_LB	• Climate Change Lower Bound Scenario 100 yr return period • 2, 295ha
100 CC_UB	• Climate Change Upper Bound Scenario 100 year return period • 2, 579ha
250 CC_LB	• Climate Change Lower Bound Scenario 250 yr return period • 2, 595ha
250 CC_UB	• Climate Change Upper Bound Scenario 250 yr return period • 2, 787ha
250 UTRCA	• Upper Thames River Conservation Authority 250 yr return period • 2, 456ha

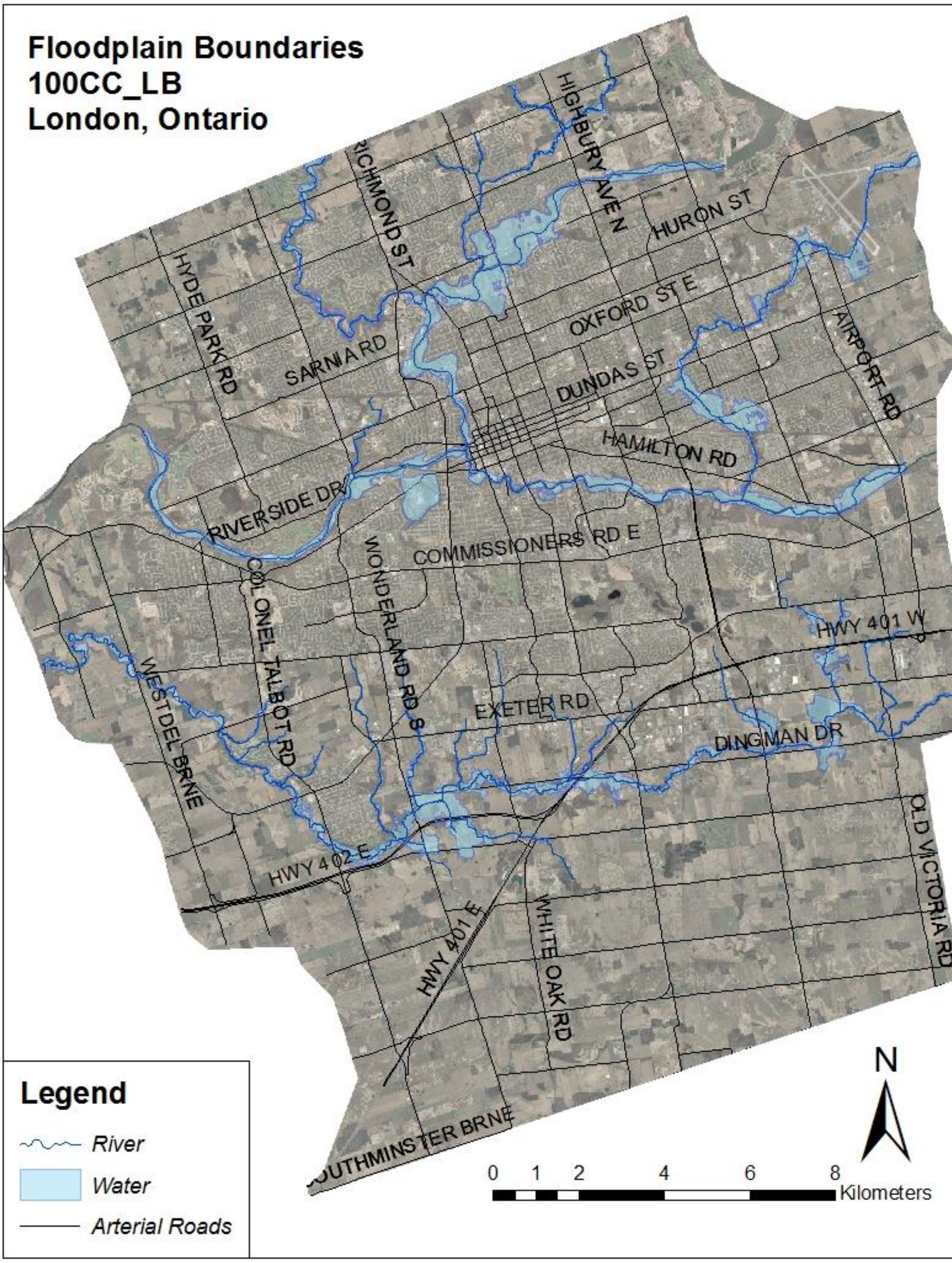

Figure 3: Extent of 100 CC_LB floodplain

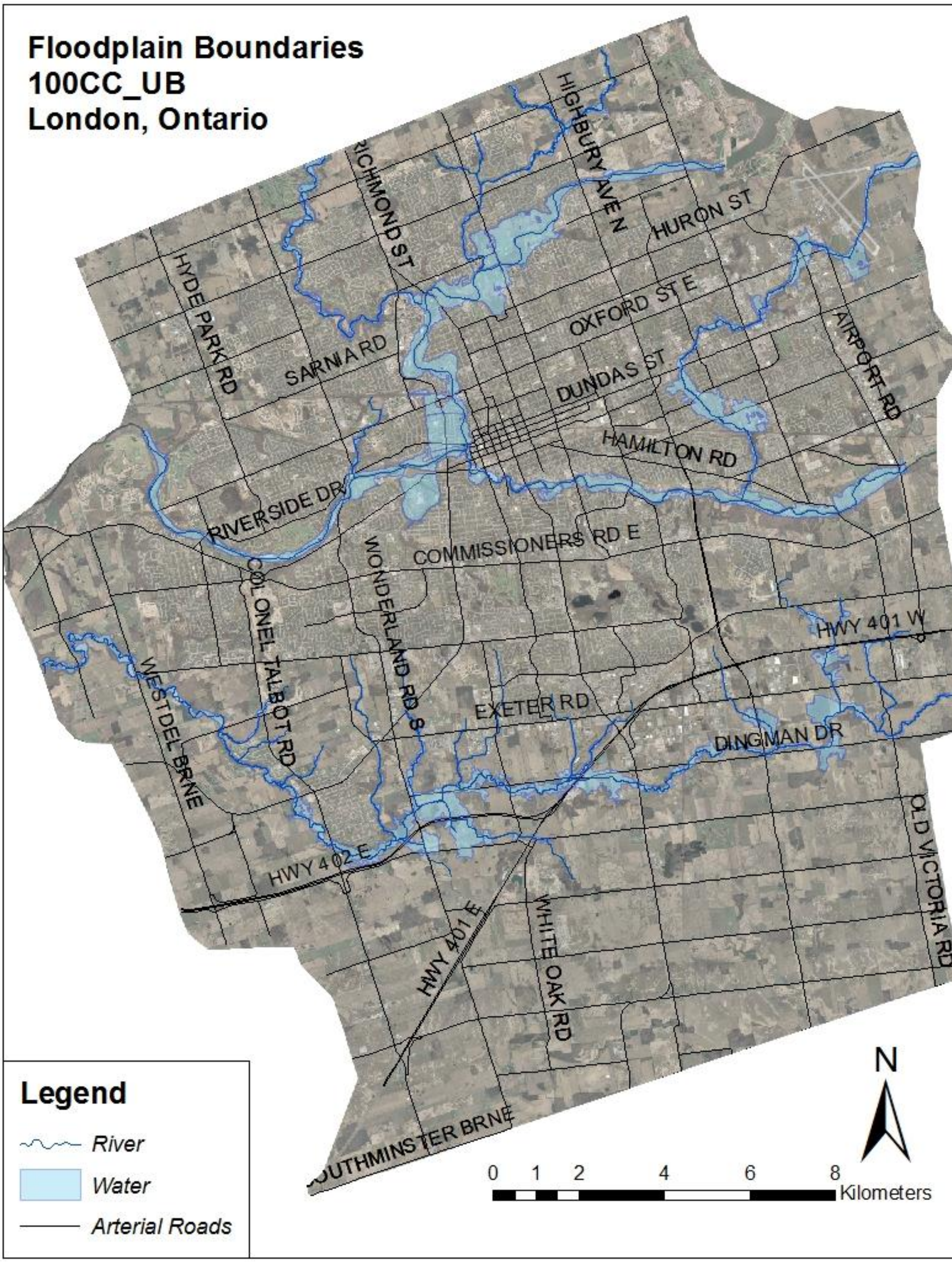

Figure 4: Extent of 100 CC_UB floodplain

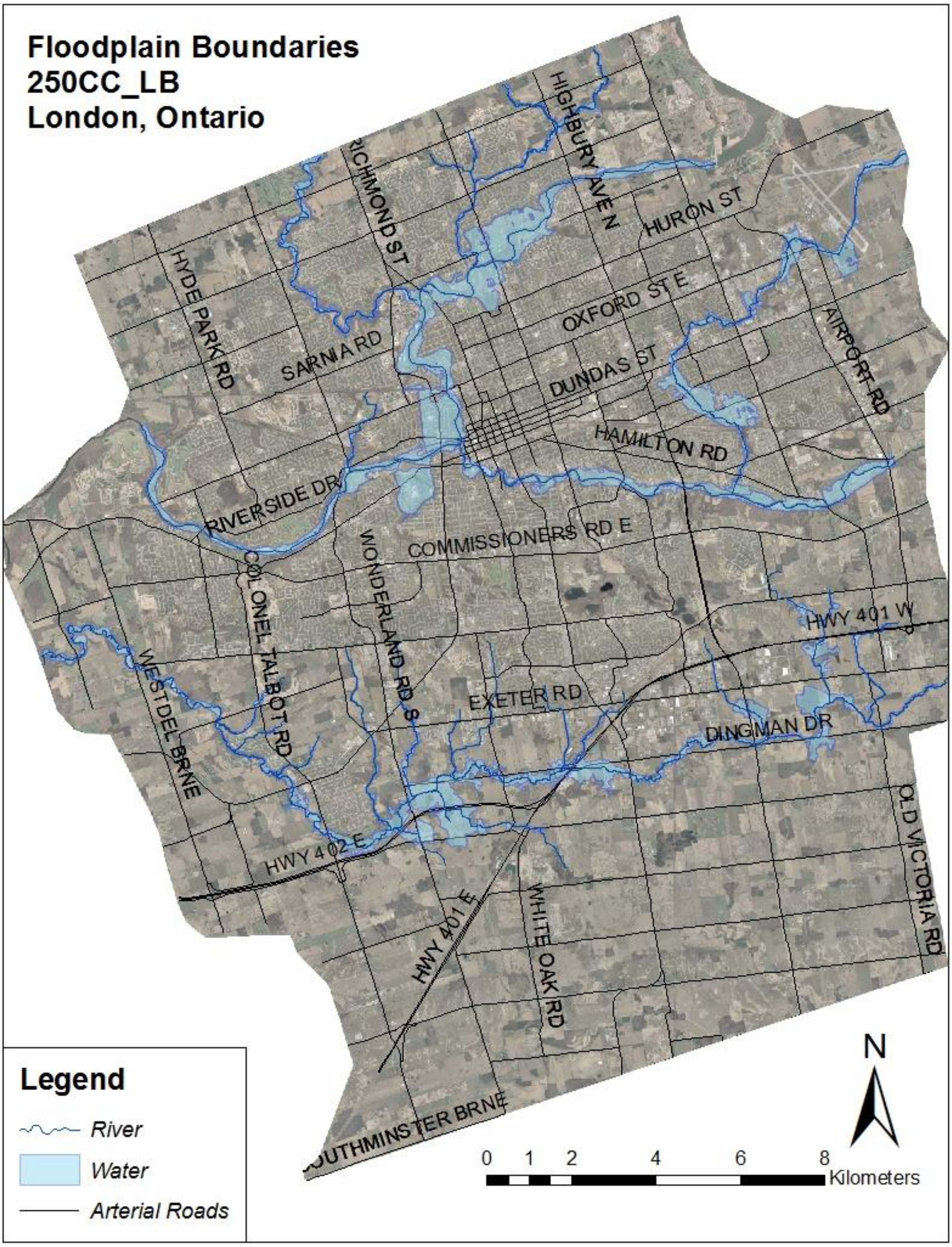

Figure 5: Extent of 250 CC_LB floodplain

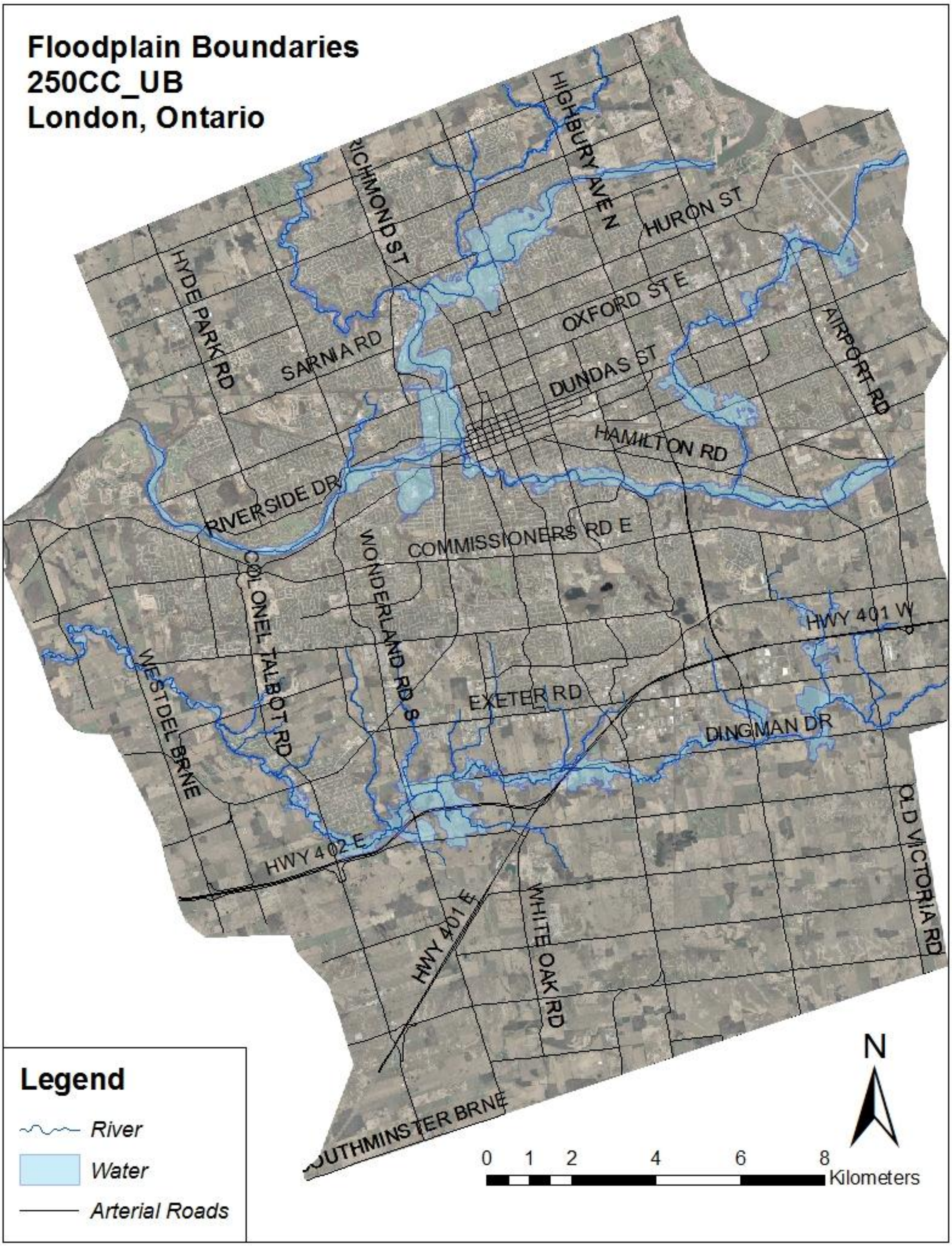

Figure 6: Extent of 250 CC_UB floodplain

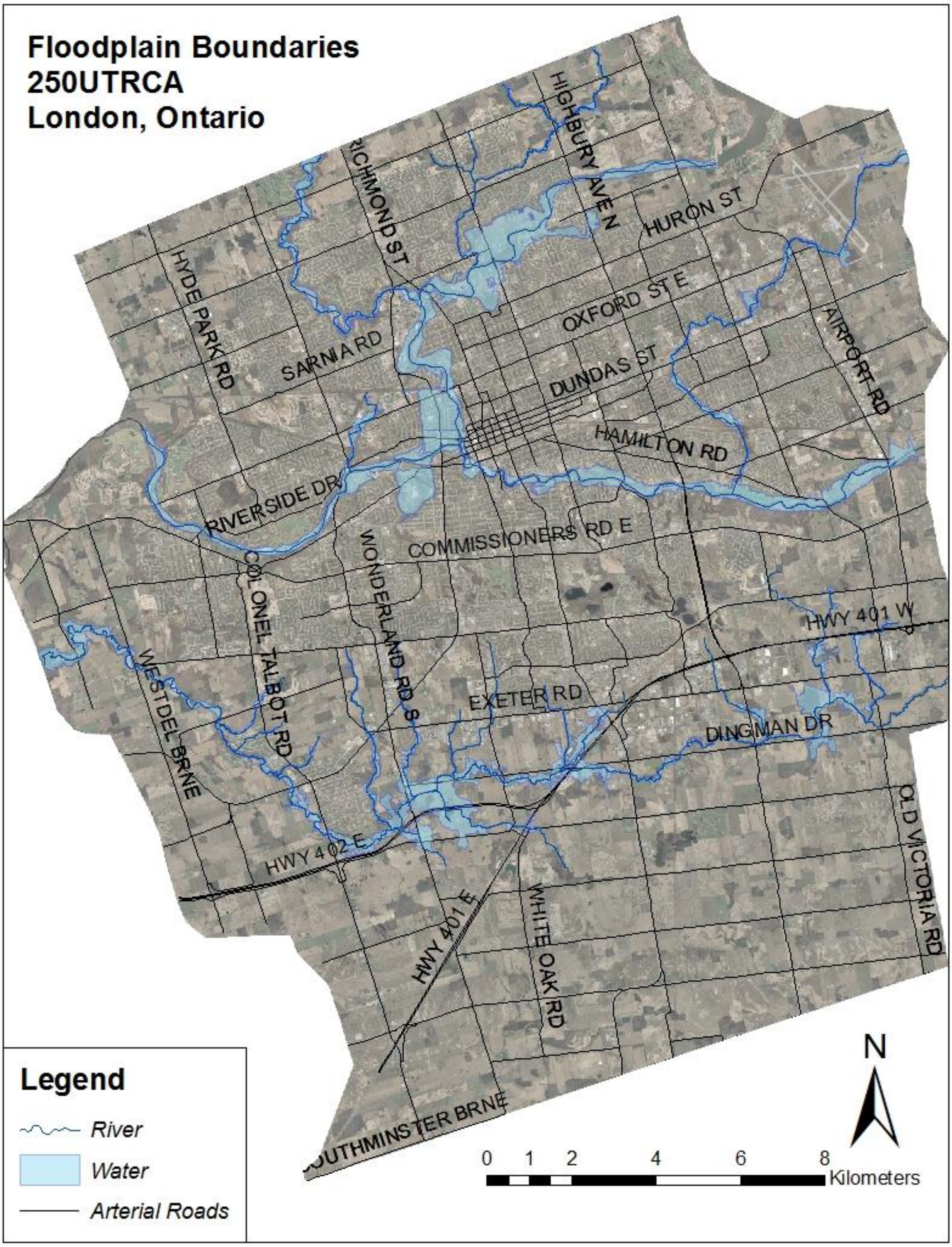

Figure 7: Extent of 250 UTRCA floodplain

3.2 Infrastructure

A summary of the type and quantities of data being considered for the infrastructure within the study is presented in Table 3. A comprehensive list of infrastructure included in the study is listed in Appendix B.

Table 3: Infrastructure Summary

Infrastructure	Quantity
Bridges & Culverts	216
Arterial Roads	520km
Buildings	>3,000*
Sanitary/Storm Pipe Network	> 1,300km
Pollution Control Plants	6
Stormwater Management Facilities	100

*within the floodplain area under consideration

The study considers transportation infrastructure (including bridges, culverts and arterial roads), buildings (residential, commercial and industrial), critical infrastructure (fire stations, Emergency Management Services (EMS), police stations, hospitals, schools and pollution control plants), flood protection structures, sanitary and storm networks and the drinking water distribution network. Each of these infrastructure elements have different failure mechanisms under flood loading. The descriptions of the infrastructure as well as their expected failure mechanisms are provided below. Figure 8 shows the infrastructure in the City that was considered in the risk assessment.

The study team conducted interviews with experts across the infrastructure categories at the City of London to better understand each system and gather input for the risk analysis. The departments and divisions involved in this process included:

- Risk Management Division,
- Wastewater and Drainage Engineering,
- Planning and Development – Building,
- Transportation Planning and Design,
- Water Operations Division,
- Water Engineering Division,
- Pollution Control Operations,
- Environmental Programs and Customer Relations, and
- Corporate Security and Emergency Management Division.

The study team also interviewed experts from the UTRCA and at the University of Western Ontario.

3.2.1 Transportation

Roads are a critical network in the event of any disaster as they allow for evacuation and rescue access for emergency services. The effect of flooding on roads has been well documented in regions such as the Gulf coast of the United States where hurricanes make flooding common. Primary failure mechanisms for an inundated roadway include scour of the embankments and subsoil (washout) and rutting. Other failures include total collapse due to extreme scour and surface wear from debris impact. One of the most common impacts of flooding on a roadway is that it decreases its design life (Mills, 2007). Therefore while the road may not experience catastrophic failure, it will become more susceptible to damages and will likely require repair at an earlier date than planned or budgeted for. The degree to which the road is damaged depends largely on the velocity and turbulence of the floodwater as well as the road surface material. An inundated road also becomes a danger to human safety and must be closed, therefore causing it to experience functional failure. This can hamper emergency access for fire, police and ambulance services.

The City of London's Transportation Master Plan (TMP), completed in the spring of 2004, indicates that the primary mode of transport for citizens is through the use of private vehicles. This demonstrates the importance of keeping the roadways in good condition in order to maintain a high level of productivity in the City.

It was agreed with the City that only arterial/primary roads would be considered in the study. There are over 520km of primary and arterial roadways within the City of London. According to the Transportation Master Plan (TMP 2004) it is recommended that the City spend 16.6 Million dollars per year on existing arterial networks and 17 Million per year on enhancing capacity over the next 20 years. Due to the size of this network and its importance for the City's day-to-day operations, emergency response and budgeted investment, it is crucial that the transportation division be prepared for an increase in the frequency of extreme flood events.

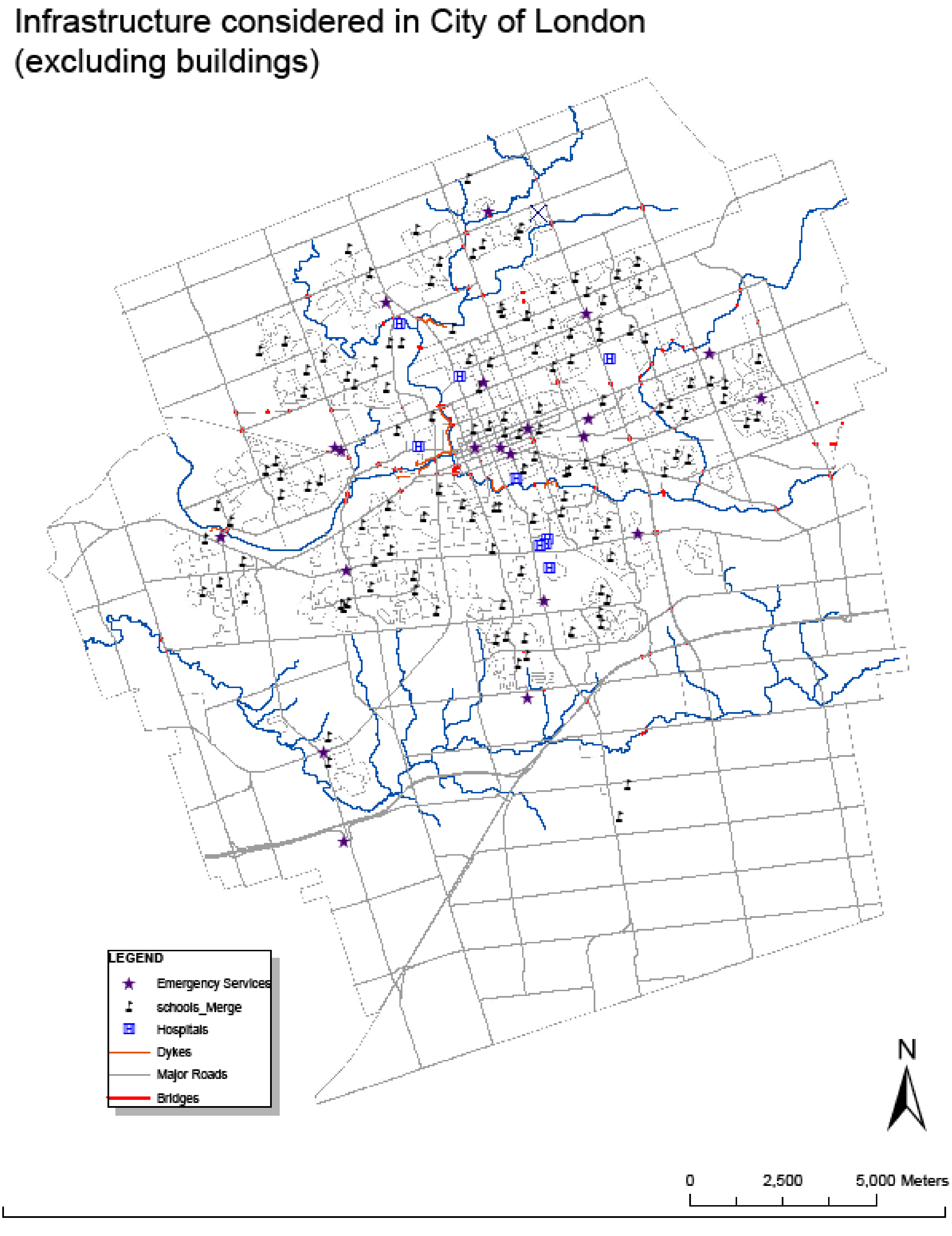

Figure 8: Infrastructure Included in Risk Assessment (not including buildings)

3.2.2 Bridges and Culverts

The bridges documented in the Bridge Management System operated by the City were included in the risk assessment process. The study includes footbridges and culverts. The main failure mechanisms of a bridge during a flood are washout due to embankment and/or pier scour from the fast moving water. Other major flood damage can be the overturning of the structure due to the forces of water and possible build-up of ice and/or debris creating a damming effect. Debris may also be expected to contribute to the damage of non-structural elements such as railings, conveyance cables and streetlights. Similar to a road, the functionality of a bridge will be compromised should the deck become submerged and the bridge is closed. This has the potential to become an even greater inconvenience and possible hazard if there is no alternate route across the river or valley is not nearby.

Culverts are designed for some overhead. However, if this is exceeded the culvert can experience the same damage as previously described for roads and bridges. In addition, the loss of function can be extended to account for the water that exceeds the culvert's design capacity. This will cause damming action behind the culvert increasing the inundation depth upstream.

There are 117 culverts, 99 bridges and 8 footbridges within the City. These structures are an integral part of the transportation network and must be prepared to cope with the increased flood load. This study examines not only the current condition of the structure and how that impacts its ability to withstand increased loads due to flow increase, but also its structural design such as capacity (culverts) and elevation (bridges) in relation to the modified design floods. The majority of the bridges are in a good condition as indicated by the Bridge Management System.

3.2.3 Critical Facilities

Critical facilities are defined in this study as the buildings which provide essential or emergency services and include: hospitals, emergency medical services, (EMS), fire, police, pollution control plants and schools. Many of these services are especially important during a flood event and so they are studied separately from the rest of the building infrastructure.

All critical facilities may experience the same failure mechanisms with respect to structural and equipment damage. Any costly equipment that is under the inundation depth may be lost and the building envelope itself may be compromised in the event of large inundation or extreme foundation scour, depending on the velocity and depth of flooding. The functionality of the critical facility may also be affected depending on its proximity to the floodplain.

Hospitals. Hospitals must have accessibility from many different routes for ambulances and possible evacuation in case of a large flood disaster. In addition, staff's access to the hospital will be impacted affecting the operations at the building even if the hospital itself is not flooded. The inflow of patients during a flood disaster event may also increase, and the hospitals should be prepared to deal with this influx of patients (as well as any from hospitals which may need to evacuate due to flooding inundation).

Fire fighting, EMS and police. Similar to hospitals, fire fighting, EMS and police infrastructure will lose functionality if major access roads are cut off due to flooding. The location of the personnel will also affect the operations of the infrastructure especially if many are located near, or cut-off by, the floodwaters. An increase in demand for emergency services must be expected during a disaster flood event.

Fire Services London manages all of the fire stations for the City. None of the stations are within the existing floodplain. However, some stations are in close proximity to high risk areas and may experience an increased demand for their services during and immediately following a flood disaster event. The main stress on the system will be the increased demand and reduced access due to flooded roads which will increase the response time. Thames Emergency Medical Services manages the emergency services for the City of London through the use of six locations. None of these locations are in the floodplain, however similar to the fire stations some will be affected due to their proximity to the areas at risk.

London Health Sciences Centre. The London Health Sciences Centre is the main teaching hospital in London, and one of the largest acute care teaching hospitals in Canada (LHSC 2010). The centre includes South Street Hospital, University Hospital, Victoria Hospital and Children's Hospital, Byron Family Medical Centre and Victoria Family Medical Centre. None of these locations are within the five modeled flood scenarios. However, the parking lots at University Hospital experience inundation during the 250 CC_UB scenario. The nature of the facility however ensures that a large flood event will have an impact regardless of direct building inundation. The access to some hospitals may be restricted due to road and bridge closures which will cause an increase in admittance to other hospitals. This increase can put a strain on the operations if they are not properly equipped to handle it. Additionally, lack of access can prevent staff entry which further strains the system.

Pollution Control Plants (PCPs). PCPs are generally located in low lying areas near the river due to the nature of their design and function, thus they are highly vulnerable to flooding. A PCP may experience partial to full failure depending on the extent of inundation it experiences. For example, if the secondary treatment system is inundated, the plant may still run primary treatment and bypass the secondary system. This is not the ideal operation, but it is better than allowing raw sewage to pass untreated into the system. However, if the outlets become submerged such that the water is backing up into the plant, a full bypass may be necessary. This means that for the duration of the high water levels, the sewage will be discharged directly to the river. Any electrical equipment that becomes inundated during a flood can also be lost or damaged by the water. A report by the Water Environment Research Foundation (2005) indicates that 1.2m of water is enough to short out all electronics. In addition, damage can be expected to include pump stations, exposed sewer mains, and washout, silt and debris interfering with manholes and mains.

This study uses inundation depth to measure flood damage and so a combination of visual inspection with structural details from each plant was used to determine the degree of failure that can be expected for those plants that fall within the flood scenarios.

London has six pollution control plants: Southland, Greenway, Vauxhall, Oxford, Adelaide and Pottersburg. Together the plants have the capacity to handle approximately 298ML/day. Currently Pottersburg, Adelaide and Greenway experience difficulty discharging during extreme flow events. Emergency overflows are in place to manage the discharge in addition to a bypass at Pottersburg. Due to the location of the plants within the floodplain, access during a flood event is a concern. Vulnerable aspects of the plant include the tanks, clarifiers and electrical equipment.

Schools. The final type of critical facilities considered is schools. It is assumed that the schools will be closed and/or evacuated in the event that it is inundated (therefore experience total failure of functionality). Structurally, a school will be affected in the same way as any other building of similar construction that experiences inundation. This structural damage is related to the velocity and depth of the floodwaters, the age and condition of the building envelope and foundation and the surrounding infrastructure (debris damage). The proximity of the school to the floodplain (if it is not within the floodplain) determines the level of its functionality loss based on the school bus access, walking access, and as the level of safety. Schools may also experience loss of contents such as computers, desks and books if the building becomes inundated. The impact of flooding on education (specifically for long duration floods) has not been studied in depth, but it is assumed that it will have a negative consequence due to rescheduling and moving classes as well as the emotional impact on the students.

3.2.4 Storm Water

The stormwater system consists of a network of sewers, manholes, outlets and stormwater management facilities. There exists over 1,300 km of storm gravity sewers, 6.7 km of combined sewers, 18,472 storm access holes and 100 storm water management facilities (SWMF). Floodwaters affect stormwater management by overwhelming the system; the pipe networks can become unable to handle the extreme volume of water causing it to back up the pipes and flood the roadways out of the manholes and inlets. In the case of combined sewer systems the sewage may back up and through basement drains cause major damage to buildings. If SWMFs are inundated fully, they will be no longer able to provide storage or treatment for the area and will therefore lose their function for the duration of the inundation.

There are two major flooding mechanisms that may affect the City. The first is flooding due to the river overtopping its banks. This type of flooding may occur due to large and intense (a large amount of precipitation within a relatively short period of time) storm events leading to increase in flow within the river which then overtops its banks. The infrastructure that is affected is therefore within the floodplains or in close proximity. The flooding of the Thames and its tributaries is the type of flooding considered in this study.

The second type of flooding may occur due to the large amount of rainfall that overwhelms the stormwater management system but not cause the river to flood. The problem may be compounded by the urbanization and the land use change which lead to a reduction of natural runoff and rainfall absorption. As land use changes from agricultural and rural to developed and urban, more stormwater infrastructure is required to manage the large volumes of rainfall runoff. When an extreme storm event occurs, both flooding types combine increasing the amount of infrastructure affected. As the stormwater system becomes overwhelmed, more water is discharged to the already full river, amplifying the flooding. Extensive hydraulic modeling is needed to fully understand and predict the response of the entire system to extreme flooding scenarios. Hydraulic modeling of storm water network is beyond the scope of this study.

The final risk maps shows the layout of the stormwater network over the infrastructure risk maps to identify key areas of the intersection of high risk areas with vulnerable storm infrastructure.

3.2.5 Water Distribution Network

The water distribution network within the City of London consists of a network of pressurized pipes. These pipes are most vulnerable at river crossings where they may experience excessive stress due to scour or erosion of river banks. Another particularly vulnerable location exists when pipelines cross under bridge decks. If the flood water levels reach the bridge deck or come close, the debris may strike the pipes causing them to fail. The risk to water distribution network was not assessed in the study due to data limitations and the need for more detailed hydraulic and geotechnical analyses to determine bank erosion.

3.2.6 Flood Control Structures

There are many flood control structures at work within the City of London. Due to the position of the City around the Thames River, and the propensity of the Thames to flooding, these control structures are important in the management of water levels for both safety and recreation in the City. The City's largest dam, Fanshawe, is located on the North Thames branch at the northeast end of the City. It is an embankment dam with concrete spillway that controls a drainage area of 1,450km^2 at its outlet (Water Survey of Canada gauge 02GD003). The total storage volume is approximately 3,560 ha.m.. According to the Dam Safety Assessment Report (DSAR) done by Acres in 2007, the dam is not overtopped during the inflow design flood (probable maximum flood with peak inflow of 3473.5m^3/s) but does not have the sufficient freeboard. The DSAR also modeled the dam under the 250 UTRCA year flood and the regional design storm (Hurricane Hazel).

The hydraulic modeling done for this study begins at the outlet of Fanshawe dam; as such the dam is not included in the study. For further information, the DSAR provides a very detailed assessment of the dam operations under varying storm and precipitation scenarios as well as a dam break analysis.

There is an extensive network of dykes designed to protect the City from flood damage. As of 2006, there was approximately 5.5 km of dykes around sections of the north, south and main Thames River. Along the south branch are the Clarence and Ada-Jacqueline dykes. Along the main branch are Riverview, Byron and Coves. The West London Dyke (WLD) is the largest. It runs along the north and main branches at the forks. Finally, the Broughdale Dyke is on the north branch. The WLD was recently repaired and some parts were replaced to bring it up to acceptable conditions and the 250 year regulatory flood levels.

The majority of the dykes within the City are earthen fill dykes. Ada-Jacqueline was repaired 20 years ago using rip rap and portions of Broughdale are composed of gabion. WLD is constructed using reinforced concrete panels and has been restored and replaced in some sections with a flood wall. The Coves contains a flap gate that is used as a stormwater management release structure. Recent vegetation and erosion studies done on the dyke network have indicated that the main vulnerabilities of the system are due to erosion from the river. This causes undercutting which can lead to failure. Failure may also be caused by overtopping or breeching of the dyke.

3.2.7 Buildings

Due to the intensive urbanization of the City, with the densest development occurring around the Forks area of the Thames, flooding has the potential to have devastating effects on residential and business properties. The study identifies all buildings which experience any level of inundation in each of the five scenarios. The level of inundation is defined in the stage-damage curves provided by Ministry of Natural Resources 2007 Flood Estimation Guide as the level of the water above the first floor entrance. For example, if a building is raised 0.5m off the ground elevation, and the water depth is 2m relative to the ground elevation, the inundation level is equal to 2m – 0.5m = 1.5 m. The amount of damage sustained by a building during a flood is typically measured using stage-damage curves. These curves are used in the study for the calculation of risk. The foundation of the building is critical in determining its response to inundation. In addition, the age, structure type and condition of the building all play an important role. This study assumes that all buildings will be evacuated in the event of a flood and therefore only structural and functional impacts are considered. The data was provided by the Municipal Property Assessment Corporation. Factors taken into consideration when evaluating the risk to buildings include age, design, value, inundation level and total area inundated.
There are approximately 3,014 buildings affected by modelled floods of which the majority (2,823) is residential. The average residential building value is $95,177 in 2008 dollars. The most common building type is property code 301 - single family detached, not on water. The next most common type is property code 370, residential condominium. Together these two categories account for 85% of the affected properties. The average age of the residential structures is 52 years.

Flooding not only impacts the physical building structure, it can also cut off access to commercial industries causing business disruption and economic damage. These damages have been taken into account in this study.

Structural detail on industrial properties is not widely available. However, the impact to industrial facilities can be estimated based on previous accounts of flooding to similar properties. Damages typically include loss of mechanical and electrical equipment.

4.0 Risk Assessment Methodology

The risk assessment methodology produces an integrated risk index for each infrastructure element considered in the study. This risk index allows for the comparison among various locations that may be flooded and is presented in tabular and spatial (maps) forms. Each risk level for a particular location provides the source of risk (type of infrastructure that may be affected) and relative contribution of each source to the overall risk.

4.1 Risk Index

Risk is commonly defined as the product between a hazard and vulnerability when used in the context of flooding (Apel, 2008). This study measures vulnerability which is defined by Engineers Canada in the context of engineering infrastructure and climate change as "the shortfall in the ability of public infrastructure to absorb the negative effects, and benefit from the positive effects, of changes in the climate conditions used to design and operate infrastructure" (Engineers Canada, 2007).

The Risk Index R introduced in this study is calculated for each infrastructure element and incorporates quantitative and qualitative data to address both objective and subjective types of uncertainty. The mathematical expression of the risk index is:

$$R_{ke} = P \times \sum_{i=1}^{3} (D_{ike} \times IM_{ike}) \qquad [1a]$$

Where:

P is the probability of occurrence of the hazard event (dmnl);
D_{ike} is the economic loss for each i, k and e ($);
IM_{ike} is the Impact Multiplier (fraction of damage sustained for each impact);
e is the infrastructure element;
k is the infrastructure type from 1 to 6, (building, bridge, barrier, critical facility, pollution control plant and road); and
i is the impact category, from 1 to 3, representing function, equipment/contents and structure.

The risk index is tabulated for each infrastructure element for each of the five scenarios (see Section 5.5). These values are then combined and provided numerically in tables and displayed spatially using GIS in the form of risk maps (see Appendix D). Risk is presented geographically by Dissemination Areas (DA) classification according to the equation:

$$R_{DA} = P \times \left(\sum_{e=1}^{m} \left(\sum_{i=1}^{3} (D_{ike} \times IM_{ike}) \right) \right) \qquad [1b]$$

where m represents the number of elements within a DA.

DAs are consistent with Statistics Canada method of representing data. There are 19,177 DAs located within Ontario - 527 within the City of London (refer to Figure 9 and Appendix C). Each DA is identified by its unique 4-digit code. Statistics Canada defines DA as "a small, relatively stable geographic unit comprised of one or more adjacent dissemination blocks." DAs were selected in part because "It is the smallest standard geographic area for which all census data are disseminated." This resolution was used to identify regions which are at risk of be flooded. The DA are divided with populations usually 400 to 700 persons while respecting the boundaries of the larger census subdivisions and census tracts (Statistics Canada, 2001). These areas remain relatively stable over time and they are considered small enough to remain significant in municipal decision making. The figure below is used as a reference for the remainder of the project to easily identify DA in the city. Refer to Appendix C to see reference cells A1:E6 blown up to include identification of each DA. Refer to Appendix J (on CD) for a list of the DA and reference cells in table format.

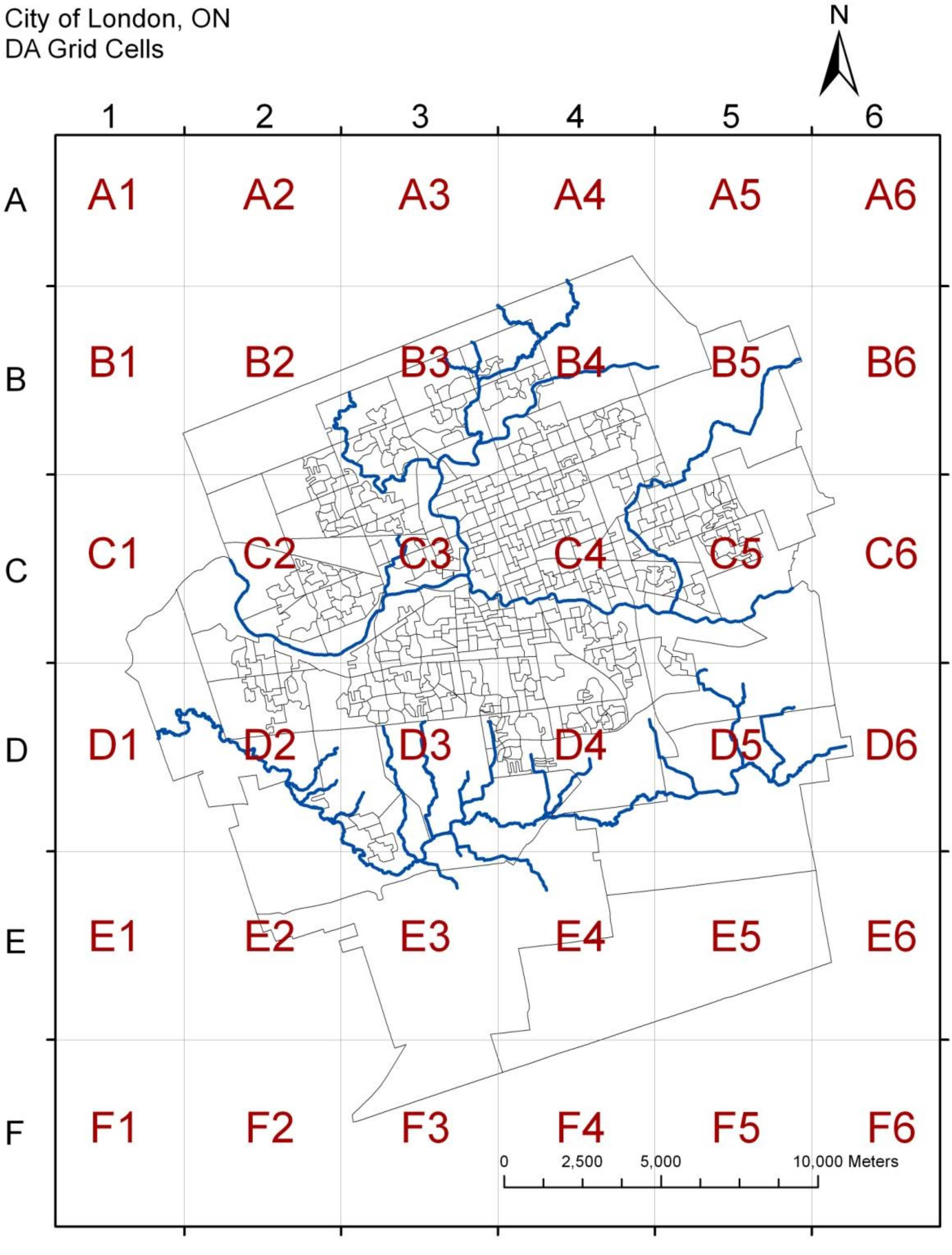

Figure 9: Dissemination Areas for London Ontario with reference grid

The risk index is used to aid in the prioritization of areas of infrastructure at risk. Equation 1b shows the calculation of risk to a dissemination area DA, for all infrastructure elements of interest (bridges, buildings, barriers, roads, critical facilities and/or pollution control plants). The risk index is tabulated for each infrastructure element for each of the five scenarios (see Section 5.5). These values are then combined and provided numerically in tables and displayed spatially using GIS in the form of risk maps (see C) for each scenario. The following sections describe in greater detail the components of the risk index.

Probability of flood hazard, P

Probability refers to the likelihood of a specific flood event occurring. This will act as a weight for each of the flood event scenarios (100 CC_LB, 100 CC_UB, 250 CC_LB, 250 CC_UB and 250 UTRCA). Although a 250-year event may create greater damage, the likelihood of this event occurring is less than a flood of smaller scale. For a 100-year flood event, the probability, P, of occurrence in any given year is 1 in 100, or 1%. Similarly, the probability of a 250-year event is 1 in 250 or 0.4%. These probabilities are used in the final risk calculation. Therefore, after applying the probability, the risk index becomes:

$$R_{ke} = \mathbf{0.01} \times \sum_{i=1}^{3} (D_{ike} \times IM_{ike}) \quad [2a]$$

for the 100 CC_LB and 100 CC_UB scenarios, and

$$R_{ke} = \mathbf{0.004} \times \sum_{i=1}^{3} (D_{ike} \times IM_{ike}) \quad [2b]$$

for the 250 CC_LB, 250 CC_UB and 250 UTRCA scenarios.

Impact Multipliers, IM_{ike}

The second element of the risk equation represents the impact to the infrastructure as a result of its interaction with the flood hazard. The damages are both direct (such as loss of structural integrity and components) and indirect (such as a loss of functionality). Damages resulting from flooding are extremely varied and include losses ranging from inconvenience to structural damage to death.

This study focuses solely on those damages affecting municipal infrastructure and considers three variables as a measure of these consequences:

1. the loss of function (IM_{1ke}),
2. loss of equipment (IM_{2ke}) and
3. loss of structure (IM_{3ke}).

Each of these factors (termed impact multipliers) is measured as a percent loss and it is calculated using both quantitative and qualitative information. They are incorporated into the risk index as demonstrated by expanding equation 1a, shown below:

$$R_{ke} = P \times (D_{1ke} \times \boldsymbol{IM_{1ke}} + D_{2ke} \times \boldsymbol{IM_{2ke}} + D_{3ke} \times \boldsymbol{IM_{3ke}}) \quad [1c]$$

The quantitative data includes the ability of the infrastructure to withstand direct damages due to flooding in addition to actual inundation measurements. This is extracted using GIS tools to obtain information such as the length, depth and area of inundation. The qualitative data includes information gathered through interviews relating to the decision makers' expertise and experience. This includes the condition of the infrastructure and how that may affect its response to flooding. 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 the varying infrastructure types; however they are consistent across any one particular infrastructure type.

Loss of Function (IM_{1ke})

The loss of function impact multiplier IM_{1ke} measures the degree to which the infrastructure has lost its functionality. This is defined in this study as the degree to which the infrastructure no longer functions at an acceptable level, relative to which it was originally designed, as a result of flooding. The value of IM_{1ke} fluctuates between 0 and 1 where 0 denotes no loss of function and 1 denotes total loss of function.

In the case of transportation infrastructure, roads, bridges, culverts and footbridges are designated as having an IM_{1ke} equal to 1 once they are inundated. Buildings and critical facilities are assigned an IM_{1ke} of 1 if they are inundated or if all possible access routes are blocked due to flooding. Flood protection structures have an IM_{1ke} value of 1 once their design capacity has been reached.

Partial loss of function may occur in the case of critical infrastructure such as fire, EMS, hospitals and schools if some, but not all, of the access routes are blocked by floodwaters. The methodology assigns a fractional value of IM_{1ke} depending on the number of incoming or outgoing major routes and the number of routes that are flooded.

The relationship used to calculate IM_{1ke} for fire and EMS buildings is:

$$IM_{1,4e} = \frac{(n - r)}{n} \quad [3]$$

Where:

k=4 (critical facility)
n is the total number of major access routes; and
r is the number of routes obstructed by floodwaters.

The entrance to the fire or EMS building is counted in the total number of routes to allow for the building to have partial access if all major (arterial or primary) routes are flooded but the building is not inundated. In this case, the $IM_{1,4e}$ value will be $1/n$ where n is the total number of access routes including the entrance. To illustrate, if there are four major routes leading from a fire station (n=4+1), and one is inundated by floodwaters (m=1), the final $IM_{1,4e}$ value will be 4/5. In the case of schools and hospitals, the loss of function multiplier is calculated based on the total number of access routes within one intersection from the building. Therefore in equation 3 the variable n takes on the value of the total number of intersections adjacent to the property (as opposed to only the major routes). This is done to more accurately represent the directionality of access. The directionality of access describes the nature of the infrastructure. Fire and EMS have vehicles and personnel leaving the building to service an emergency, whereas schools and hospitals receive people.

For pollution control plants, the loss of function is 0 or 1. IM_{1ke} is 1 if the danger flow or elevation danger point as indicated by the City of London Flood Plan (2007) is exceeded, or the outlet invert is inundated up to the plant elevation.

Loss of Equipment (IM_{2ke})

The second impact multiplier IM_{2ke}, estimates the percent of equipment lost as a direct result of inundation. Equipment is defined as contents or non-structural components of the infrastructure. In the case of residential buildings this would be the housing contents or anything that would be expected to be taken in a move (Water's Edge et. al., 2007). Transportation infrastructure (roads, bridges, culverts and footbridges) and flood protection structures (dykes) do not have an IM_{2ke} component. Buildings and critical facilities have equipment values estimated using methods based on building type and value and are estimated as 30% of the total structure's value as done in the Glengowan Study (Marshall, 1983). The equipment values for pollution control plants are estimated based on the City of London's 2010 Wastewater Budget (London, 2010).

Loss of Structure (IM_{3ke})

The final impact multiplier, IM_{3ke} measures the percent structural loss of the infrastructure. This is the degree to which the structural integrity is compromised as a result of flooding. The flood depth was used in the calculation of IM_{3ke} in addition to the infrastructure element's condition, age, capacity and other knowledge gained during interviews with experts in each area. IM_{3ke} is a measure of both quantitative and qualitative structural loss. The methodology uses an innovative approach in the incorporation of qualitative and subjective data with the quantitative measures. The qualitative portion uses fuzzy set theory to allow for subjectivity and differences of opinion with respect to the condition of the infrastructure, its failure mechanisms and its response to flooding. This combination gives a more comprehensive representation of risk.

The deterministic element of IM_{3ke} is calculated using stage damage curves. These curves use the inundation depth as input to estimate the percent damage to the infrastructure (both structural and contents) as a result of flood inundation. They are specific to the building type (for both residential and commercial) and the region (based on local conditions, codes and construction methods). Stage-damage curves are commonly used in the assessment of flood-based damage.

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. 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 E.

Stage-damage curves are required for all infrastructure types to quantify the deterministic measure of structural damage (LS). However, these curves are not available for each infrastructure type encompassed by this study. Therefore, stage-damage curves were created for use in the methodology 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. The bounds of the curve were defined using the maximum and minimum flood inundation depths that were calculated for each infrastructure type in the previous steps of the risk assessment methodology. These curves are provided in Appendix E.

For the development of the bridge stage-damage curve the experts were asked to describe the damage that could be expected given varying levels of inundation. The answers were based on the type of bridge (that is its material and structural description). It was determined that bridges are designed to have a freeboard of 1m, thus as the water levels approach this limit and surpass it, damage begins to occur due mainly to debris. Once the bridge deck has become inundated, further studies show that the force of the water can be related to the ratio of the thickness of the bridge deck to the depth of submersion (Turner-Fairbank, 2009) giving the second portion of the curve. Below 1m from the deck, damage occurs mainly as a result of scour action along the pier base and abutments.

These curves are used to estimate the percent of structural damage that could be expected based on experts' experience and opinion. They may be used to estimate the damage and the number obtained (LS) is used within the methodology to calculate the final risk index.

The qualitative element of IM_{3ke} was used to quantify the subjective uncertainty associated with potential failure of the infrastructure system. Assessment of subjective uncertainty was conducted with the assistance of experts for various types of infrastructure. A qualitative component of IM_{3ke} allows for the measure of partial failure as well as the impact of the structure's current conditions on its response to flooding as perceived by experts in the field. This qualitative component is measured using 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 will affect the amount of structural damage sustained by the infrastructure during a flood. The condition of the infrastructure is not quantified by the stage-damage curves and therefore the input of those who are the most familiar with infrastructure may provide for the more accurate assessment of the risk. The condition of the infrastructure was measured using fuzzy analysis through interviews performed with experts within the City. What follows is a brief introduction and description of this theory as it pertains to this study.

Fuzzy set theory is used to address ambiguity and uncertainty in data. 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 the 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 fraction of failure – membership between 0 and 1.

The use of the fuzzy set allows for each opinion on what constitutes failure to be considered and defines the degree to which the system has failed with respect to the varying opinions on acceptable failure. The ability to measure varying levels of failure is particularly significant in a study such as this when hundreds of infrastructure elements are under consideration. It enables a much more inclusive measure of risk.

Functions describing the membership of an element to a certain set were created through interviews and previous experience. These functions are termed membership functions. The FRE_{ke} (the second component of IM_{3ke}) uses two membership functions to measure the infrastructure's performance: a) system-state membership function and b) acceptable level of performance membership function (see Figure 10). The FRE_{ke} is calculated based on the area of overlap between these two curves. This overlap is termed the acceptable partial system failure. In most cases, the larger the acceptable partial failure, the more risk the expert is willing to take on.

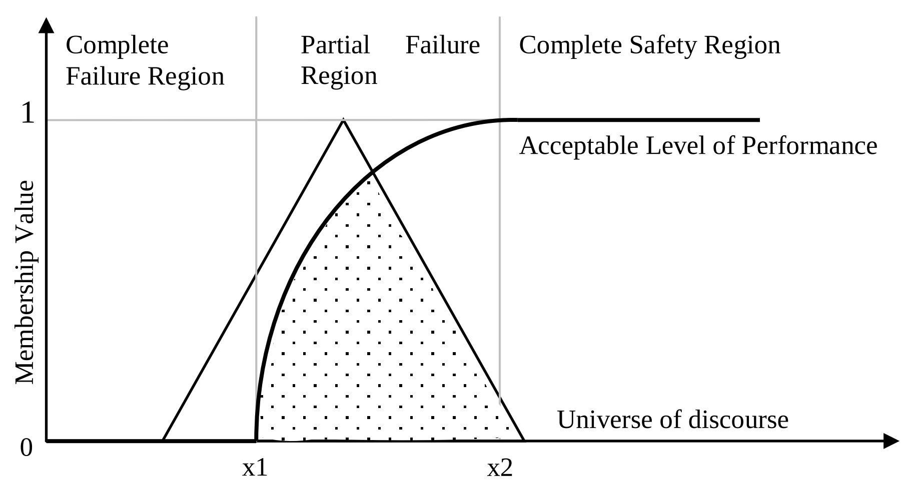

Figure 10: Membership Functions of System-State and Acceptable Level of Performance

The membership functions describing the current state of the system as well as the acceptable performance state of the system were created for each infrastructure category. The system-state membership functions describe the condition of the infrastructure element based on factors such as age, material and design life. A system-state membership function was created for each infrastructure element under consideration. Interviews were conducted within the relevant departments in the City of London as well as with varying infrastructure experts to aid in the development of these curves (see Appendix F). This process is described further in the report.

The second set of curves – the acceptable level of performance functions, was created for each infrastructure *type.* For example there is one function that defines the acceptable performance for a culvert (as opposed to a function for each culvert in the study). These curves were also created using the input from various interviews conducted over the course of the study. The acceptable level of performance function may be different for each decision maker based on previous experience, education, expertise and personal perception of risk.

As previously mentioned, FRE_{ke} is calculated using the area of overlap. The fuzzy compatibility measure (CM_{ke}) is used to measure the extent of this area. CM_{ke} is calculated using a weighted area method since the higher the membership values become, the more significant they are. CM_{ke} is calculated using the following equation:

$$CM_{ke} = \frac{\text{Overlap area}}{\text{Area of system-state function}} \qquad [4]$$

The fuzzy reliability index can then be calculated as:

$$FRE_{ke} = CM_{ke} \qquad [5]$$

A FRE_{ke} value of 1 indicates that the system-state is fully within the acceptable level of performance – no failure. That is, the system is completely safe. Conversely, a FRE_{ke} value of 0 signifies no overlap between the system-state and the acceptable level of performance indicating that the system is in a complete failure state. Therefore the greater the overlap between the system state and the acceptable level, the greater the FRE_{ke} will be, and the more desirable the scenario.

For this study, the system state was considered as a triangular distribution and describes the condition of the infrastructure type based on its age, structural properties and factors such as annual average daily traffic (for transportation structures). The condition is measured on a relative scale of 0 to 10 where 10 represents perfect condition. The acceptable limit state curves are trapezoidal and based on what is deemed acceptable condition for each infrastructure type, with a value of zero being completely unacceptable and a value of ten being completely acceptable. The combination of these two curves allows for the calculation of the compatibility measure describing the fuzzy reliability as explained above. Since the acceptable limit state curve increases to a fuzzy membership of one (with perfect condition being the most acceptable state) an increase in the compatibility measure indicates an increase in the infrastructure's condition being acceptable – lower level of partial damage.

Once combined with a flood event, the condition of the infrastructure will affect its structural loss measure therefore, to calculate IM_{3ke} the fuzzy risk index and the deterministic measure must be combined. An increase in the compatibility measure indicates a decrease in risk to the particular infrastructure (i.e. a bridge that is considered to be not very acceptable with respect to its condition will experience higher damage than a bridge that is considered to be perfectly acceptable). To represent this inverse relationship in the calculation of the loss of structure impact multiplier (IM_{3ke}), the following equation is used:

$$\mathrm{IM}_{3\mathrm{ke}}(CM_{ke}) = \begin{cases} 1, & CM_{ke} = 0 \\ \mathrm{Min}\left(1, \mathrm{LS}_{\mathrm{ke}} \times \frac{1}{\mathrm{CM}_{\mathrm{ke}}}\right), & CM_{ke} > 0 \end{cases} \qquad [6]$$

Where:

IM_{3ke} is the loss of structure impact multiplier used in Equation 1b;
CM_{ke} is the compatibility measure (Equation 5); and
LS_{ke} is the percent loss of structure from the stage damage curves ($LS_{ke} \leq 1$)

Therefore in this study when CM_{ke} is 0, the structure is deemed to be completely unsafe, or experiencing a total loss ($IM_{3ke}=1$). The stage damage curves are assumed to represent the damage to a structure at a completely acceptable limit state. As such, for CM_{ke} less than 1, the risk to the infrastructure will increase proportionally. A CM_{ke} value of 1 (completely safe) will yield $IM_{3ke}=LS_{ke}$.

This procedure produces a comprehensive risk measurement that includes the infrastructure's condition, how the condition may affect the response to the flood hazard as well as its expected failure mechanisms.

Economic Loss

Economic loss refers to the potential monetary damage incurred by an infrastructure element as a result of a flood event. Assigning a monetary damage to each infrastructure element provides valuable information to prioritize the protection of the infrastructure which could potentially cause the most interference as a result of a flood event. The economic loss factor is different for each piece of infrastructure. There is an associated economic loss value for each type of impact multiplier (IM_{1ke}, IM_{2ke}, IM_{3ke}) as shown in equation 1c.

$$R_{ke} = P \times (\boldsymbol{D_{1ke}} \times IM_{1ke} + \boldsymbol{D_{2ke}} \times IM_{2ke} + \boldsymbol{D_{3ke}} \times IM_{\boldsymbol{3ke}}) \qquad [1c]$$

Where:

D_{1ke} may be referred to as monetary losses due to loss of infrastructures function per infrastructure type, k and element, e,
D_{2ke} are the monetary losses associated with infrastructure's equipment per infrastructure type and element, and
D_{3ke} is the monetary loss incurred by damage to the infrastructure itself per infrastructure type and element.

The economic loss due to loss of function (or partial loss), D_{1ke}, may depend on many factors. These are the monetary damages that may be incurred as a result of losing an infrastructure's function - including possible indirect monetary consequences associated with the structure no longer performing the function it was designed for. These values may include the cost of traffic rerouting, alternative transportation arrangement or lost profit. The economic losses related to the function of residential buildings include those costs for evacuating, sheltering and food. In transportation these costs are associated with mobility and consequently lost economic activity. Flooded roads and bridges that are essential to access businesses result in a loss of profit and economic action. Economic losses resulting from the loss of pollution control plants and critical infrastructure are related to inconvenience, mitigation costs and supplemental or emergency measures. Due to the complexities involved in estimating these values, the indirect (loss of function) damages are estimated as a percentage of the direct damages as per the Glengowan report (Marshall, 1983). Refer to Appendix G for indirect damage estimates. For all buildings, the loss of function is measured using the current value assessment (CVA) supplied by MPAC. This is a valuation method that uses profits as a measuring base. Therefore, by back-calculation, approximations can be made as to the profits lost during inundation time. The CVA is calculated by dividing annual profits by the capitalization rate. Therefore, to estimate the profits lost, the CVA is multiplied by the capitalization rate. The annual profit can then be factored to represent the profits lost during inundation. For this study, the inundation period is assumed to be 5 days, which is the window used in the hydrologic portion of the study.

Economic loss due to loss of equipment, D_{2ke}, is the monetary value of the equipment which may be damaged in a flood event. This value is the minimum of the repair or replacement cost of the equipment. Some infrastructure do not have equipment associated with them (e.g. roads), and as such will not have a value for D_{2ke}. For commercial, residential, institutional, industrial and critical facilities the value of this measure is based on reports and interviews which identify the contents as a percent of the total value of the infrastructure. The residential and industrial/commercial buildings are assumed to have a content value of 30%. This assumption follows assumptions made in the Glengowan assessment (Marshall, 1983). The value of contents for pollution control plants are taken from budgets.

The final economic loss value, D3ke, is related to loss of structure. This value is the minimum of the replacement or repair costs for rehabilitating the infrastructure. These values were determined using reports and available budgetary information. The majority of the building value data was provided by the Municipal Property Assessment Corporation. The value provided is not the market cost of an infrastructure; it is the present value of an infrastructure. It should be noted that there is a disconnection between the information provided by the Municipal Property Assessment Corporation and the MNR's tables used for calculating damages. The MNR's tables speak of damage costs mounting to several times the present value of the houses. This disconnect will not affect the relative value for the risk between buildings since the final risk value is relative. Since each building is valued using the same dataset, the final result for the building risk map will not be affected. However, this value will affect the overall risk since the damage values between each infrastructure type affect the final rankings. Since the building costs are assumed to be capped at the building value, and the MPAC building value is very low compared to the MNR tables, the final building damages are generally dominated by the building value. Therefore, a change in building value will modify the relative risk between buildings and all other infrastructure.

Road cost data was provided in a report prepared for Transport Canada by Applied Research Associates, Inc (2008). Repair costs are calculated on a per-m or per-m^2 basis. To incorporate this into the assessment the inundated lengths and areas of the infrastructure are determined for each climate change scenario. The rehabilitation and repair costs per lane km in Southern Ontario are assumed to be 2, 881$, as per the value presented in Table 53 of the Transport Canada report for municipal, urban, arterial roadways.

All economic loss values were updated to reflect their 2009 value based on the Consumer Price Index (CPI) provided by Statistics Canada. In this way, the monetary values are comparable to each other. The relationship used to update the financial data to reflect the CPI is as follows:

$$YearY = YearB \times \left(\frac{YearY\text{index}}{YearB\text{index}}\right) \qquad [7]$$

Where,

$YearY$ = The monetary value for the year of interest ($);

$YearB$ = The monetary value for the base year ($);

$YearYindex$ = The CPI value provided by Statistics Canada for the year of interest; and

$YearBindex$ = The CPI value provided by Statistics Canada for the base year

Appendix H provides a list of average Consumer Price Indices over the last 25 years (based on available data) as provided by Statistics Canada. These economic loss values are used in risk calculation for each piece of infrastructure.

The damages and impact multipliers are then summed and multiplied by the probability for each scenario as per equation 1b, to obtain the risk index for each infrastructure element, for each scenario.

4.2 Example Calculation of Risk Index

The following is an example of flood risk index calculation for an individual residential building in an average income neighbourhood that falls within the 100-year CC_LB scenario floodplain.

Example building properties:

- Building (k=1) on South Thames with element ID of 555
- Two story residential property with a basement level just above ground level
- No pool
- Area of 102 m^2
- Actual value of home is approximately $95,000 (2008)

Flood inundation characteristics:

- Maximum depth at building is 0.33m

Equation 1b must be solved to calculate the Risk Index for the residential building.

$$R_{1,555} = P \times (D_{1,1,555} \times IM_{1,1,555} + D_{2,1,555} \times IM_{2,1,555} + D_{3,1,555} \times IM_{3,1,555}) \qquad [1c]$$

The building under consideration is within the 100-year CC_UB scenario floodplain. The probability of this hazard occurring in any particular year is 1 in 100. That is, the likelihood of this particular flood event occurring is:

$$P = \frac{1}{100} = 0.01 = 1\% \qquad [8]$$

The next term in the risk equation represents the impact of the loss of function of the structure. Since the structure is inundated, as per the study assumptions, the impact multiplier, $IM_{1,1,555} = 1$, indicating a loss of function. The economic costs associated with the loss of function of a residential building are considered indirect costs. This study does not measure the indirect losses due to loss of function of a residential structure. Thus, $D_{1,1,555}=0$.

$$(D_{1,1,555} \times IM_{1,1,555}) = 0$$

The terms $(D_{2,1,555} \times IM_{2,1,555})$ and $(D_{3,1,555} \times IM_{3,1,555})$ represent the impact due to the loss of equipment/ contents and the structure itself, respectively. The contents are assumed to be 30% of the total worth of the structure, therefore 28, 500$. This assumption is in accordance with the Flood Damage Estimation Guide (Water's Edge, 2007) which also contains the building stage-damage curves. Using the inundation depth of 0.33m and the building classification of *2 storey with basement*, the curves are used to extract the damages.

For the area of 102 m^2, the total damage to the structure is 150,000 CAD2005$ according to the Flood Damage Estimation Guide (2007). Since this is more than the value of the house, the economic loss factor for the building is equal to the value of the home of 95, 000 CAD2008$. And the total loss of structure becomes 1. These costs are updated to 2009 values.

$$(D_{2,1,555} \times IM_{2,1,555}) = \ 28{,}500$$

$$(D_{3,1,555} \times IM_{3,1,555}) = 95{,}000$$

Where $D_{3,1,555}$ *= replacement cost for building 555*

So the Risk Index for the example 2 storey building in the 100 CC_LB Scenario is:

$$(\text{Risk Index})_{\text{building 555}} = 0.01 \times (0 + 28{,}500 + 95{,}000)$$
$$= 1235$$

4.3 Application of Risk Assessment Methodology to the Study Area

The summary procedure of the risk assessment methodology applied is as follows:

1. Gather data and determine the infrastructure elements to be analyzed,
2. Pre-process the data for compatibility with GIS software in preparation for steps 3 and 4,
3. Overlay maps of the infrastructure with the five flood inundation scenarios,
4. Extract the flood depths for each scenario at each infrastructure location,
5. Calculate the Risk Index for each infrastructure element based on the inundation depth, expected impacts and associated costs,
6. Prioritize the infrastructure with respect to the Risk Indices, presenting the result as both maps and tables.

This was an iterative process from steps 1 through 5 requiring continual re-working as data insufficiencies were discovered or new data was acquired. The final maps were created using GIS.

Data Sufficiency and Collection

As mentioned before, data was gathered from the City of London, UTRCA, Statistics Canada and the Municipal Property Assessment Corporation. The data covers all areas of infrastructure and was provided in GIS shapefiles form, reports and budgets. A number of interviews were conducted to collect additional information. The interview sheets and results are provided in Appendix F. The hydraulic data is presented as raster and shapefile layers. These files are provided in Appendix J on the CD along with the DA shapefile from Statistics Canada. The depth of inundation raster has a spatial resolution of 2 m.

The risk assessment methodology used in the study is data intensive. There were some limitations in data gathered.

Data quality. The data gathered in this study has often been inconsistent and poorly documented. Some of the GIS datasets had no accompanying documentation to describe the columns of data in the attribute tables. There are identified inconsistencies in the building footprint file and no supporting documentation. Although these inconsistencies may result in inaccuracies of the study results, they may not have a significant impact on the main findings of the study.

Data quantity. The amount of data available varied depending on infrastructure type. Buildings have a much better data related to structural response to flooding and stage-damage information.

Resolution of data. The grid size of the floodplains created in hydraulic analysis is 2m by 2m; therefore a resolution of 4m^2 is the degree of accuracy achieved in the study.

Data suppression. During the interviews with technical experts in the field it was observed that often multiple experts completed the same survey (group input instead of individual input). When requested to fill out a questionnaire on the individually, the experts were often uncomfortable. The internal work hierarchy apparently lead the younger, less experienced experts to be reticent to provide input different from their superiors. Thus there was some suppression of individual opinion which affects the use of the fuzzy set theory analysis and description of risk perception.

Infrastructure which is not in the floodplain was not of considered in the study. In reality there is a potential for flooding of properties which are not in the floodplains. This may be due to sewer surcharges coming back through in-home fixtures or spouting through manholes to spill over onto roads. These flooding incidents were not considered in the study. They require a detailed hydraulic modeling which is beyond the scope of the study.

Floodplain accuracy. Some of the water infrastructure/barriers are not represented in the hydraulic analysis to be consistent with current UTRCA model.

Railways are not considered but railway tracks may be affected by flooding. Many of the railway lines in the City of London cross the Thames River, although most are located at high elevations. Even though the City is not directly responsible for these damages, there could be serious indirect economic and social consequences resulting from the loss of a rail line.

A detailed list of the data collected and used in the study is in Appendix I.

Data Pre-Processing

The infrastructure data collected as shapefiles was processed to be used in ArcGIS 9.3 GIS software. This includes: arterial roads, bridges, culverts, pedestrian bridges, sanitary and storm pipe network, sanitary and storm outlets, critical facilities (EMS, fire stations, hospitals, schools and pollution control plants), buildings and dykes. The layers were first referenced to the projected coordinate system NAD_1983_UTM_Zone_17N and geographic coordinate system GCS_North_American_1983 to ensure compatibility and data interoperability. The city was divided into 8 subsections (see Figure 11 below) for ease of data processing:

1. Main Thames Branch
2. North Thames Branch
3. South Thames Branch
4. Mud Creek
5. Medway
6. Pottersburg
7. Stoney
8. Dingman

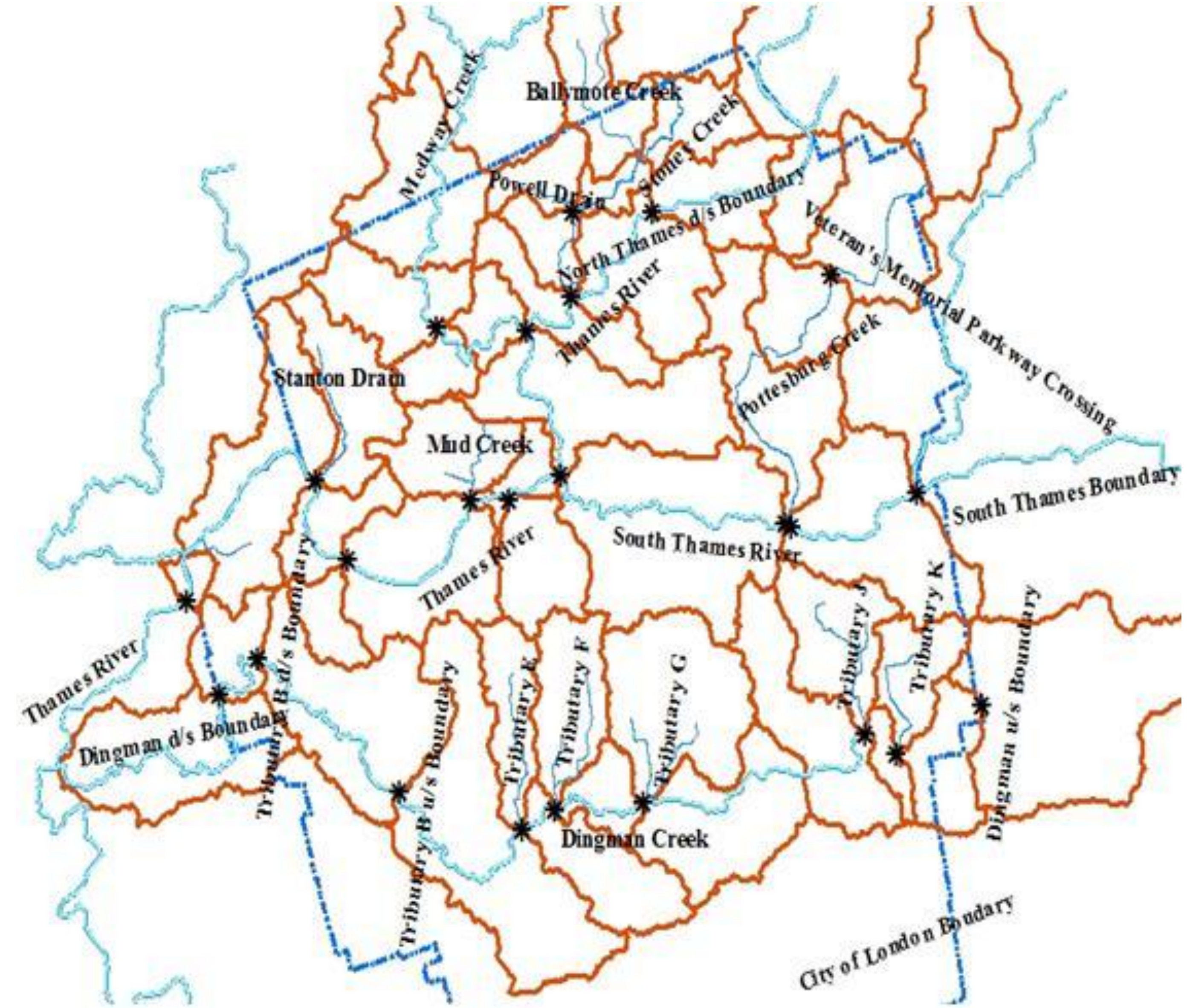

Figure 11: River sub-watersheds used for data processing (from Background Report 1)

The infrastructure layers were then clipped to the appropriate extent to be analyzed for each subsection.

Each of the flood scenarios (100 CC_LB, 100 CC_UB, 250 CC_LB, 250 CC_UB and 250 UTRCA) were provided as polygon shapefiles (extent of flooding) and rasters (depth of flooding) for each subsection listed above. These are shown in Appendix J. The infrastructure shapefiles were overlaid with each flood scenario polygon and clipped to the appropriate extent. Where the infrastructure files were not in the form of point shapefiles, new layers were created. The line files (roads and dykes) were broken into points at 1m intervals along the line. Since the resolution of the flood raster files is 2m, the 1m interval negates the possibility of data loss during depth extraction. The polygon shapefiles (buildings) were converted to point clusters. These modified infrastructure shapefiles were then used in the depth extraction.

Depth Extraction

The key flood damage indicator used in this study is the inundation depth. This value was extracted for each infrastructure element using ArcGIS 9.3. The flood scenario raster file was intersected with each clipped infrastructure layer and the depths at each infrastructure were extracted using raster processing tools. Where more than one point existed in the infrastructure layer (i.e. roads and buildings), the methodology extracted the maximum inundation depth. The depths for each infrastructure element, in each of the five scenarios, were then exported to be processed and used in the risk index calculation.

5.0 Results

5.1 Assumptions

The development of risk assessment methodology, presented in this report, required some assumptions implemented at different stages of the risk assessment process. Many of these assumptions were made as a result of data quality or data insufficiency, to best support the methodology. They are of high importance for the interpretation of the study results.

(i) The stage-damage curves used with buildings of similar type (e.g. two story home with a basement) assume similar structural reaction in a flooding situation. In reality, each home is not expected to react the same and many reasons, including quality of construction, may play an important factor in structural response during a flood.

(ii) The stage-damage curves available do not provide a category for apartments. This risk assessment assumes that an apartment performs similarly to a two story home.

(iii) In the risk analysis, any building that was identified as a residential shed or garage is assumed to have zero risk because stage-damage information for these structures was not available. In the event that data is not available for a specific building structure (not including sheds or garages), its value is estimated relative to structures of similar type and age that are located in the same area.

(iv) There are different levels of school closures. The decision whether a school remains open or not, relies heavily on the ability of safe bus transportation to school. The cancellation of buses is dependent on driving conditions and when they are no longer considered acceptable, a cancellation notice is issued. The time of day when the cancellation is made is also important to whether a school will be closed. Because of the subjective nature of school closure and its dependence on the individual school and bus companies, it is difficult to determine exactly if or when a school would be closed in potential flooding situations. Therefore, this study assumes that when access to the school itself is limited, it impairs the schools ability to provide services. Thus the degree to which the roads surrounding the school are flooded will represent the function of the schools operations (loss of function consequence in risk assessment).

(v) A "low risk" and "high risk" values were assumed in developing the fuzzy membership functions. The creation of the fuzzy membership functions takes the interviewees' responses as the mean value. The upper and lower bounds of the curve are taken as 1 unit higher and lower, respectively, than the mean value provided by respondents. This range is appropriate given the fact that the fuzzy membership function describes the experts opinion, and in this case the perspectives of the multiple experts interviewed was observed to differ by one or two degrees.

(vi) This study assumes that all infrastructure elements considered do not have flood proofing measures implemented. Infrastructure with protective measures may experience a lower flood risk than this study suggests.

5.2 Results

The vulnerability of the City of London Infrastructure to climate change-caused flooding is presented in the form of maps and tables. A map was produced for each climate scenario: 100 CC_LB, 100 CC_UB, 250 CC_LB, 250 CC_UB, and the 250 UTRCA scenario (Appendix D). The resolution of these maps is 4 m^2. The Risk was calculated for each Dissemination Area with the areas at higher risk shown in darker shades of colour. These levels are indicated in the legend of each map. Further detail is presented in the risk tables associated to each scenario with the highest level of risk indicated by a 1 and no risk is represented by a 0. It is intended that these risk maps be used in conjunction with the risk tables provided to aid in urban planning, emergency management and decision making.

Subsequent analysis was performed resulting in a total of 30 maps for other comparisons which may be of interest. These maps and their associated tables are listed in Appendix D. The first column identifies the Dissemination Area for which the risk index is measured across each scenario. Columns 2 through 8 contain the reference cells for the DA map (Appendix C) and the remaining columns contain the results from the five comparison cases discussed below. The body of the table contains the percent change in risk indices for each Dissemination Area, in each comparison. Further details of the analysis are provided in Appendix J on the CD. Detailed tables containing the risk indices for each infrastructure element in the study are included in the file: Risk_Tables_London.xlsx. Included with the document is a readme file that explains all of the worksheets. The risk indices are provided for each element as well as summarized for each infrastructure type. The comparison scenarios and specific, normalized risk scenarios are included for both the citywide analysis (included in the body of the report) and the infrastructure types (shown in Appendix D). Along with the tables are two reference tables for the DA and reference cells as depicted in Appendix C. Each infrastructure element is referenced to a DA. By using the provided lookup table, the reference cell can be found for each specific infrastructure.

The Risk Index has been normalized for ease of comparison across the infrastructure category for the citywide risk index maps (Appendix D, Figures D.1 through D.5). Therefore a Risk Index of 1 for a particular element indicates the highest possible risk (undesirable) and a risk index of 0 indicates no risk. It is observed that as the flooding intensity increases, so too does the risk index. The normalization method used is indicated in each case.

The categories in the table include:

- Bridges
- Arterial Roads
- Pollution Control Plants
- Critical Facilities
- Dykes
- Buildings (non-critical facilities)

The pipe network and outlets have been overlaid in the maps as described in the next section. Thus they are not represented in the tables.

5.3 Discussion of Results

This study considers five risk comparison cases as follows:

- **Case 1:** Contribution of climate change;
  Change in risk index between 250 UTRCA scenario and 250 CC_UB scenario
- **Case 2:** Comparison of 100 year climate change events;
  Change in risk index between 100 CC_LB scenario and 100 CC_UB scenario
- **Case 3:** Comparison of 250 year climate change events;
  Change in risk index between 250 CC_LB scenario and 250 CC_UB scenario
- **Case 4:** Comparison between lower bound scenarios;
  Change in risk index between 100 CC_LB scenario and 250 CC_LB scenario
- **Case 5:** Comparison between upper bound scenarios;
  Change in risk index between 100 CC_UB scenario and 250 CC_UB scenario.

The first set of data analysis looks at a comparison of all infrastructure at risk within the City, across the five modeled scenarios. Risk index is calculated for each infrastructure element, for each climate scenario. This gives five risk indices for each infrastructure element: 100 CC_LB, 100 CC_UB, 250 CC_LB, 250 CC_UB and 250 UTRCA. These risk indices were then summed for each dissemination area for the entire infrastructure therein, giving the total risk index for a dissemination area, for each climate scenario.

The normalization used for each scenario to represent relative risk is:

$$\overline{R_{DAj}} = \frac{R_{DAj} - R_{min}}{R_{max} - R_{min}} \qquad [9]$$

Where:

$\overline{R_{DAj}}$ = the normalized risk index for dissemination area DA, scenario j;
R_{DAj} = the risk index for dissemination area DA, scenario j;
R_{min} = the minimum risk index across all dissemination areas for scenario j; and
R_{max} = the maximum risk index across all dissemination areas for scenario j

This normalization across the scenarios allows for the comparison between all DAs with the maximum risk index of 1, and minimum risk index of 0. Thus conclusions can be drawn from the overall patterns of changing risk as well as the changes in risk within a dissemination area across scenarios. One effect of normalizing across the entire dataset is that the presence of a few DAs with large risk values will suppress the small differences at the lower risk values. It is recommended that the risk tables provided be studied along with the maps to give the best presentation and insight into the magnitude of the overall risk.

The major finding from the risk analysis across the City and all climate scenarios is that the pollution control plants dominate the risk index value. This is due to the fact that they have a very high value of vulnerable equipment and that they are at high risk due to their location in the floodplain. It is important to note that this risk dominance is highly dependent on the economic data and flood prevention measures that may or may not be implemented at a site.

The second infrastructure type at high risk is the barriers. The risk factor for the barriers is based on the consequence of a breach. The more potential damage to an area protected by a dyke, the higher the associated risk factor is for the dyke. This translates to a high risk factor over the dissemination area(s) containing the flood protection structure.

The following cases use the following formulas for calculating the differences in risk between climate scenarios.

For Case 1:

$$\text{Change} = [(R_{DA(250CC\_UB)} - R_{DA(250UTRCA)})/R_{DA(250UTRCA)}] * 100 \qquad [10]$$

For Case 2:

$$\text{Change} = [(R_{DA(100CC\_UB)} - R_{DA(100CC\_LB)})/R_{DA(100CC\_LB)}] * 100 \qquad [11]$$

For Case 3:

$$\text{Change} = [(R_{DA(250CC\_UB)} - R_{DA(250CC\_LB)})/R_{DA(250CC\_LB)}] * 100 \qquad [12]$$

For Case 4:

$$\text{Change} = [(R_{DA(250CC\_LB)} - R_{DA(100CC\_LB)})/R_{DA(100CC\_LB)}] * 100 \quad [13]$$

For Case 5:

$$\text{Change} = [(R_{DA(250CC\_UB)} - R_{DA(100CC\_UB)})/R_{DA(100CC\_UB)}] * 100 \quad [14]$$

where:

$R_{DA(100CCC\_LB)}$ = Risk Index for dissemination area DA, 100 CC_LB scenario;
$R_{DA(100CC\_UB)}$ = Risk Index for dissemination area DA, 100 CC_UB scenario;
$R_{DA(250CC\_LB)}$ = Risk Index for dissemination area DA, 250 CC_LB scenario;
$R_{DA(250CCC\_UB)}$ = Risk Index for dissemination area DA, 250 CC_UB scenario;
$R_{DA(250UTRCA)}$ = Risk Index for dissemination area DA, 250 UTRCA scenario.

A negative number indicates reduction of risk.

During the discussion of the differences between the two scenarios it is important to note that the 250 CC_UB and 250 UTRCA scenarios were created using two completely different methods. The 250 CC_UB was modeled as described in this report (Section 2) using HEC-RAS and HEC-GeoRAS whereas the 250 UTRCA floodplain is created manually and provided as a shapefile from the UTRCA. In the event that one scenario considered a tributary which the other did not, the non-compatible tributary portion was removed to minimize the differences.

It is important to reiterate that these climate change scenarios serve as the bounds of a range of possible climate change. In risk assessment, the scenarios within the range between the lower and upper bounds are all equally likely to occur (i.e. the 100 CC_LB scenario is just as probable as a 100 CC_UB flood event).

Case 1: Comparison between 250 UTRCA and 250 CC_UB scenarios

As mentioned previously in the report, the comparison between the 250 UTRCA flood scenario and the 250 CC_UB scenario may not be as accurate as the other four comparisons due to the manner in which the UTRCA flood scenario was created. However, the general observations will remain the same. Figure 12 shows the percent change in risk factor value from the 250 UTRCA scenario to the 250 CC_UB Scenario – in other words the contribution of climate change to the change in risk factor value. These values are provided in Table 4.

There is a demonstrated increase in risk due to climate change from the current, 250 year regulatory floodplain (UTRCA scenario) to the climate change 250 CC_UB scenario. The approximate increase in risk over the entire city is 75%. As shown in the map (Figure 12) the red areas are the areas which have the highest percent increase in risk from the 250 UTRCA scenario to the 250 CC_UB Scenario. The particular areas of interest in this comparison case are:

(a) Cells B3/B4: Along North Thames before confluence with Stoney Creek;
(b) Cells C1/D1/D2: Along Dingman Creek, west of Westdel Bourne, south of Oxford;
(c) Cells D5/E3/E4: Along Dingman Creek, south of Highway 402 and 401; and
(d) Cells B5/C4: Along Pottersburg Creek, north of Trafalgar to the airport.

The first area of interest is the DA 35390668, B3/B4 (Stoney Creek, north-east of Fanshawe and Adelaide) with an increase in risk of over 50%. This is due mainly to the roads and bridge which experience deeper inundation in the 250 CC_UB scenario. The bridge 3-Br-01 on Highbury Ave. N. experiences more damage due to scour of its foundation under the 250 CC_UB scenario. While the bridge deck is not overtopped, the clear area between the water surface and the deck is decreased from the 250 UTRCA to the 250 CC_UB. Additionally, approximately 30m of Highbury Ave N., just north of 3-Br-01, is flooded during the 250 CC_UB to a depth of approximately 0.3m at its deepest point. During the 250 UTRCA, it is not flooded.

Nearby, in B3, DA 35390669 has very little risk in the 250 UTRCA scenario, but due to an increase in the flood extent in the 250 CC_UB, the area has a high percent change in risk. The increased extent includes the inundation of 2 apartment buildings on Fanshawe Rd. across from Fremont Ave. It is important to note that an EMS facility (Ambulance station 4) is located at 1601 Trossacks Ave., which is located within this DA. This station, while not inundated, has a major route blocked due to flooding in both scenarios. The bridge 2-Br-10 along Grenfell Dr. is inundated in both scenarios, blocking the main route out of the EMS facility.

Table 4: 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

250 UTRCA vs. 250 CC_UB				
DAUID	Cell Index			% Increase
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
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

250 UTRCA vs. 250 CC_UB							
DAUID	Cell Index						% Increase
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

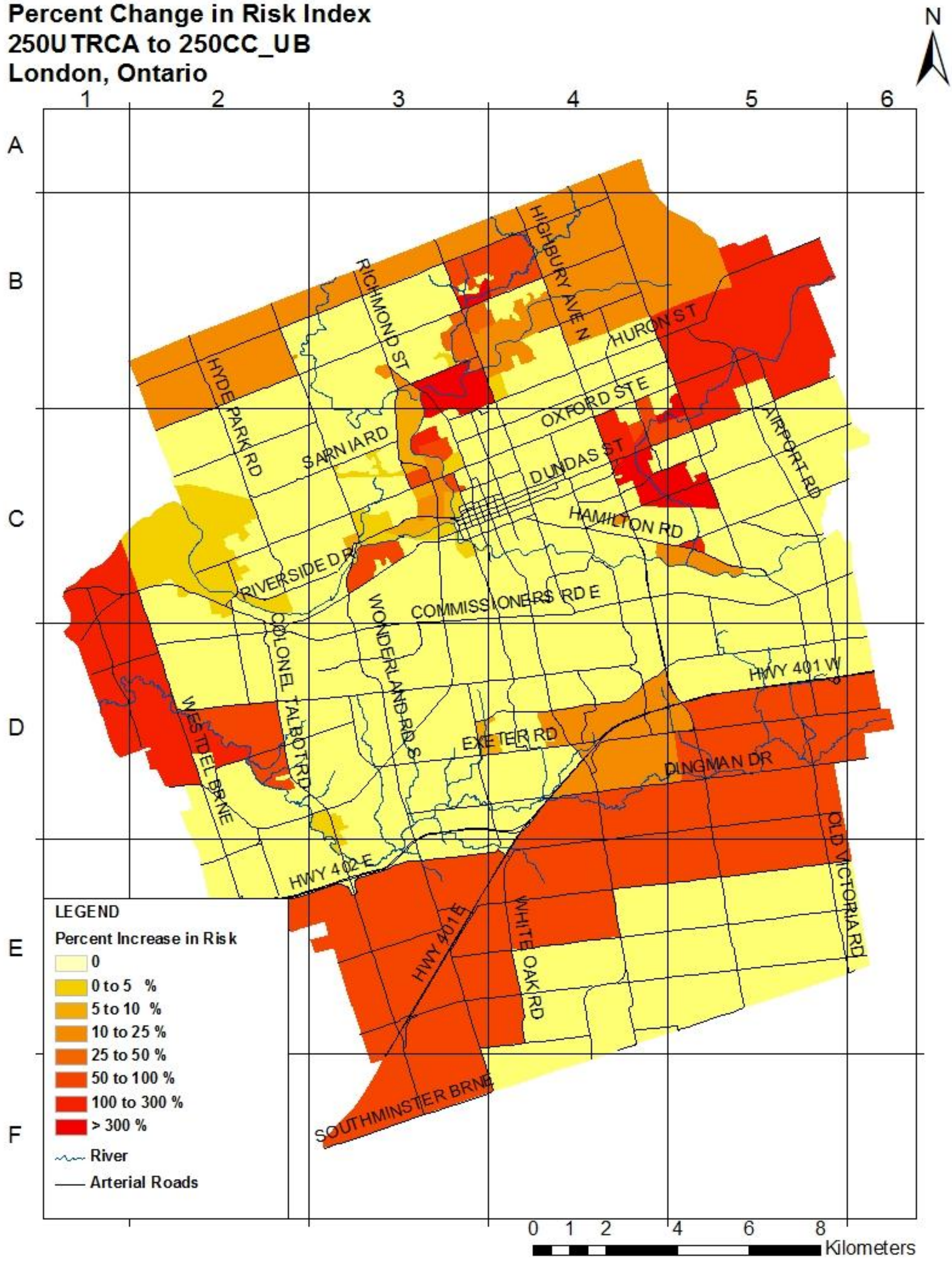

Figure 12: Percent change in risk between 250 UTRCA and 250 CC_UB scenarios

Also in cell B3, DA 35390032 experiences an increase in risk that is 7 times higher in the 250 CC_UB than the 250 UTRCA. This is the area bounded by Windermere Rd to the north, Richmond to the east, Adelaide to the West and North Thames to the south. This increase is due to an increase in flood extent in the 250 CC_UB scenario which causes the additional flooding of 7 houses along Tetherwood Blvd, several homes along Exmoor Place and partial inundation of the Ivey Spencer Leadership Conference Building and grounds. Additionally, the intersection of Windermere and Adelaide is inundated in both scenarios. The 250 CC_UB scenario shows an inundation depth of 0.76m while the 250 UTRCA shows an inundation depth of 0.45m. Also in this DA is the Adelaide PCP which experiences full inundation under the 250 CC_UB scenario and only partial inundation under the 250 UTRCA scenario (Figure 13). Adelaide PCP is located in the bottom right-hand corner of the Figure 13. The pink boundary is the 250 CC_UB scenario while the blue boundary is the 250 UTRCA scenario. Note that the intersection of Kipps Lane and Adelaide St. is also inundated in both scenarios.

Figure 13: Inundation of Adelaide PCP under 250 UTRCA and 250 CC_UB scenarios

Under the 250 CC_UB scenario, houses are flooded along both sides of Raymond Ave., and along Richmond between Raymond and Parkdale Ave. Additionally, 5 homes are flooded on the north side of Tower Lane. Elgin Residence (part of UWO) is partly inundated on its north edge under the 250 CC_UB.

In Cell C3, an increase in the extent and depth of flooding in the 250 CC_UB causes an increase in risk to buildings in DA 35390328, 35390329 and 35390323. Homes along Sherwood Avenue and The Parkway, Victoria St. and Gibbons Place, Gower St. and Fernley Ave plus a few homes along Oxford between Fernley and Gower are at a high risk for flooding. A notable building located within this area of high risk is Jean Sauve French Immersion Public School which is inundated in both scenarios but deeper in the 250 CC_UB.

In cell C3, the DA 35390706 bounded by Main Thames to the north, Springbank to the South, the Coves to the west and Wonderland Rd. to the East, experiences a 70% increase in risk due to flooding as a result of Greenway PCP (see Figure 14). The yellow floodplain represents the 250 CC_UB scenario. The green is the 250 UTRCA extent. Greenway experiences partial inundation under the 250 UTRCA which increases in area and depth under the 250 CC_UB scenario. Also during the UB scenario, the road access to the plant may be cut off. The entrance is inundated to a depth of approximately 0.3m.

Figure 14: Inundation of Greenway PCP under 250 UTRCA and 250 CC_UB scenarios

Finally, Wonderland Rd. bridge (1-BR-09) can be expected to experience more damage to its piers due to the increase in water depth during the 250 CC_UB scenario. In cells C1, D1 and D2, the DAs 35390745 and 35390459 experience approximately double the risk in the 250 CC_UB than the 250 UTRCA scenario. This is a result of increased damage expected to bridges: 7-Br-02 (Woodhull Rd.), 7-BR-03 (Westdel Bourne), 7-BR-04 (Pack Rd.), 7-CU-30 (Colonel Talbot) and 7-CU-31 (Colonel Talbot). 7-CU-30 experiences inundation of the deck under the 250 CC_UB scenario, the others do not.

The increase in risk along Dingman Creek from E3 to D5 is attributed to the size of the DA's as well as the increase in depth of flooding at bridges and culverts (though not overtopping) and the increased extent of flooding which causes additional inundation of buildings. Notably, four homes on the south side of Dingman Drive in cell D5 and 2 houses at Dingman Drive and Avenue are inundated in the 250 CC_UB scenario.

Moving to the Pottersburg Creek area, an increase in risk is seen most prominently in cells C4 and B5. This is due to the 250 UTRCA scenario not modelling the damming action caused by the CN Rail embankment near Trafalgar and Clarke Rd. (see Figure 15). This damming action causes an increase in flooding extent and depth which leads to an increase in number of flooded buildings. Two apartments on the south side of Trafalgar to the west of Pottersburg creek are inundated. Additionally, St. Pious X Separate School and Princess Anne French Immersion Public school are inundated. Houses along Moffat Cres., Vancouver St., Condor Crt., Balfour Place, Falcon St., Whitehall and Atkinson are inundated under the 250 CC_UB scenario (Figure 16). Further upstream along Pottersburg, houses are inundated along Hale St, Abbot St., Graydon St., Pritchard Place, Bridges St. west of the river, and Wavell St. east of the river (Figure 17).

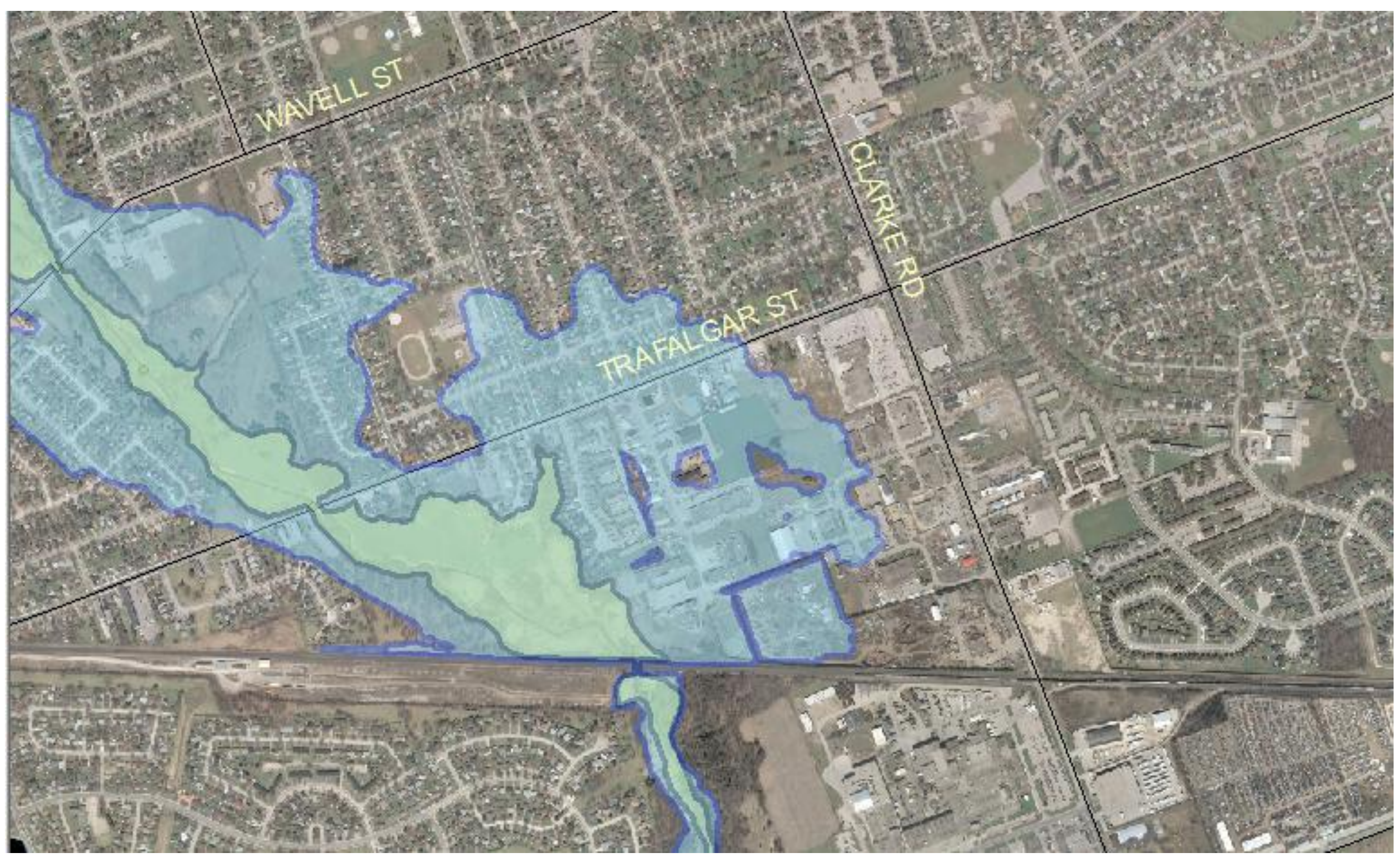

Figure 15: Damming of water behind culvert on Pottersburg Creek; 250 UTRCA and 250 CC_UB scenarios

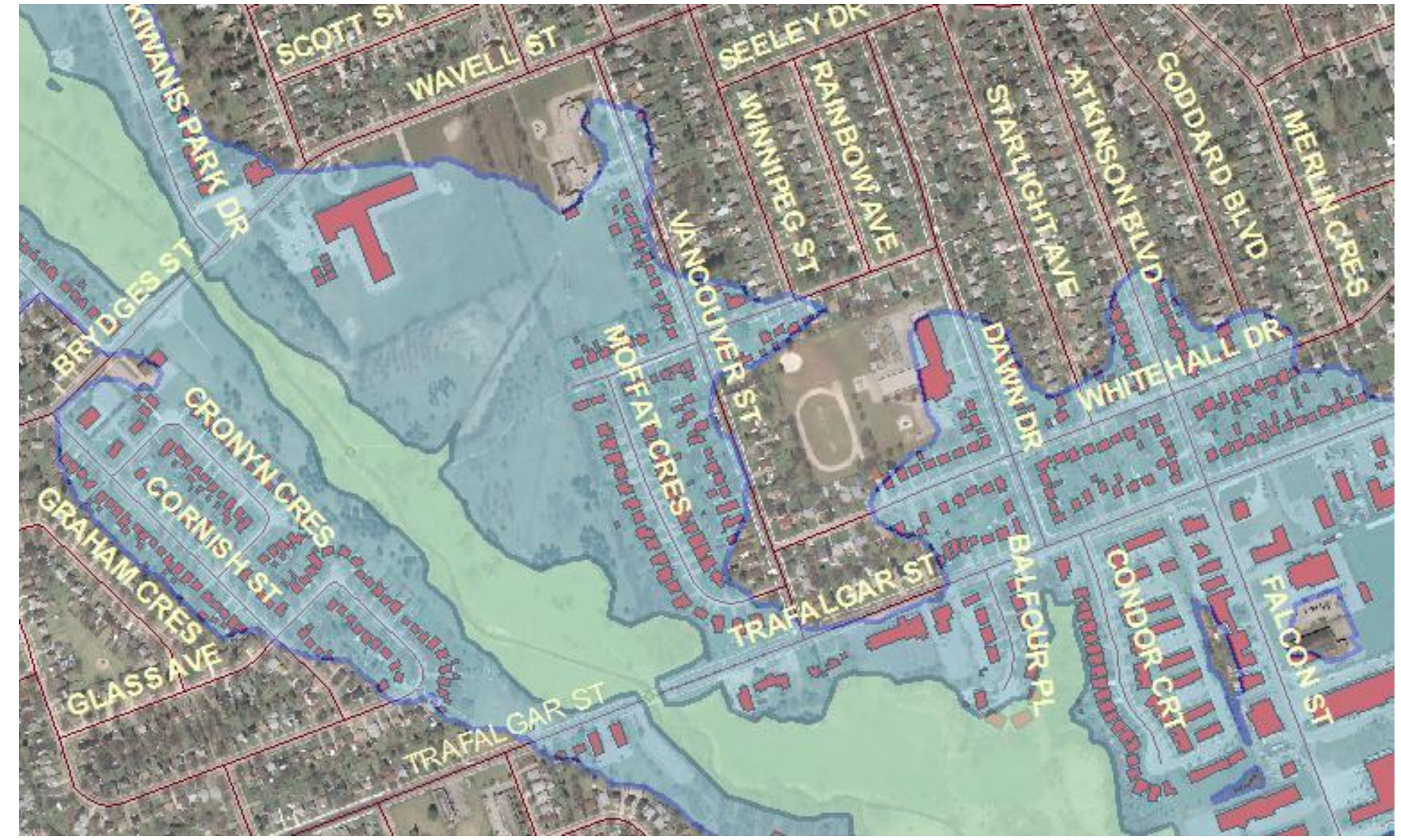

Figure 16: Inundation of building structures and roads along Pottersburg Creek; 250 UTRCA and 250 CC_UB scenarios

Figure 17: Inundation of building structures along Pottersburg Creek; 250 UTRCA and 250 CC_UB scenarios

Finally, the cell B5 shows the DA 35309859 with a high increase in risk due to climate change as a result of flooding of the Oxford and Veteran Memorial Parkway intersection and Oxford and Crumlin intersection. These are critical areas as they allow access to and from the London International Airport (see Figure 18). Additionally, the bridge along Oxford St. E., 3-BR-14 is inundated with a depth of approximately 1.4m over the bridge deck under the 250 CC_UB flood, which does not occur with the 250 UTRCA scenario. The bridges along VMP (3-BR-17) and Crumlin (3-BR-15) are not overtopped, but there is no clear space between the bottom of the deck and the surface of the water under the 250 CC_UB scenario.

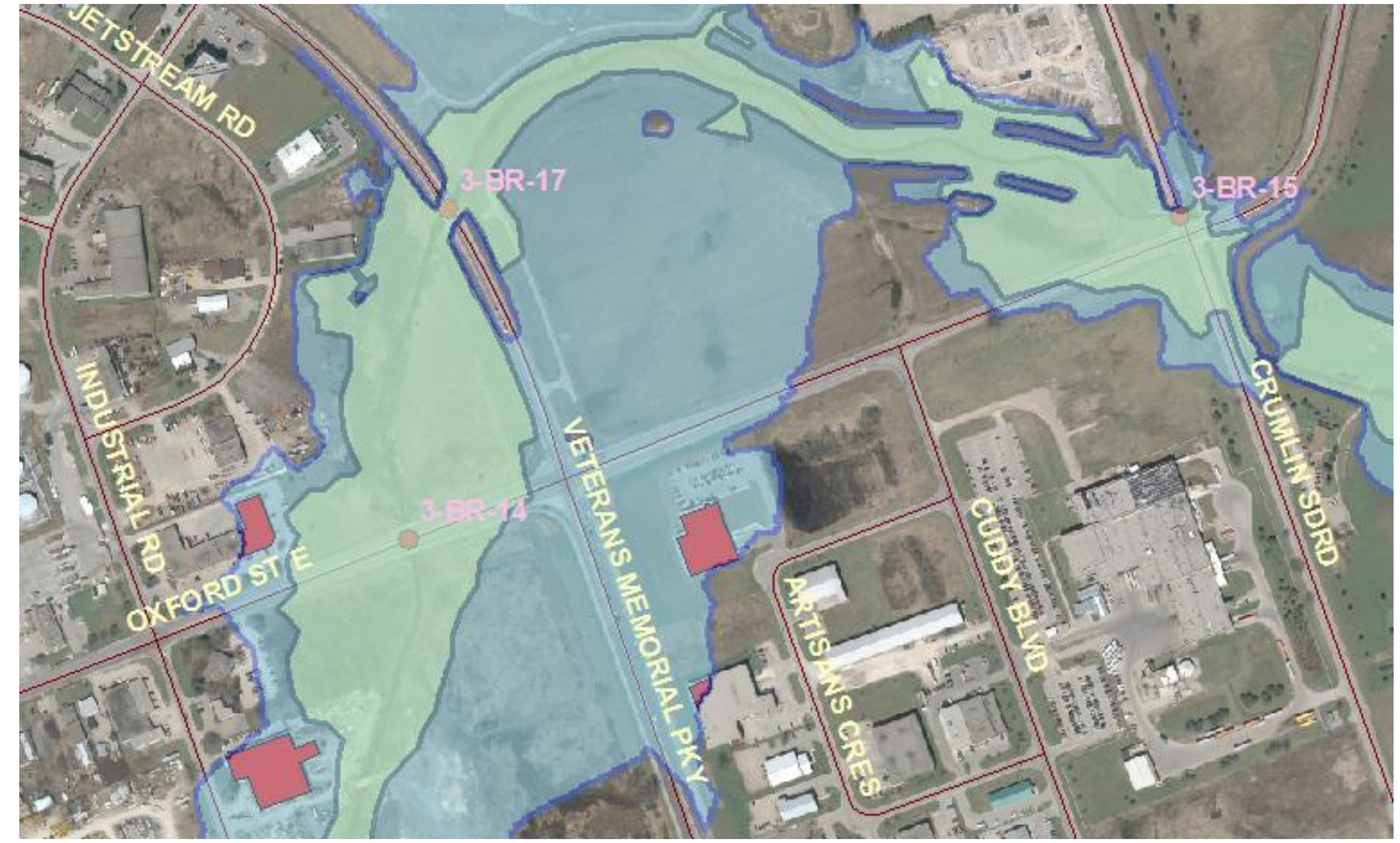

Figure 18: Inundation of critical transportation routes; 250 UTRCA and 250 CC_UB scenarios

Case 2: Comparison between 100 CC_LB and 100 CC_UB scenarios

Climate risk, in general, increased across the Thames River and Tributaries from 100 CC_LB to 100 CC_UB scenario illustrating the range of potential climate change impact on the 100 year regulatory floodplain. The citywide risk doubles across the 100 year scenarios (an increase in risk of 106%). This is shown in Figure 19 and Table 5. The most significant changes include region at the Forks of the Thames and along the stretch of North Thames before confluence with Stoney Creek. Areas for further investigation and discussion include:

(a) Cells B3/B4: Along North Thames before confluence with Stoney;
(b) Cell C3: Forks of Thames River;
(c) Cell C3: Dissemination Area 0706; and
(d) Cells C4/C5: Pottersburg Creek.

The inundation extent (area) and depth of Adelaide PCP is largely responsible for increased risk along North Thames before Stoney Creek in the 100 CC_UB scenario. In the 100 CC_LB scenario most of the plant and its structures are still operational and are not flooded. In the 100 CC_UB scenario, most of the plant (including primary and secondary clarifiers) become inundated resulting in raw sewage bypass, damage to structures and equipment and therefore increased risk. In general, PCPs contribute greatly to overall risk and therefore small changes in depth can result in large increases in risk.

Increased risk along the North Thames just before the Forks can be attributed to increased flood extent (area) behind the Broughdale dyke. As a result, more structures (approximately 70; mostly residential) are flooded. The depth of flooding for residential homes in general, also increases. Most residential homes experiences greater inundation depth under the 100 CC_UB scenario. Deeper floodwaters have greater potential to cause damage to structural components and building contents, leading to increased risk displayed in 100 CC_UB risk scenario. At the Forks downtown location, the 100 CC_LB scenario does not overtop the West London Dyke. The structures protected by the dyke are not flooded and no direct damages are expected due to overtopping. In the 100 CC_UB scenario, the elevation of the river exceeds the height of the dyke, causing widespread flooding of the area directly behind the dyke. This area is characterized by mainly residential homes and notably, an elementary school (Jeanne Sauve French Immersion Public School) which becomes inundated in the 100 CC_UB scenario. Therefore, risk behind the dyke significantly increases in the 100 CC_UB scenario as a result of expected damages to these buildings.

Table 5: 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

100 CC_LB vs. 100 CC_UB		
DAUID	Cell Index	% Increase
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

100 CC_LB vs. 100 CC_UB		
DAUID	Cell Index	% Increase
35390889	C3	0.9
35390890	C3	0.7

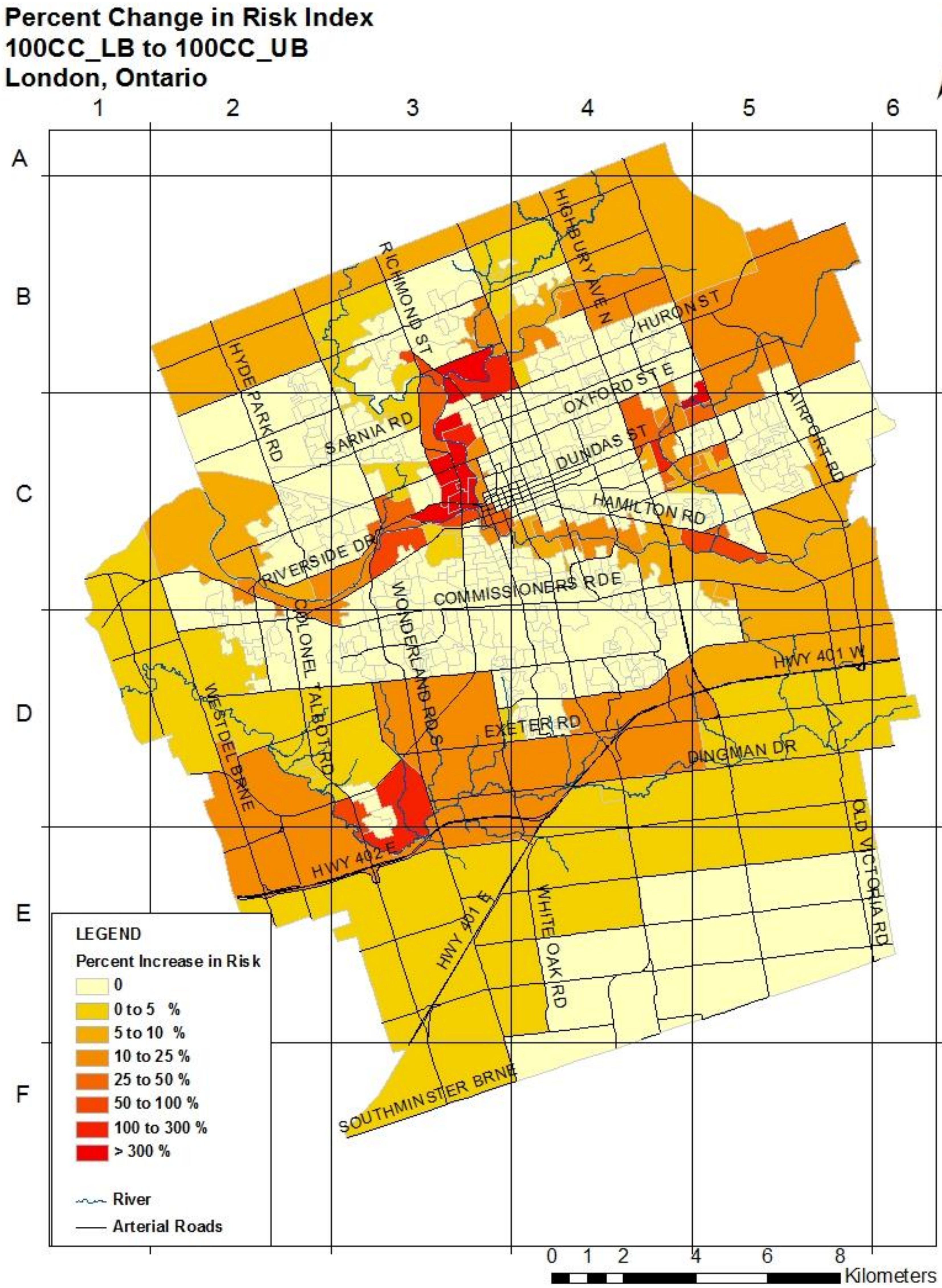

Figure 19: Percent change between 100 year climate change events

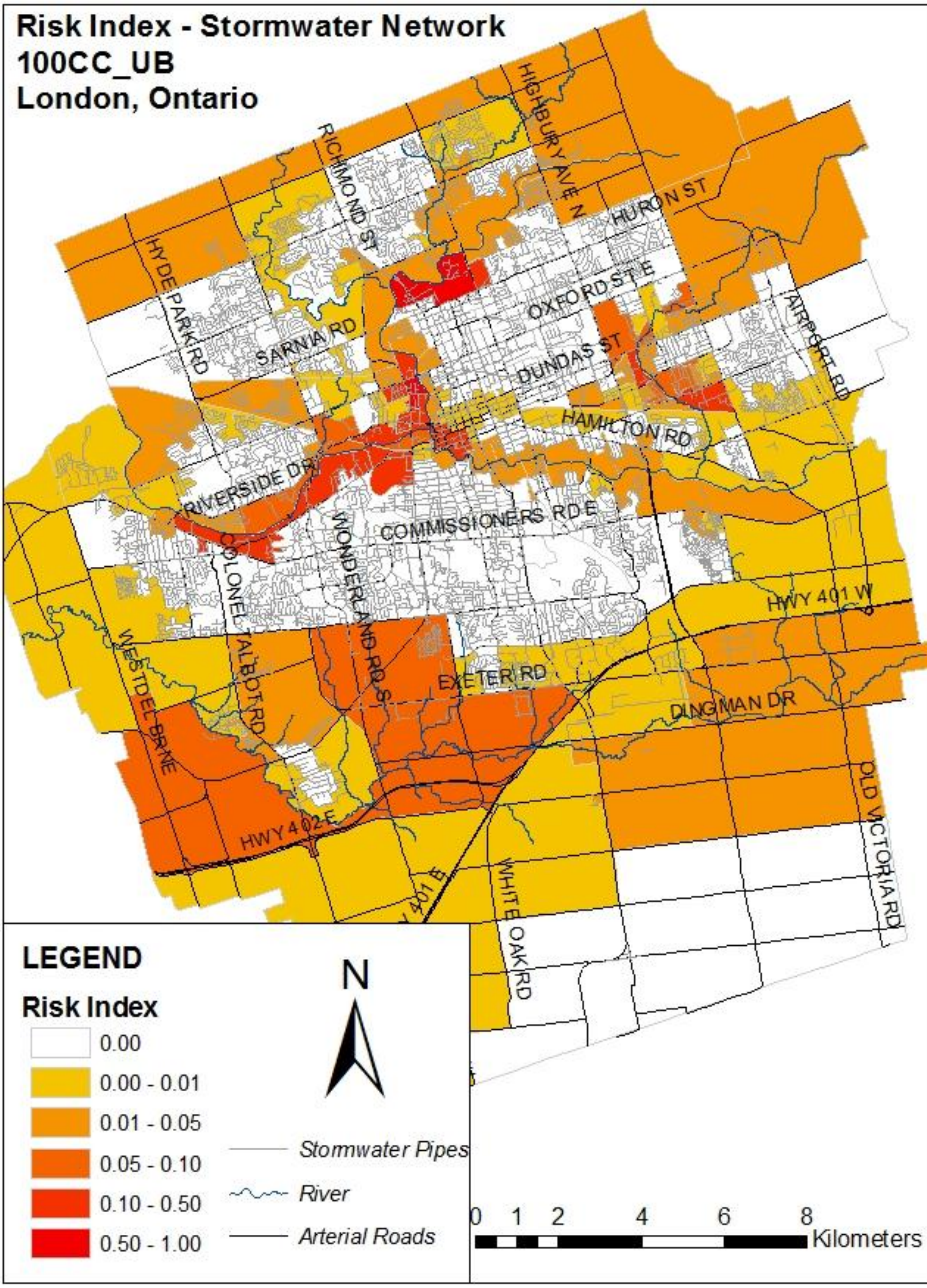

Figure 20: Stormwater Pipe Network under the 100 CC_UB scenario

Risk is almost double in the 100 CC_UB scenario at DA 0706 (Cell C3) as a result of increased floodwater depth and extent at Greenway PCP. The 100 CC_LB floodwaters encroach on the Greenway PCP property, but do not flood many structures or much equipment in the facility. The plant also remains fully accessibly during this flood scenario and it is expected that most of the functionality of the plant is able to be maintained during the flood event. Greenway PCP incinerates waste removed from sewage and in the 100 CC_UB scenario, the incinerated waste (ash) basins awaiting removal, likely to landfill or St. Mary's Cement (Environment Canada, 2010) become inundated causing potential water quality and health issues. Adelaide, Oxford, Pottersburg, Southland and Vauxhall PCPs haul their sludge to Greenway where sludge is kept in holding tanks awaiting dewatering and disposal (City of London, 2010). In the 100 CC_UB scenario, the plant is still accessible for receiving waste from other plants but one of the holding tanks is inundated, which may cause additional problems for disposal from all plants. Aeration tanks at Greenway also become overwhelmed in the 100 CC_UB scenario and flooding may influence the ability of the plant to treat wastewater. Biological processes in the aeration tanks are disrupted and effective removal of impurities may not be achievable and secondary bypass may be required.

The increase in risk at upstream locations of Pottersburg Creek is the consequence of floodwater backup behind a railway bridge (acting more like a culvert) that causes increased floodwater depth along the river banks and nearby properties. Between the 100 CC_LB and 100 CC_UB scenario, there are minimal changes in flood extent (<0.25km^2). It is the increase of depth that is largely responsible for increased damages to structures which are inundated in both climate scenarios.

The risk to Dissemination Area 0466 (Cells D3/E3) on West Dingman Creek increases from 100 CC_LB to 100 CC_UB scenario. Building risk remains relatively constant between the two scenarios as does the risk to roads, therefore most of the additional risk is potential damage to bridges; in particular the Wonderland Road Bridge (6-BR-08) and 7-BR-07. Wonderland Road Bridge experiences no risk under the 100 CC_LB scenario, but that is not the case in the 100 CC_UB scenario. Bridge 7-BR-07 does not incur any loss of function or structure in the 100 CC_LB scenario, but because of the increase in depth of water in the river in the 100 CC_UB scenario, this modifies the risk in the 100 CC_UB scenario and increases to an estimated 40% damage due to debris and scour.

Figure 20 shows an overlay of the stormwater sewer network (pipes) and the 100 CC_UB scenario. It can be seen from the figure that the majority of the sewer network lies outside the high risk areas. However, the area located to the east of the Forks (downtown London) is an area of high risk that also has a dense concentration of sewer pipes. Therefore recommendations are made that the pipes in this area be closely inspected and maintained to avoid further vulnerabilities.

Case 3: Comparison between the 250 CC_LB and 250 CC_UB Scenarios

The increase in risk from the 250 CC lower bound scenario to the upper bound scenario follows the same patterns as those demonstrated by the change in risk from the 250 UTRCA scenario to the 250 CC_UB scenario. Figure 21 and Table 6 show the changes in risk from the lower bound scenario to the upper bound scenario for the 250 year flood. The total increase in risk across the range of 250 scenarios is 46% what represents the range of potential climate change impact on the 250 year flood event. Areas of interest that show a high increase in risk are:

(a) Cell C4: Vauxhall PCP;
(b) Cell C3: Greenway PCP and North Thames near UWO;
(c) Cell B3: Confluence of Stoney Creek and North Thames, near Fanshawe and Adelaide;
(d) Cell B5: Pottersburg Creek near Airport; and
(e) Cells E3/E4 & D4/D5 Dingman Creek.

The inundation of the Vauxhall PCP increases from the lower bound to upper bound scenario. Under the lower bound scenario only 2 of the clarifiers are partially inundated. However, under the 250 CC_UB scenario all 4 of the clarifiers are within the floodplain boundary (see Figure 22). The increase in extent and depth contributes to a large increase in risk in the DA 35390106 which is located in Cell C3, south of Hamilton Rd between Egerton and St. Julien St. The light blue is the 250 CC_UB extent and the yellow is the 250 CC_LB extent.

Table 6: 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

250 CC_LB vs. 250 CC_UB		
DAUID	Cell Index	% Increase
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

250 CC_LB vs. 250 CC_UB		
DAUID	Cell Index	% Increase
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

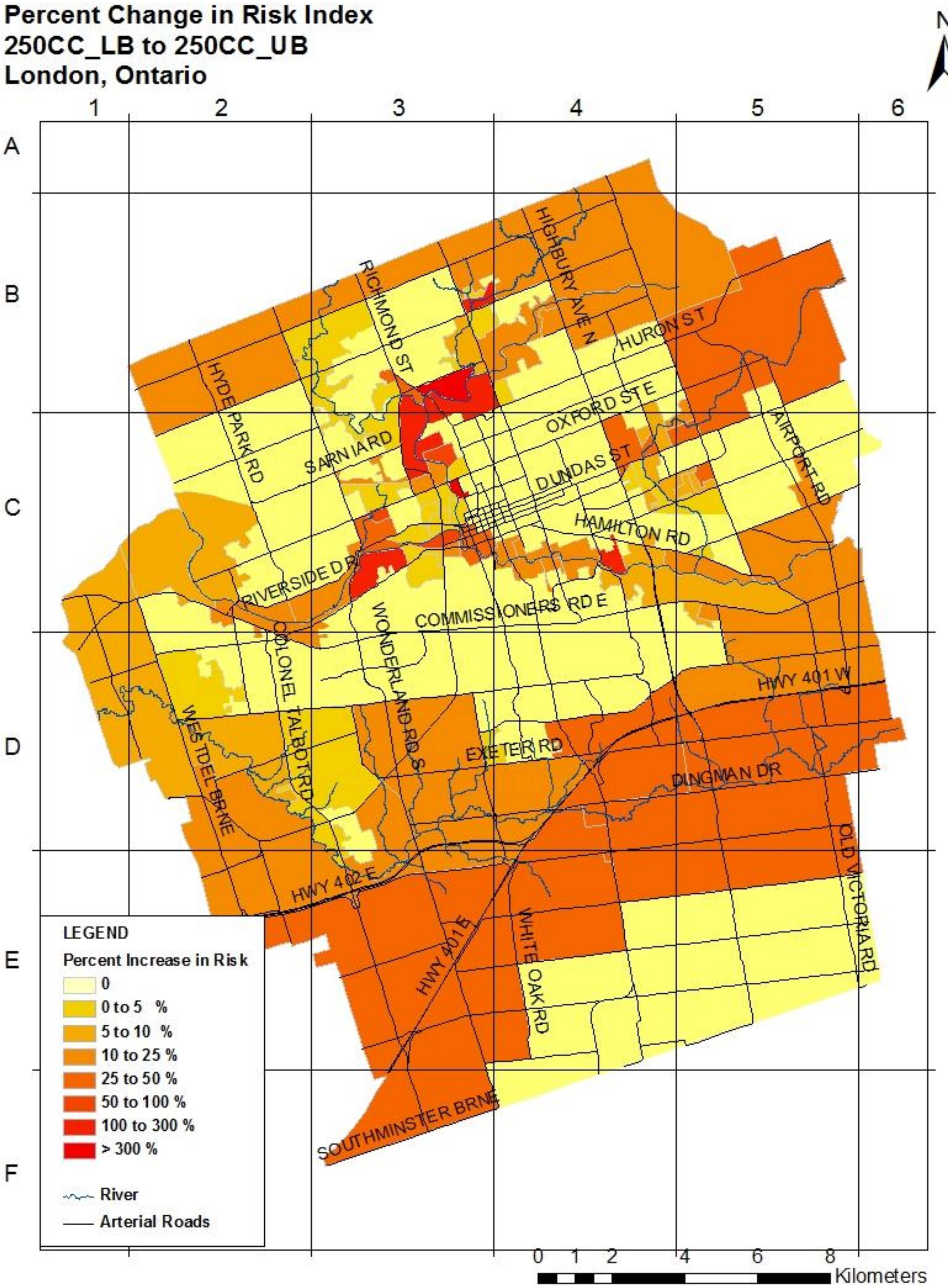

Figure 21: Percent change in risk between 250 CC_LB and 250 CC_UB scenarios

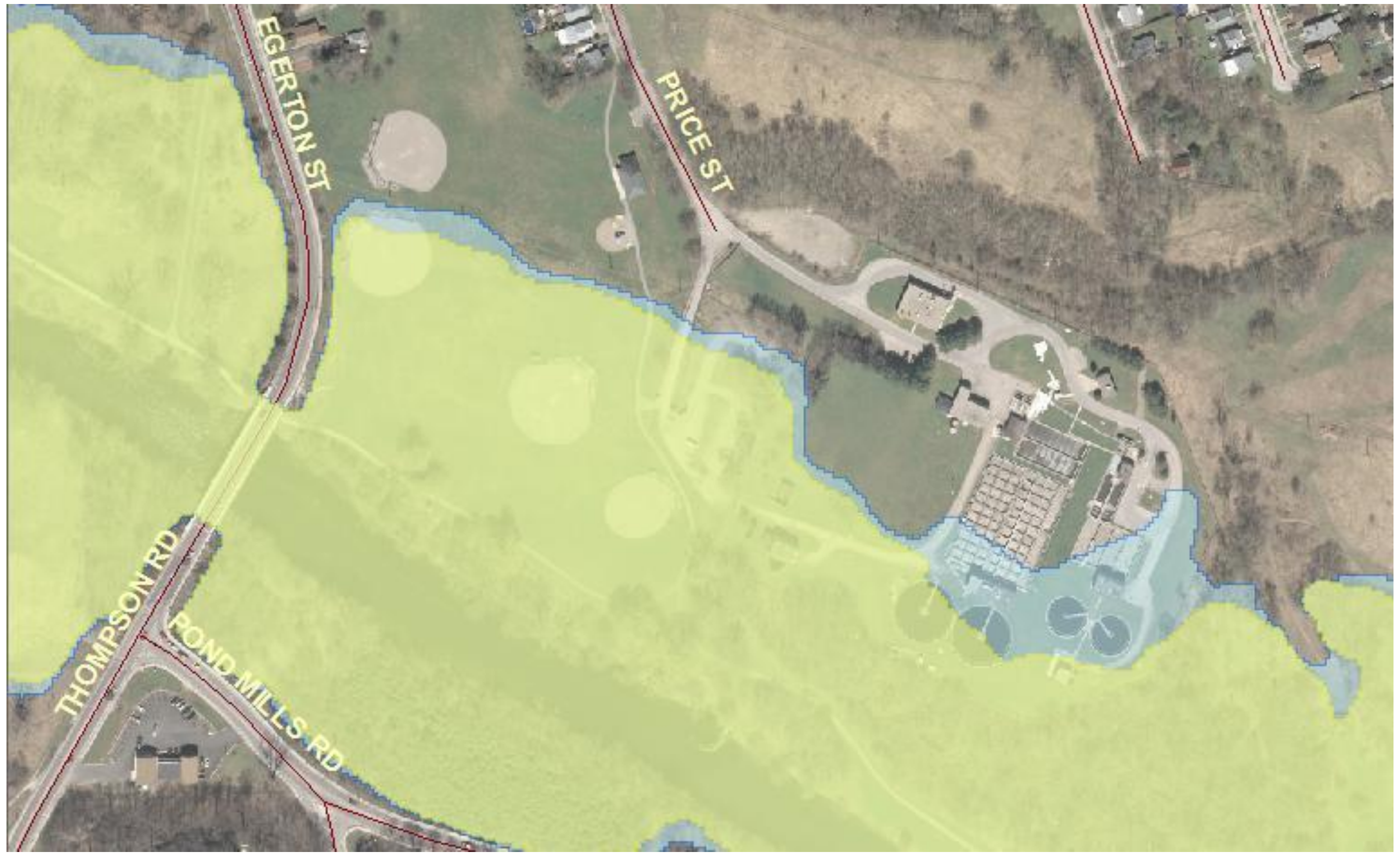

Figure 22: Vauxhall PCP inundation; 250 CC_LB and 250 CC_UB scenarios

Another PCP that experiences an increase in inundation across the range of 250 scenarios is Greenway (see Figure 23). Under the 250 CC_LB scenario the plant is barely inundated, with only a section of the aeration tanks under water. However, under the 250 CC_UB scenario, the entirety of the aeration section and a portion of the clarifiers is inundated. In addition, the access to the plant is inundated with approximately 0.3m of water. The incineration ash storage piles are also submerged.

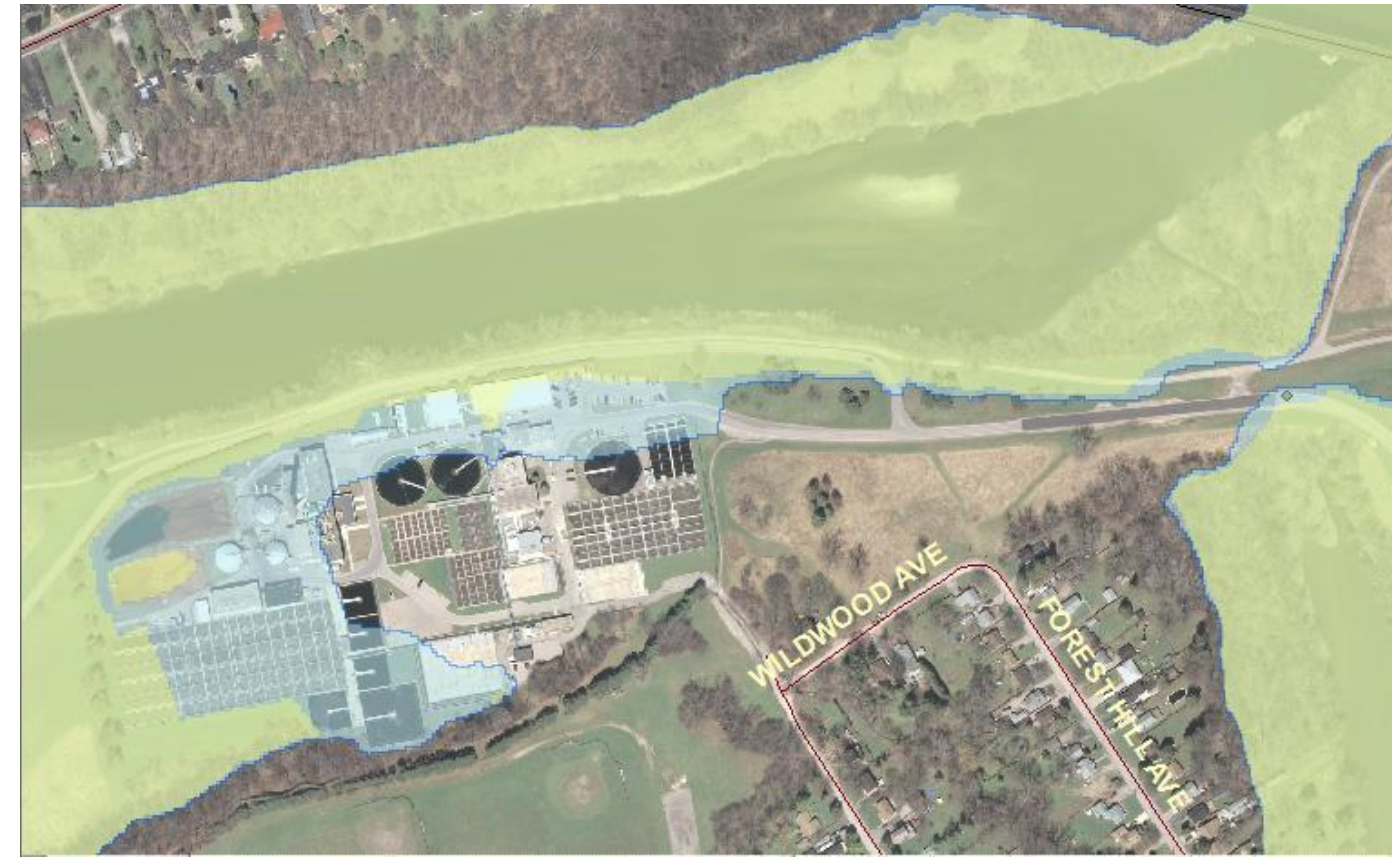

Figure 23: Inundation of Greenway PCP under 250 CC_LB and 250 CC_UB scenarios

Also within cell C3, the bridge along Wonderland Rd. S. (1-Br-09) is expected to incur greater damage in the UB scenario due to the decrease in clearance between the water surface and the bottom of the deck. However, the bridge is not overtopped in either scenario. Similarly, Wharncliffe Rd. bridge (1-BR-07) is likely to experience greater damage (but no overtopping) in the 250 CC_UB scenario. Some homes are flooded along Riverview Ave. and Evergreen Ave.

An increase in the flood extent between the two scenarios leads to greater building damage and risk. Areas that experience an increase in risk due mainly to building risk are: Goddard Blvd and Whitehall Drive (DA 35390071, C5); Dundas at First St. (DA 35390590, C4); and Industrial Rd. between Oxford and Page St. (DA 35390859, B5).
The increase in risk along Dingman Creek is due mainly to an increase in inundation depth for buildings and roads. The large size of the DAs along Dingman means that slight increases in risk will sum up to show the increase over a wide area.

One important area to note is DA 35390068, B5, which contains both Prince Charles Public School and St. Pious X Separate School (see Figure 24). Both schools are inundated in each scenario, however the increase in risk from one scenario to the next is only 7%.

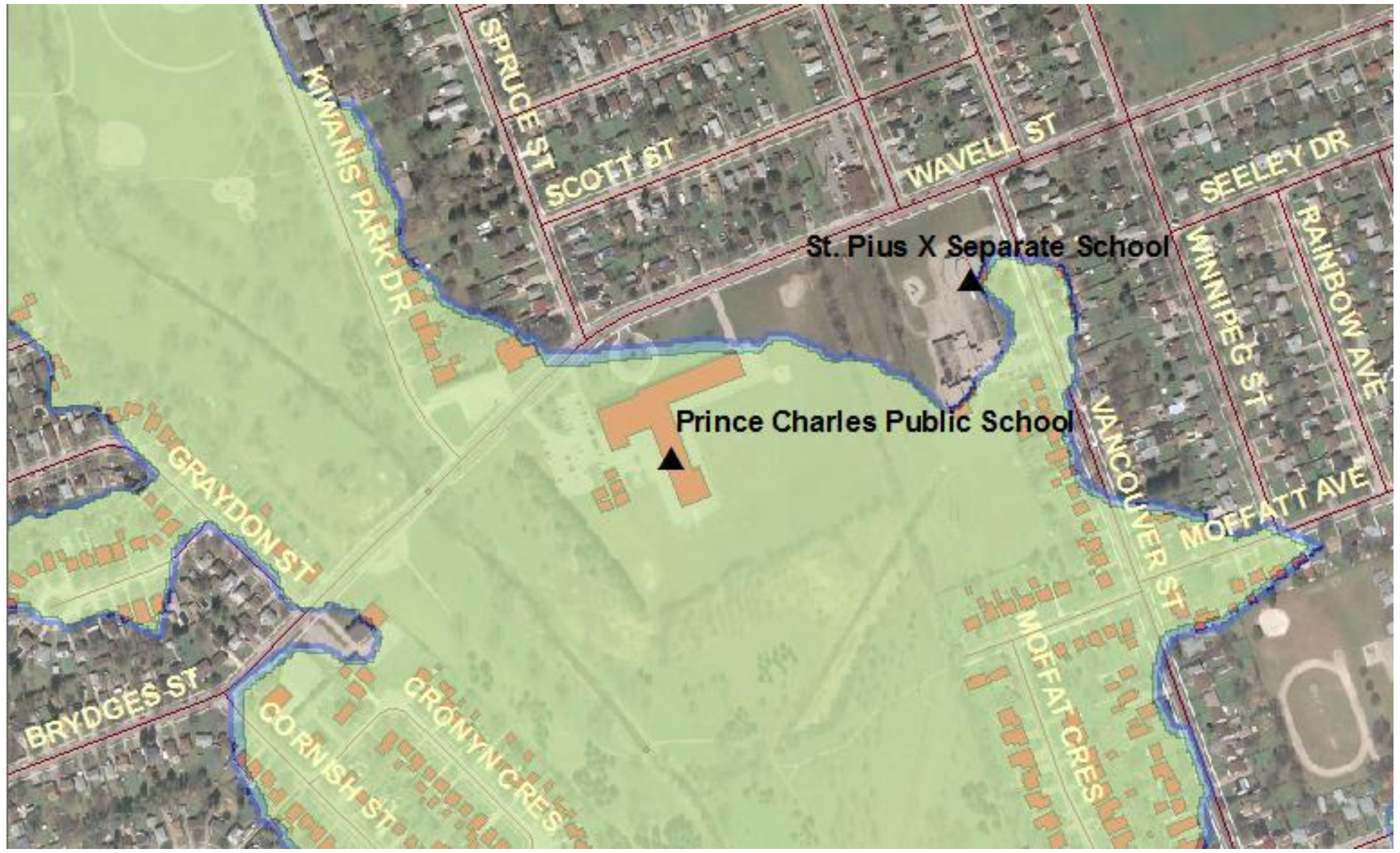

Figure 24: Inundation of schools; 250 CC_LB and 250 CC_UB scenarios

Case 4: Comparison between the 100 CC_LB and 250 CC_LB Scenarios

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. Figure 25 and Table 7 show the results for the lower bound comparison. The reason for the widespread decrease in risk from the 100 CC_LB to the 250 CC_LB is that despite the increase in flood extent and depth, the probability of the hazard occurring is much lower for the 250 year scenario. Since risk is a product of probability, hazard and damages, a lower probability will contribute to lower risk. The decrease is seen along Dingman Creek, Main Thames, South Thames, Medway and the majority of Pottersburg. The areas of increasing risk are the key areas to explore as these indicate damages that overcome the low probability – meaning that the potential for damage is so high, the risk to the area increases. These areas are:

(a) Cells C4 and C5: Along Pottersburg Creek where the extent of flooding increases such that DAs which had no flood damage in the 100 CC_LB now experience damage in the 250 CC_LB;
(b) Cell C3: Behind the WLD;
(c) Cell B3: Confluence of North Thames and Stoney Creek; and
(d) Cell D3: Dingman Creek near Hwy 402E and Wonderland Rd. S. (DA 35390466).

Table 7: 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

100 CC_LB vs. 250 CC_LB		
DAUID	Cell Index	% Change
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

100 CC_LB vs. 250 CC_LB		
DAUID	Cell Index	% Change
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

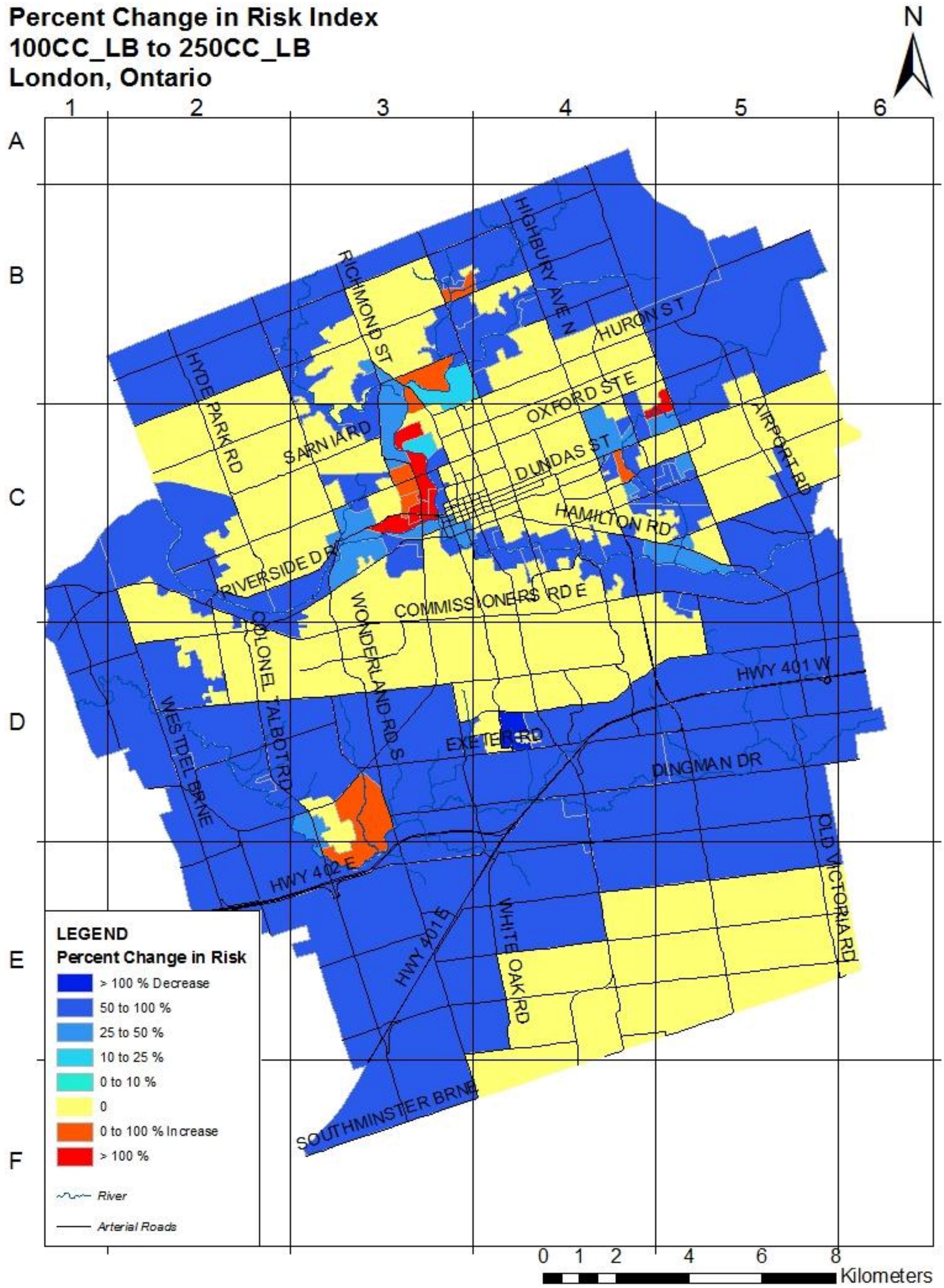

Figure 25: Change in risk between 100 CC_LB and 250 CC_LB scenarios

In the Pottersburg Creek area (cells C4 and C5) there is an increase in flooding extent such that buildings become inundated in the 250 CC_LB scenario that were not in the 100 CC_LB. Thus the risk to these areas increases. This is seen in DA 35309064, C4 (between Dundas St., Pottersburg Creek, Brydges St. and Hale St.) and DA 35390660, C5 (bounded by Parkhurst Ave., Third St., Culver Dr. And Clarke Rd.) - see Figure 26.

Figure 26: Inundation at Pottersburg Creek; 100 CC_LB and 250 CC_LB scenarios

The largest area of increase in the area behind the West London Dyke (Cell C3) near the Forks. This increase in risk is due to the fact that under the 100 CC_LB scenario the water does not overtop the dyke. However, in the 250 CC_LB scenario, the dyke is overtopped, leading to the flooding of the area (as shown in Figure 27) bounded by the North Thames, Main Thames, Oxford St. W. and the ravine just east of Woodward Ave. The areas showing highest risk are those east of Wharncliffe.

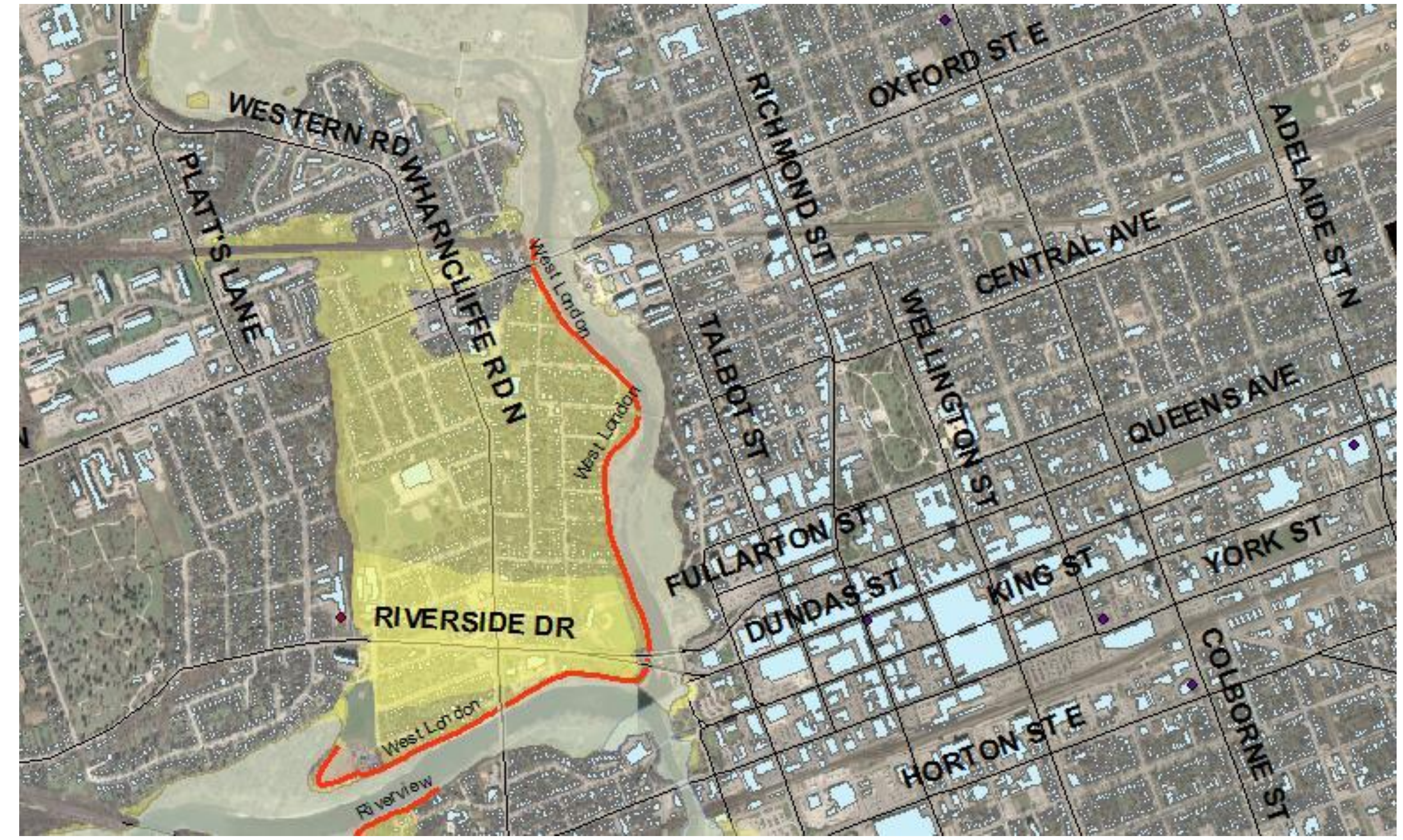

Figure 27: Inundation behind the West London Dyke - 100 CC_LB and 250 CC_LB scenarios

At the confluence of Stoney Creek and North Thames (Cell B3) there is a slight increase in risk due to an apartment building of Fanshawe Park Rd. which becomes inundated under the 250 CC_LB scenario. In addition, the Stoney Creek footbridge (2-FB-02) is inundated at a depth increase of 10cm between the scenarios. The 100 CC_LB scenario does not inundate the bridge; however the 250 CC_LB scenario reaches the capacity of the bridge opening, causing more damage.

Case 5: Comparison between 100 CC_UB and 250 CC_UB scenarios

In the comparison map, increases and decreases in risk are both observed between the 100 CC_UB and 250 CC_UB scenarios. This is shown in Table 8 and Figure 28. The total decrease in risk across the city is 47%. One general observation is that many bridges (particularly on Stoney and Pottersburg Creeks) expect to see flood waters reach and surpass the height of the deck. This puts a great deal of pressure on the bridges and many require extensive recovery and maintenance after flooding. Another general observation is that those areas which experience a high decrease in risk (>100% decrease as indicated by map legend) are a result of similar flood extent as the 250 CC_UB scenario, but because the 100 CC_UB scenario is more *likely* to happen, the risk index value due to this scenario often supersedes the additional flood extent of the 250 CC_UB scenario. However, there are areas of particular interest where even given the increased likelihood of the 100 CC_UB event, the 250 CC_UB risk is still higher.

Table 8: 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

100 CC_UB vs. 250 CC_UB		
DAUID	Cell Index	% Change
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

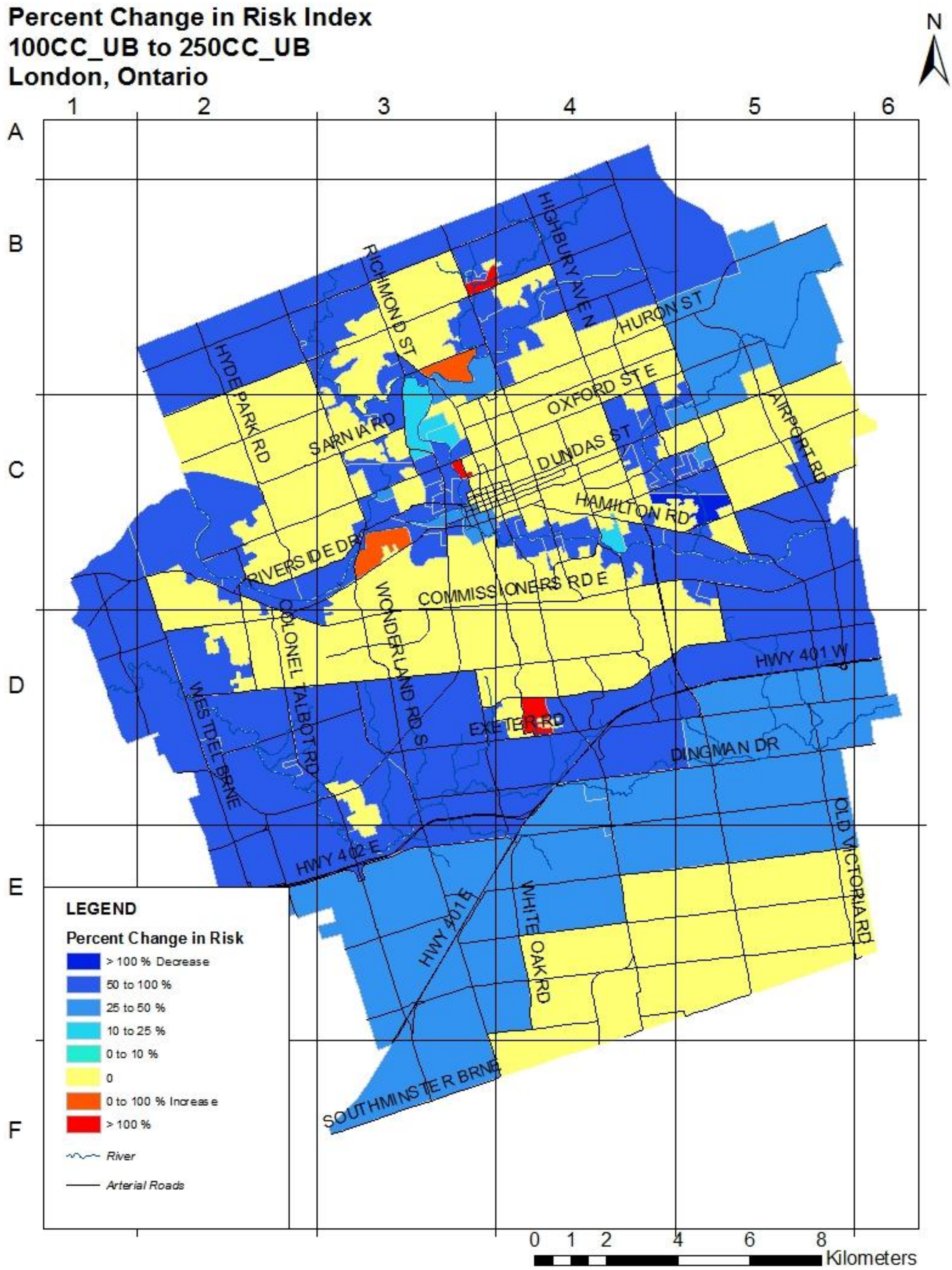

Figure 28: Change in risk index value between 100 CC_UB and 250 CC_UB scenarios

Key areas of interest include:

(a) Cell B3: DA 0669 on Stoney Creek;
(b) Cell B3: DA 0032 on North Thames;
(c) Cell C3: DA 0541 on North Thames;
(d) Cell C3: DA 0706 along Main Thames; and
(e) Cell D4: DA 0671 on Dingman Creek.

The flood extent is larger for the 250 CC_UB scenario in DA 0669 (Cell B3) on Stoney Creek. The road bridge crossing Stoney Creek middle reach (2-BR-11) is supported by a single pier. The bridge is expected to incur some damage as a result of high flood waters. Depth of water at the bridge under 250 CC_UB scenario is approximately 20cm higher than the 100 CC_UB scenario, but overall the risk index value is higher for the 100 CC_UB scenario because of the greater probability of the 100 year event to occur. Under both climate scenarios, the Stoney Creek Footbridge (2-FB-02) crossing the middle reach of Stoney Creek experiences water up to the bridge deck. Expected damages are higher in the 250 CC_UB scenario, but the 100 CC_UB scenario is more likely to occur (higher probability) and therefore the risk to the footbridge is higher in the 100 CC_UB scenario. The 250 CC_UB flooding inundates four additional apartment buildings not flooded in the 100 CC_UB scenario. The expected damages to these buildings are higher than the contribution to risk by the more likely 100 CC_UB scenario, thus the increase in the DA is in direction of the 250 CC_UB scenario. Road bridge on the lower reach (2-BR-09) has two piers that contribute to potential damage to the structure. Similar to the earlier bridge, some damage is expected as a result of high flood waters. Depth of flood water in the 250 CC_UB scenario is approximately 15cm higher than the 100 CC_UB scenario, which does not greatly contribute to difference in risk between the two scenarios. The 100 CC_UB scenario is still associated with greater risk because of the greater likelihood of the flood event.

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.

Under 250 CC_UB scenario, DA 0541 (Cell C3) is almost triple the risk factor than in the 100 CC_UB scenario. The flood extent is larger in the 250 CC_UB scenario and there are three more buildings flooded in this scenario; a community hall/Polish Association, office buildings and a retail glass store. These commercial buildings contribute greatly to the risk factor value in this DA and are the driving factors behind very high risk associated with 250 CC_UB scenario.

DA 0706 (Cell C3) on the Main Thames River increases in risk under the 250 CC_UB scenario. This is a result of increased flood extent at Greenway PCP. In 100 CC_UB scenario, the plant is able to maintain partial functionality as primary treatment processes appear relatively unaffected by the flooding. Waste (ash) disposal is impeded in both climate scenarios, for the piles are submerged. Under 250 CC_UB scenario, some of the primary treatment components are inundated, requiring complete bypass of raw sewage from the plant into the Thames River. This decreases the quality of water in the river and has the potential for detrimental environmental and health consequences. Access in the 250 scenario is also restricted. There is only a single access point into the plant and this road becomes inundated in the 250 CC_UB scenario. This affects the functionality of the plant and delays response and recovery actions. In the 250 CC_UB scenario, there are some PCP buildings that become flooded. Some of these buildings contain administrative work and records while others are directly related to proper treatment processes of the PCP. The inundation of these buildings causes additional damage to the plant.

DA 0671 along Dingman Creek displays high increase in risk from 100 CC_UB scenario to 250 CC_UB scenario. The DA does not actually incur any risk under the 100 CC_UB scenario, but because there is a small amount of risk associated with it under the 250 CC_UB scenario, the relative change in risk appears to be large. The risk is solely attributed to the height of floodwaters in the river increasing and contributing to risk of a culvert (6-CU-26) bordering the DA. Under 100 CC_UB scenario, the water level in the river is not expected to inflict significant damage to the culvert, however in the 250 CC_UB scenario, the water level is 0.93m from the bottom of the bridge deck. This is closer than the critical threshold of 1m (the level at which river debris may cause damage to a bridge or culvert). As a result of crossing this critical threshold, culvert 6-CU-26 incurs damage and contributes to the risk of DA 0671.

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6.0 Preliminary Recommendations

The results of the study provide insight in the climate change-caused flood risk to municipal infrastructure. Various recommendations are provided to assist the City of London in developing a viable climate change adaptation policy. Recommendations are classified into three major themes: (i) engineering; (ii) operational; (iii) policy and regulatory. Although they have been classified, there are recommendations that may cross these themes.

6.1 Engineering recommendation

Recommendation E1 - The region behind the Broughdale dyke is at high risk. Possible alternatives to mitigate this risk include: raising the height of the dyke; extending the dyke east to prevent encroaching floodwaters; floodproofing structures behind the dyke; temporary sandbagging efforts to increase the height of the dyke in the case of a flood event; regular maintenance and inspection. It is recommended that the area behind the dyke that may be affected be prepared for the possibility of dyke failure. This should be included in emergency plan and preparedness for this area.

Recommendation E2 - The area behind the West London dyke is at high risk. The recent repair of the dyke will contribute to its safety but will not prevent the protection from climate change-caused flooding. It is recommended that the repair of remaining sections of the dyke be completed together with: floodproofing structures behind the dyke; development of the detailed emergency management plan for temporary sandbagging efforts to increase the height of the dyke in the case of a flood event; and regular maintenance and inspection. It is recommended that the detailed emergency management planning is in place for the area behind the dyke that may be affected by the possible dyke failure.

Recommendation E3 - The CN rail embankment in Pottersburg Creek (southwest of Trafalgar St. and Clarke Rd.) backs up floodwaters and behaves like a dam. This phenomenon does not occur to such an extent in the 250 UTRCA scenario and this contributes to the great difference in risk to areas upstream of the culvert. Infrastructure not inundated in the 250 UTRCA scenario becomes inundated in the 250-yr climate change scenarios, creating the large difference in risk for DAs upstream. This is an area of high concern and a more detailed hydrologic and hydraulic study is suggested for this location. Culvert modifications and alternatives may need to be considered to mitigate the high risk of flooding. It is recommended that this region considers the use of 100 CC_UB scenario for floodplain management, decision making and regulations to capture the high risk nature of this area.

Recommendation E4 - The City would benefit from improved data collection, data documentation and data dissemination procedures. All infrastructure data should be kept in a database with consistent format and documentation procedures.

Recommendation E5 - Increasing the number of flow monitoring stations across the City may provide better input into risk assessment and provide real-time data related to flood hazard. This has potential to allow sufficient time to disseminate flood warnings and prepare for disaster management.

Recommendation E6 - Due to the variability and inconsistency in bank slopes and over-water infrastructure, it is recommended that the City resurveys the bridges and bank slopes within the City boundaries; the City should consider updating their topographic information. This would improve hydraulic calculations, floodplain accuracy and provide a more representative risk assessment.

Recommendation E7 - It is recommended that the City continue to expand the infrastructure considered in the risk analysis. Infrastructure selection for this study is driven by data availability and quality. As more detailed data becomes available the City is recommended to continue efforts to extend the risk analysis to include other infrastructure types such as public utilities, sanitary sewer networks and storm sewer networks.

Recommendation E8 - The flood scenarios considered in this risk assessment are all static events, that is, they are a snapshot of the flood at a moment in time. The City would benefit from a dynamic simulation model and risk assessment procedure to help capture the dynamic nature of flood events. Overland flow modeling would change the nature of the flood and provide additional flood impacts. There may be regions outside of the floodplain that flood as well which would require extensive overland flow analysis. This could contribute to a more complete flood model and risk assessment.

6.2 Operational recommendations

Recommendation O1 - Pollution Control Plants (PCPs) would benefit from a detailed emergency plan with regards to the critical flood scenarios in this study. In the event of a flood Greenway, Adelaide, Vauxhall and Pottersburg PCP may have limited access. There should be preparatory procedures in place to maintain safety (or potentially evacuation) at the plant. Access may also be restricted in the recovery phase of flooding due to unfavorable road conditions and should be considered in recovery plan. To maintain functioning capacity during a flood event it is recommended that all four of the aforementioned PCPs raise or make mobile their essential operational equipment. In the event of a flood these equipment will experience less damage and be able to maintain partial functionality. Any of these PCPs in the recovery stages of a flood may not be able to run at full capacity. It would be beneficial to have a flood recovery plan outlining procedures to manage and maintain the plant during this stage.

Recommendation O2 - Bridges with piers are greatly affected by scour during flood situations; it is the single most important parameter for bridge failure during high water events. Thus, it is recommended that bridges with piers be closely monitored on a regular basis for signs of scour and pier degradation; with particular emphasis on monitoring before and after a flood event of both 100 and 250 year magnitude.

Recommendation O3 - The City is advised to maintain detailed historical records of damages during high water events for all critical facilities and city-owned infrastructure. Damages to building structure, foundation, equipment, contents and lost profits can be used to improve flood damage estimates and modify flood risk assessment.

Recommendation O4 - Four schools are affected in the flood scenarios; Prince Charles Public School, Princess Anne French Immersion Public School, St. Pius X Separate School and Jeanne Sauve French Immersion Public School. These schools should have very detailed protocol and procedure in case of a flood event. These schools would benefit from a program and training in emergency response for all staff and students. It is important that there is organization and preparedness in the response to natural hazards to avoid confusion and chaos.

Recommendation O5 - Monitoring and regular inspection of the Broughdale and the West London dykes will have to be strengthen due to the fact that they will be overtopped by the climate change-caused floods.

6.3 Policy recommendations

Recommendation P1 - The City is recommended to fund additional studies related to the response of bridges and pollution control plants at high risk to better understand their response to flooding and potential risk-reducing measures.

Recommendation P2 - Infrastructure may also be affected by other climate change factors including temperature extremes and shifts in freeze/thaw cycles, among others. The City is recommended to investigate these other climate change factors that may affect the region and further impact municipal infrastructure.

Recommendation P3 - This study did not directly consider sanitary and storm network infrastructure in risk assessment but it is recommended that those areas considered at high risk which also contain a dense network of sanitary and storm infrastructure should be investigated. The additional pipe infrastructure may result in even higher risk to these areas and these pipe networks should be regularly inspected.

Recommendation P4 - It is advised that the City considers both the risk to municipal infrastructure and social vulnerability when addressing climate change adaptation and planning strategies. Although the purpose of this study is to assess the effects of flooding on municipal infrastructure, it is important to mention that physical structures are not the only element at risk during a flood event. Natural disasters have very significant social impacts as well. It is the combination of both infrastructure and social risk that could change the magnitude and spatial distribution of risk. When intersected with high infrastructure risk regions, these are areas of particular concern and both infrastructure and social risks require attention. One of these cases includes the Coves. Although this region was classified at risk, the region does not appear to experience one of the highest risks. However, the region is dominated by trailer homes, most of which require complete reconstruction after any of the flood scenarios considered in this study. These trailer homes may not be worth as much as residential structures in other flooded areas, therefore the region will show lower risk. However the people living in the Coves may be especially vulnerable. The entire community may be inundated and recovery can be especially difficult for those with limited access to resources. This is why it is important to consider social risk in combination with infrastructure risk before making any critical decisions based on this study's analysis.

Recommendation P5 - This study indicates that there is a need to consider future regulations and possible change of the regulatory floodplain to include impacts of climate change. An economic analysis is recommended to assess the consequences of changing regulations and perform the cost-benefit analysis using the results of this study – to find out the cost of risk reduction.

Recommendation P6 - The final recommendation is to initiate the process of change of the infrastructure design criteria to include climate change impacts. Risk increase identified in this study points out that the future infrastructure will have to be designed to withstand the potential impacts of climate change. This recommendation should complement the recommendation P3.

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