8-15-2019 10:00 AM

A Methodology for Assessing Dynamic Resilience of Coastal Cities to Climate Change Influenced Hydrometeorological Disasters

Angela Peck, *The University of Western Ontario*

Supervisor: Simonovic, Slobodan P., *The University of Western Ontario*

A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Civil and Environmental Engineering

Abstract

Confronted with rapid urbanization, intensified tourism, population densification, increased migration, and climate change impacts, coastal cities are facing more challenges now than ever before. Traditional disaster management approaches are no longer sufficient to address the increased pressures facing urban areas. A paradigm shift from disaster risk reduction to disaster resilience building strategies is required to provide holistic, integrated, and sustainable disaster management looking forward. To address some of the shortcomings in current disaster resilience assessment research, a mathematical and computational framework was developed to help quantify, compare, and visualize dynamic disaster resilience. The proposed methodological framework for disaster resilience combines physical, economic, engineering, health, and social spatio-temporal impacts and capacities of urban systems in order to provide a more holistic representation of disaster resilience.

To capture the dynamic spatio-temporal characteristics of resilience and gauge the effectiveness of potential climate change adaptation options, a disaster resilience simulator tool (DRST) was developed to employ the mathematical framework. The DRST is applied to a case study in Metro Vancouver, British Columbia, Canada. The simulation model focuses on the impacts of climate change-influenced riverine flooding and sea level rise for three future climates based on the results of the CGCM3 global climate model and two (2) future emissions scenarios. The output of the analyses includes a dynamic set of resilience maps and graphs to demonstrate changes in disaster resilience in both space and time. The DRST demonstrates the value of a quantitative resilience assessment approach to disaster management. Simulation results suggest that various adaptation options such as access to emergency funding, provision of mobile hospital services, and managed retreat can all help to increase disaster resilience. Results also suggest that, at a regional scale, Metro Vancouver is relatively resilient to climate change influenced-hydrometeorological hazards, however it is not distributed proportionately across the region. Although a pioneering effort by nature, the methodological and computational framework behind the DRST could ultimately provide decision support to disaster management professionals, policy makers, and urban planners.

Keywords

climate change adaptation; geographic information systems; hydro-meteorological disaster management; resilience quantification; system dynamics simulation

Summary for Lay Audience

Coastal cities are facing more challenges now than ever before. Traditional disaster management approaches are no longer sufficient to address the increased pressures facing urban areas. A shift from disaster risk reduction to disaster resilience building strategies is required to provide sustainable disaster management. Disaster resilience is the ability of a system (like a city) to respond and recover from a disaster and includes conditions that allow the system (city) to "bounce back". In order to address some of the shortcomings in existing research, a framework was developed to help quantify, compare, and visualize dynamic disaster resilience. The proposed framework combines physical, economic, engineering, health, and social impacts to determine a city's resilience in time and space. A tool like the one presented in this dissertation can assist emergency planners and decision makers in preparing for, and responding to, disaster situations.

A computerized tool was developed to employ the framework. This tool uses local data related to buildings, people, cell phone towers, power distribution, and the economy to simulate how various city systems behave before, during, and after a flood event. The tool outputs graphs and maps to show the changes in both time and space. The results demonstrate the value of a quantitative resilience assessment approach to disaster management. The results for a case study in Metro Vancouver, BC, Canada shows that emergency funding, provision of mobile hospital services, and managed retreat can all help increase disaster resilience. The framework used to develop the tool could ultimately provide decision support to disaster management professionals, policy makers, and urban planners.

Co-Authorship Statement

This Monograph format thesis dissertation was written in its entirety by the author. The author also produced all of the figures shown herein except where indicated by citation. Although this is an original dissertation, the content contained herein was based on work completed by the author in collaboration with others as follows:

Paper 1

The non-threshold dynamic resilience definition (presented in Chapter 3, sections 3.2.1 and 3.2.2) was published in a paper by the author in collaboration with Professor S.P. Simonovic in the following article:

Simonovic, S.P. and Peck, A. (2013). *Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities – Quantification Framework.* British Journal of Environment and Climate Change, 3(3): 378-401.

The contributions of Simonovic and Peck were about 60% and 40%, respectively. The conceptual development of the space-time dynamic resilience measure (STDRM) and production of the manuscript was primarily led by S.P. Simonovic. The discussion on the implementation of the STDRM through the Resilience Simulator Tool was primarily led by A. Peck. A. Peck also contributed to the production of the manuscript, primarily in the description of system impacts and production of the manuscript figures and provided review and feedback on the manuscript submission.

Paper 2

A tight-coupling approach was used in this dissertation (discussed in Chapter 4, section 4.2.4) to provide the required capacity for handling bidirectional and synchronized interactions of operations between system dynamics (SD) and Geographic Information System (GIS). This approach was initially illustrated in a fictitious spatial system dynamics (SSD) environment called Daisyworld, published by the author in collaboration with C. Neuwirth and S.P. Simonovic in the following article:

Neuwirth, C., Peck, A. and Simonovic, S.P. (2015). *Modeling Structural Change in Spatial System Dynamics: A Daisyworld Example*. Environmental Modelling & Software, 65:30-40.

The contributions of Neuwirth and Peck were equal; both contributed to the conceptual development of SSD, implementation of SSD (Python programming), and production of the manuscript. S.P. Simonovic initiated the collaboration, offered guidance, and provided review and feedback on the manuscript.

Paper 3

In addition, the author was involved in collaborative efforts pertaining to the implementation of spatio-temporal simulation models in the following article:

Neuwirth, C., Hofer, B. and Peck, A. (2015). *Spatiotemporal Processes and their Implementation in Spatial System Dynamics Models*. Journal of Spatial Science, 12pp. Doi: 10.1080/14498596.2015.997316.

In this work, the contributions of Neuwirth and Hofer were much more significant than the contribution of Peck (10%). Neuwirth and Hofer led the discussion and categorization of SSD process models, produced a hypothetical model of flow processes and landscape evolution, and led the production of the manuscript. A.Peck's primary contributions consisted of conceptual SSD simulation modelling (through previous work of Neuwirth, Peck, and Simonovic (2015)); implementation assistance (through Vensim-Python programming) and the review, feedback, and editing of the final manuscript submission. This article is referenced in this dissertation, forming part of the literature review of SSD processes (Chapter 4, section 4.2.4), but is otherwise not explicitly used in this dissertation.

Acknowledgments

You'll have to bear with me, as over the course of my many years at Western I have come into contact with many magnificent and supportive people; some of whom I'd like to mention here.

First, I'd like to thank all of the staff, faculty, and students whom I've had the pleasure of meeting for all of their support both in my research and teaching endeavors. Over the years I've been fortunate to be a part of Western community in the capacity of an undergraduate student, graduate student, TA, and instructor; all experiences I have immensely enjoyed and will never forget. I have learned a lot from you all and endeavor to continue learning.

My PhD research provided me the opportunity to be a part of an international and interdisciplinary initiative called Coastal Cities at Risk (CCaR). I'd like to thank all of my CCaR colleagues for their collaboration and contributions. A special thanks to the teams from the Philippines and Thailand for hosting me in your beautiful countries; the experiences were unforgettable.

I would also like to thank IDRC, along with Canadian Institute of Health Research (CIHR), Natural Sciences and Engineering Research Council of Canada (NSERC), and Social Sciences and Humanities Research Council of Canada (SSHRC) for awarding funding to the CCaR project under the International Research Initiative on Adaptation to Climate Change (IRIACC). Without this funding, the CCaR project and everything we've been working on would not have been possible. Thanks also to Markus Schnorbus (PCIC), Francis Zwiers (PCIC), staff at BC Ministry of Forests Lands and Natural Resource Operations (MFLNRO), Metro Vancouver, and BC Assessment (BCA) for assisting my data collection efforts. I am also grateful to NSERC for the doctoral CGS scholarship award, which helped support me and my research throughout graduate school.

The summer of 2013 provided me the opportunity to work with an international PhD student from Austria. Through a few intense months of work, Christian and I were able to contribute some interesting research to the fields of system dynamics and spatial modeling and during that time, were able to build a friendship that spans oceans.

A special thanks goes out to my friend Jonathan Pietrobon for his programming support and continued friendship throughout my graduate studies. Thanks to all of my other friends in London and beyond for your patience and humour in the times it was most needed.

Best wishes to FIDS colleagues and alumni. We've shared many brainstorming sessions, picnics, and life events together; it's been a pleasure.

I've been blessed with a wonderful family who've always been there for me. Thanks for your support in every aspect of my life.

This journey would never have begun if it weren't for the conviction and guidance of my supervisor, Professor Simonovic; my inspirational mentor. Thanks for this opportunity.

Finally, I'd like to thank everyone who has in many ways, small and large, contributed to "my one small step, my walk on the moon."

Dedication

In loving memory of my cat Skyttles.

Table of Contents

Abstract ... ii

Summary for Lay Audience ... iv

Co-Authorship Statement ... v

Acknowledgments ... vii

Dedication ... ix

Table of Contents ... x

List of Tables ... xiv

List of Figures ... xv

List of Appendices ... xx

Acronyms and Terminology ... xxi

Chapter 1 ... 1

1 INTRODUCTION ... 1

1.1 Risk to Resilience: A Changing Disaster Management Paradigm ... 1

1.2 Adaptation to Climate Change Influenced Disasters ... 3

1.3 Thesis Objectives ... 3

1.4 Thesis Contributions to Research ... 5

1.5 Thesis Organization ... 7

Chapter 2 ... 9

2 RESEARCH MOTIVATION AND LITERATURE REVIEW ... 9

2.1 Research Motivation: Climate Change and Natural Hazards ... 10

2.2 Research Motivation: Megacities ... 14

2.3 Research Motivation: Disaster Resilience ... 18

2.3.1 Resilience Quantification, Tools and Applications: How is disaster resilience being assessed? ... 23

2.4 Summary of Motivation for the Research ... 31

Chapter 3 ... 34

3 FRAMEWORK AND METHODOLOGY FOR RESILIENCE QUANTIFICATION ... 34

3.1 Setting the Resilience Landscape: Resilience Definition ... 36

3.2 Setting the Resilience Landscape: Resilience Quantification ... 36

3.2.1 Dimensions of resilience ... 37

3.2.2 Impacts and capacities ... 39

3.2.3 Thresholds ... 44

3.3 Setting the Resilience Landscape: Focal Scale ... 49

3.3.1 Characterizing Resilience: Interdisciplinary Resilience Domains ... 52

Chapter 4 ... 53

4 IMPLEMENTATION: AN INTEGRATED CITY SYSTEM ... 53

4.1 Implementation: Disaster Resilience Simulation Tool (DRST) ... 54

4.1.1 System Dynamics Applications in Disaster Management ... 60

4.2 Implementation: Data Collection ... 61

4.2.1 Implementation: Focal Scale and Geographic Scales in Spatial Resilience Modelling ... 62

4.2.2 Implementation: Spatial Analysis ... 64

4.2.3 Implementation: Geographic Information Systems (GIS) ... 64

4.2.4 Implementation: Integrated spatio-temporal modelling ... 65

4.3 Implementation: Systems Model ... 67

4.3.1 Physical Hazard Domain: Description ... 69

4.3.2 Physical Hazard Domain: Implementation ... 71

4.3.3 Economic Domain: Description ... 86

4.3.4 Engineering Domain: Description ... 93

4.3.5 Engineering Domain: Implementation ... 94

4.3.6 Health Domain: Description ... 98

4.3.7 Health Domain: Implementation 102
4.3.8 Social Domain: Description 107
4.3.9 Social Domain: Implementation 109
4.4 Integrated Resilience 111
4.5 DRST Programming and Simulation 112
4.6 Adaptation Options 112
Chapter 5 114
5 APPLICATION IN METRO VANCOUVER, BRITISH COLUMBIA, CANADA 114
5.1 Primary Motivation for Disaster Resilience Quantification Application in British Columbia 114
5.2 Setting the Resilience Landscape: Research Questions and Problem Definition 117
5.3 Implementation 118
5.3.1 Implementation: Data Collection and Identifying Key Elements to Describe Systems 118
5.3.2 Implementation: Climate Change Influenced Hazard Definition 128
5.3.3 Implementation: Generating Adaptation Options 142
5.3.4 Implementation: Identifying Thresholds 145
5.4 Running the DRST 146
5.5 Results 146
5.5.1 Spatial Representation of Resilience 147
5.5.2 Temporal Representation of Resilience 162
5.6 Chapter Summary 169
Chapter 6 172
6 CONCLUSIONS 172
6.1 Summary of Methodology and Contributions to the Disaster Management Research Field 172
6.2 Scope, Limitations, and Uncertainty 174

6.3 Recommendations for Future Research 177
6.3.1 Refinement of the DRST 178
6.3.2 Extension of the DRST 179
6.3.3 Resilience Outputs 180
6.3.4 Model Evolution 180
References 181

List of Tables

Table 1: The basic characteristics of a subset of quantitative, temporally dynamic, threshold-based resilience assessment tools as originally identified in Sharifi (2016).......................... 26

Table 2: A list of recent resilience assessment and quantification tools to complement the resilience tools identified by Sharifi (2016).. 31

Table 3: Industry-specific economic model sectors... 91

Table 4: Streamflow projection availability through PCIC Portal for selected GCM and emissions scenarios... 135

Table 5: Statistical 100-, 200-, and 500-year streamflow values for three climate scenarios and four stream gauge locations along the Fraser River and its tributaries................................. 137

Table 6: Manning roughness coefficients for Fraser River and its tributaries...................... 139

Table 7: Summary of hydraulic, SLR, and adaptation options tested using the DRST........ 145

Table 8: Thematic representations of geographic data 205

Table 9: Description of Model Input Data.. 244

List of Figures

Figure 1: Projected population growth; red dots indicate megacities (≥ 10 million people) (image from: (UN DESA, 2018)) 15

Figure 2: Framework for disaster resilience quantification and methodology for its implementation 35

Figure 3: Conceptual definition of STDRM using system performance graph (modified after Simonovic and Peck, 2013) 39

Figure 4: Illustration of dynamic system resilience in performance space 42

Figure 5: Illustration of dynamic system resilience in resilience space demonstrating examples of resilience which returns to pre-shock levels (solid line); exceeds pre-shock levels (dash-dot line); and does not recover to pre-shock levels (dotted line) 43

Figure 6: Illustrative dynamic resilience map in time (t) and space (x,y) using STDRM where the changing colours represent changes in resilience 44

Figure 7: Four types of threshold responses including (a) no response; (b) step-change; (c) alternate stable state; and (d) irreversible change (adapted from Walker and Salt, 2012) 46

Figure 8: Schematic example of a moving threshold 47

Figure 9: Schematic of conceptual thresholds in performance space for (a) Scenario A: higher threshold; and (b) Scenario B: lower threshold 48

Figure 10: A non-exhaustive example of multiple (hierarchical/vertical) multi-level governance scales which may be involved in the mitigation, planning, response, or recovery decisions and/or actions in the event of a natural disaster 51

Figure 11: Generic implementation methodology 55

Figure 12: Generic stock and flow diagram 58

Figure 13: Technical implementation schematic for the DRST 66

Figure 14: Generic model structure for each domain (I-n) 68

Figure 15: Physical domain workflow diagram; tasks 4, 5, and 6 are completed for each unsteady flow simulation scenario 73

Figure 16: General river network digitization scheme (based on USACE (2011)) 75

Figure 17: Pathways of global CO_2 concentrations for AR5 emissions scenarios (from IPCC (2013)) 76

Figure 18: Simulation results of CO_2 in the atmosphere if the land and ocean can no longer absorb close to half of all climate-warming CO_2 emissions (from NASA (2015)) 76

Figure 19: Projected SLR for RCP 2.6 (lower, blue projected line) and RCP 8.5 (higher, red projected line) (IPCC, 2013) 79

Figure 20: Climate model ensemble mean relative sea level change (m) (between 1986-2005 and 2081-2100) for (a) RCP 2.6; and (b) RCP 8.5 (adapted from IPCC (2013)) 79

Figure 21: VIC hydrological modelling schematic (from Liang et al., (1994)) 82

Figure 22: River schematic identifying locations which require the specification of boundary conditions and where climate change is incorporated into the hydraulic modelling process . 85

Figure 23: Schematic of physical domain output (a) generated from hydraulic unsteady flow simulation; (b) when combined with spatial topographical information to generate a time series of inundation maps (adapted from USACE 2010) 86

Figure 24: Schematic of spatial overlay and infrastructure attributes contributing to economic CGE model 91

Figure 25: Schematic of the economics domain GAMS modelling and optimization; this process is completed only once, at the end of the simulation 93

Figure 26: Schematic of engineering domain calculations for a single infrastructure element (adapted from Nastev and Todorov (2013)) 95

Figure 27: Engineering resilience spatial implementation, direct damages workflow diagram this process is completed for each time step (t) in the simulation 97

Figure 28: Implementation of the spatial health domain cost-distance algorithm................ 106

Figure 29: Health resilience spatial implementation, cost-distance workflow diagram; this process is completed for each time step (t) in the simulation 107

Figure 30: Social resilience spatial implementation, communications workflow diagram this process is completed for each time step (t) in the simulation 110

Figure 31: Region of Metro Vancouver (and population estimates) in the province of British Columbia, Canada (inset image courtesy of Metro Vancouver (2017)) 115

Figure 32: Dissemination Areas (orange boundary lines) in the Region of Metro Vancouver (white shaded area) 115

Figure 33: A selection of spatial inputs collected for use in disaster resilience quantification as part of the DRST 120

Figure 34: Dynamic disaster resilience quantification Vensim model 121

Figure 35: Emergency funding component of the DRST Vensim model............................ 121

Figure 36: Disaster resilience calculation component of the DRST Vensim model 125

Figure 37: Metro Vancouver, the Fraser River, and its tributaries as: (a) a DEM of low elevations (black shade) and high elevations (white shade); and (b) a TIN of low elevations (blue colour) and high elevations (red colour)... 130

Figure 38: The four Water Survey of Canada gauge sites (08MH024; 08MF005; 08MH001; 08MG013) in British Columbia along the Fraser River and its tributaries (provided by Markus Shnorbus, PCIC 2014) 135

Figure 39: HEC-RAS model geometry (river centerline and cross sections)....................... 140

Figure 40: Example of one of the cross sections from the HEC-RAS model....................... 140

Figure 41: A sample map of the cost-distance algorithm output used by the DRST in the calculation of health resilience for one scenario (Baseline), for one time step (*t=0*); the 'H' symbols represent hospitals; yellow is low cost-distance, purple is high cost-distance 147

Figure 42: Spatial engineering resilience for Scenario 2 across dissemination areas for Metro Vancouver (14 total time steps); maps in NAD 83 CRCS 150

Figure 43: Engineering resilience at one time step (t = 7) for (a) Scenario 1; (b) Scenario 2; and (c) Scenario 5 near the Fraser River in the member municipalities of Coquitlam, Surrey, and Pitt Meadows.. 151

Figure 44: Spatial health resilience for Scenario 2 across dissemination areas in Metro Vancouver (14 total time steps); maps in NAD 83 CRCS 155

Figure 45: Hospitals (non-auxiliary) near the City of Delta 155

Figure 46: Health resilience at one time step (t = 7) for (a) Scenario 1; (b) Scenario 2; and (c) Scenario 4 for the cities of Richmond, Delta, Surrey, and White Rock 156

Figure 47: Spatial social resilience for Scenario 2 across dissemination areas in Metro Vancouver (14 total time steps); maps in NAD 83 CRCS 160

Figure 48: Difference in social system impacts for one time step (t = 4) for (a) Scenario 1; and (b) Scenario 2 161

Figure 49: Engineering resilience (Metro Vancouver) 163

Figure 50: Social resilience (Metro Vancouver).. 164

Figure 51: Health resilience (Metro Vancouver) 165

Figure 52: Economic resilience (Metro Vancouver) 166

Figure 53: Economic resilience modelled over a longer (nearly 4 year) time period........... 167

Figure 54: Total resilience (Metro Vancouver) 168

Figure 55: Spatial data as layers 205

Figure 56: Two types of spatial data structures representing (a) spatially discrete features as vector data; and (b) spatially continuous data as raster data 207

Figure 57: Representation of spatially discrete features as (a) vector data; and (b) raster data 207

Figure 58: Spatially discrete features (houses) represented in various vector formats (a) points; (b) lines; and (c) polygons 208

Figure 59: Extract analysis tools (a) clip, (b) select, and (c) split 211

Figure 60: A subset of the overlay analysis tools (a) union; (b) intersect; and (c) erase..... 212

Figure 61: Cost distance proximity analysis... 213

Figure 62: Spatial raster reclassification.. 214

Figure 63: Schematic of a geometric network 215

Figure 64: Schematic of geometric network with flow direction 216

Figure 65: Flags (sources), barriers, and weights 216

Figure 66: Conceptual results from a trace downstream operation in a geometric network 217

Figure 67: Structure of a GAMS program 230

Figure 68: Organization of GAMS program... 231

Figure 69: Flow split assumptions for the Fraser River and its tributaries........................... 249

Figure 70: Jacob Haldi Bridge from Fort Langley to McMillan Island, BC (Google Maps, 2014) 251

Figure 71: DRST graphical user interface (GUI) screen 255

List of Appendices

Appendix A An Introduction to Spatial Data, Spatial Data Tools, and their use in the Development of the DRST 203

Appendix B VIC Hydrologic Model Equations 218

Appendix C HEC-RAS Hydraulic Modelling Equations 226

Appendix D GAMS Programming and Documentation 229

Appendix E Data to Support the Application of Resilience Quantification Framework for Metro Vancouver, British Columbia, Canada 243

Appendix F Disaster Resilience Simulation Tool (DRST) and Python Code 247

Appendix G Fraser River Hydraulic Modelling Assumptions and Limitations 248

Appendix H Disaster Resilience Simulation Tool (DRST) Graphical User Interface (GUI) 254

Appendix I Curriculum Vitae 259

Acronyms and Terminology

ABM	Agent Based Model
API	Application Programming Interface
AR4	IPCC's Fourth Assessment Report
AR5	IPCC's Fifth Assessment Report
BC	Boundary Condition
BC	British Columbia
BCA	British Columbia Assessment [Corporation]
BCSD	Bias Corrected Spatial Disaggregation
CGE	Computable General Equilibrium [model]
CLARA	Coastal Louisiana Risk Assessment Model
DA	Dissemination Area
DALY	Disability Adjusted Life Year
DEM	Digital Elevation Model
DLL	Dynamic Library Link
DMAF	Disaster Mitigation and Adaptation Fund
DRST	Disaster Resilience Simulation Tool
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute

FBC	Fraser Basin Council
GAMS	General Algebraic Modeling System
GCM	Global Climate Model
GCS	Geographic Coordinate System
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GHG	Greenhouse Gases
GIS	Geographic Information System
GMSL	Global Mean Sea Level
GUI	Graphical User Interface
HEC-GeoRAS	the Hydrologic Engineering Centers Geographic River Analysis System
HEC-RAS	the Hydrologic Engineering Centers River Analysis System
HFA	Hyogo Framework for Action
ICIP	Investing in Canada Infrastructure Program
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MFLNRO	Ministry of Forests, Lands and Natural Resource Operations
MGI	McKinsey Global Institute
NASA	National Aeronautics and Space Administration

NGO	Non-Governmental Organization
NHC	Northwest Hydraulic Consultants
PAHO	Pan American Health Organization
PCIC	Pacific Climate Impacts Consortium
PCS	Projected Coordinate System
PIF	Performance Influencing Factors
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SAM	Social Accounting Matrix
SD	System Dynamics
SLR	Sea Level Rise
SRES	Special Report on Emissions Scenarios [scenarios]
STDRM	Space-Time Dynamic Resilience Measure
SWAT	Soil Water Assessment Tool
UN DESA	United Nations Department of Economic and Social Affairs
UNISDR	United Nations International Strategy for Disaster Risk Reduction
USACE	United States Army Corps of Engineers
VIC	Variable Infiltration Capacity [model]
WHO	World Health Organization

Chapter 1

1 INTRODUCTION

Cities are complex systems facing a diverse set of issues including: rapid population growth; environmental threats; resource shortages; social inequalities; disruptive technologies; and complex governance. The World Economic Forum anticipates that by 2050 over 68% of the global population will live in urban areas (UN DESA, 2018) which will only exacerbate existing problems. As cities progressively increase in size and complexity, good governance and decision making will be imperative to managing the demands, threats, and sustainability of urban systems.

Over the last several decades, cities have faced a diverse set of issues. Coastal cities in particular must manage the growing threat of sea level rise and the impacts of climate change on hydrometeorological hazards. Extreme variations in the hydrologic cycle, in addition to long-lasting alterations of physical conditions and urban intensification, can impact environmental, economic, engineering, health, and social systems causing devastation to a city.

This chapter introduces disaster management approaches and climate change-influenced hazards. It outlines the main objectives, research questions, and contributions of this work to the scientific and disaster management communities.

1.1 Risk to Resilience: A Changing Disaster Management Paradigm

There are practical links between disaster risk management, climate change adaptation, and sustainable development that lead to reduction of disaster risk and reinforce resilience as a new development paradigm (de Bruijn et al., 2017). The past couple of decades have experienced a noticeable change in disaster management approaches; a switch from traditional disaster risk and vulnerability reduction strategies to progressive disaster resilience development strategies. Traditional risk and vulnerability approaches focus on system deficiencies whereas resilience approaches are a more proactive and positive expression of community engagement within natural disaster management. A resilience approach focuses on the inherent and adaptive coping capacities of a community and places an emphasis on local strengths and opportunities to “build back better” (Clinton, 2006; Gupta, et al., 2010; Fan, 2013; World Health Organization, 2013). In the past, disaster management planning emphasized the documentation of roles, responsibilities, and procedures. Increasingly, these plans consider arrangements for prevention, mitigation, preparedness, response, and recovery. However, over the last ten years, substantial progress has been made in establishing the role of resilience as part of sustainable disaster management (Adger, 2007, Nelson et al., 2007). Multiple case studies around the world reveal links between attributes of resilience and the capacity of complex systems to absorb disturbances while still maintaining a certain level of functioning. There is a need to focus more on action-based resilience planning to strengthen local capacity and capability, including a greater emphasis on community engagement, to gain a better understanding of the diversity, needs, strengths, and vulnerabilities within communities. This research recognizes the paradigm shift from disaster risk to resilience and formalizes the qualitative and quantitative definition of resilient systems. This research also demonstrates a mechanism by which disaster resilience can be represented and quantified.

Disasters do not impact every community in the same way. It is clear that problems associated with sustainable human wellbeing in urban regions calls for new scientific and practical approaches. Cities may be viewed as living systems (i.e. a systems of systems), constantly self-organizing in many varied ways in response to both internal interactions and the influence of external factors. Resilience is an appropriate matrix for investigation considering the essential overlaps between the built environment, physical environment, social dynamics, metabolic flows, and governance networks (Simonovic and Peck, 2013). This research seeks to address the need to model the complex interdependencies of urban systems as they relate to disaster resilience. Furthermore, this research incorporates the diversity of urban regions and recognizes the importance of formulating resilience-based strategies in a local context. Therefore, although the resilience theory and methodology presented may be generally applied to any region, the application of a resilience simulator tool presented in this research was developed specific to Metro Vancouver, British Columbia, Canada.

1.2 Adaptation to Climate Change Influenced Disasters

As the climate changes, global average sea level is rising and will continue to rise for centuries even after greenhouse gas emissions have stabilized (IPCC, 2012). The change in sea level poses both a current and future threat to coastal regions around the globe. Even minor sea level rise has significant societal, health, and economic impacts through coastal erosion, increased susceptibility to storm surges and flooding, salt water intrusion into ground water supply, loss of coastal wetlands, and other issues. Global climate changes combined with trends of increasing urbanization in coastal areas requires a coordinated effort to minimize impacts of natural hazards and build effective and adaptive capacity (McBean and Rodgers, 2010). Therefore, there is a need for quantitative assessment of climate change caused natural disaster impacts on coastal regions and analyses of various adaptation options.

1.3 Thesis Objectives

The research documented in this dissertation (i) offers a novel conceptual, mathematical, and computational resilience framework; (ii) proposes an integrated, dynamic resilience quantification method; and (iii) provides an application of the resilience framework and quantification methods for the purpose of assessing hydrometeorological disaster resilience. The framework combines more traditional disaster management risk reduction strategies with novel integrated resilience-building mechanisms. The quantification methodology provides an improved holistic representation of disaster resilience by combining physical, economic, engineering, health, and social resilience indicators. The disaster resilience simulation tool (DRST) implements the resilience framework and dynamic resilience quantification method to study the dynamic spatio-temporal behaviour of city systems, particularly in the event of a disaster. The DRST integrates temporal and spatial analyses using system dynamics modelling and simulation, spatial analysis using geographic information systems, and optimization modelling in order to examine the dynamic behaviour of complex systems' response to hydrometeorological hazards. Therefore, the tool provides an opportunity to explore implementation of cross-disciplinary adaptation options on a metropolitan wide scale. The result is an improved understanding of real-world city system dependencies and enhanced identification of cross-disciplinary system interactions in the event of a disaster. Simulations using the DRST provide insight into the spatial and temporal patterns of resilience. Through testing various adaptation options, the DRST can help guide disaster management decision making.

Therefore, the main goal of the presented research is development of a tool that allows simulation of disaster resilience policy scenarios (also called adaptation scenarios) and observation of changes in resilience behavior over both time and space in the event of a hydrometeorological natural disaster. Simulating dynamic resilience behavior in response to various policy actions helps to: identify disaster-resilient systems; determine why some systems are more resilient than others; and prioritize adaptation actions. Thus, the main objectives of this research are as follows:

1. To provide a framework for dynamic spatio-temporal representation of disaster resilience;

2. To develop a framework for combining multiple domains of disaster resilience to offer a more holistic representation of disaster resilience;

3. To provide a mechanism for quantifying disaster resilience;

4. To develop a modelling tool which simulates dynamic space-time disaster resilience using the temporal modelling and simulation capabilities of system dynamics (SD) combined with the spatial analysis capabilities of geographic information systems (GIS); and

5. To test and assess various adaptation policies in the context of disaster resilience.

The purpose of pursing this research is to gain insight into the following research questions:

1. *Are coastal cities becoming more (or less) resilient to natural disasters?*

2. *What factors contribute most (and least) to disaster resilience?*

3. *Which systems are least (and most) resilient? In which disaster phase are they least (and most) resilient? Where are these system deficiencies (and strength and opportunities) located?*

4. *Which strategies may offer coastal cities the best opportunities to adapt to and cope with the impacts of climate-change influenced hazards?*

To obtain the answers to these questions, the concept of disaster resilience is used as a measure by which to analyze and compare various climate change adaptation strategies. An original framework is developed for the quantification of dynamic resilience through integrated spatio-temporal system dynamics, geographic information systems, and economics optimization to assess the impacts of climate change on coastal megacities. A quantitative, Space-Time Dynamic Resilience Measure (STDRM) is used as a measure of resilience which combines economic, engineering, health, physical, and social impacts of disasters. A resilience simulator tool (DRST) was developed which uses the STDRM calculation, combined with other spatio-temporal tools and methods, to simulate dynamic spatio-temporal resilience behaviour of city systems.

1.4 Thesis Contributions to Research

Resilience-based approaches to disaster management offer a framework for deeper engagement on the behaviour of complex adaptive systems. While the concept of resilience in disaster management is not new, methods and frameworks for resilience quantification remain in its infancy. Furthermore, while there is general agreement in the scientific community that resilience involves spatial and temporal dynamic processes, there is a limited research describing just how to capture them.

While the resilience concept has gained momentum in disaster management literature, most of the discussion revolves around qualitative descriptions of resilience; few attempts have been made to resilience quantification and much research is still required to fill this gap.

This research offers a pioneering effort in dynamic disaster resilience quantification, modelling, and simulation to help advance the fields of system dynamics simulation, climate change adaptation, and disaster resilience theory, methods, and applications. The more specific contributions of this work are as follows:

Theoretical and Analytical contributions

1. Resilience definition, quantification method, and assessment that is dynamic in both time and space (work published in Simonovic and Peck, 2013);

2. A methodological and computational framework and analysis method for dynamic disaster resilience quantification;

3. A methodological framework that enables the integration of multiple disaster resilience domains including interrelated physical, economic, engineering, health, and social disaster impacts and capacities used to provide a comprehensive description of disaster resilience;

4. The integration of system dynamics simulation, economic optimization, and geographic information systems methods and tools for dynamic spatio-temporal resilience simulation and mapping (foundations of this work published in Neuwirth et al., (2015));

Computational contributions

5. Disaster resilience quantification with the ability to capture system improvements in the process of recovery (i.e. recovery levels exceeding pre-disaster levels);

6. Disaster resilience quantification with the ability to capture the impact of performance thresholds;

Additional contributions

7. A middleware program designed to communicate between a system dynamics simulation model (created in Vensim software (Ventana Systems Inc., 2009)), an economics optimization model (created using the General Algebraic

Modelling System (GAMS) software (GAMS Development Corporation, 1987)), and spatial data analysis models (created in ArcGIS software (ESRI, 2011)); and

8. A proof-of-concept application of the proposed resilience quantification framework and methodology to Metro Vancouver in British Columbia, Canada.

1.5 Thesis Organization

The following chapters focus on the procedure for developing a framework, methodology, and tool to quantify and assess resilience to climate change influenced hydrometeorological disasters.

Chapter 2 examines the state of climate change and disaster management research. An argument is made for a paradigm shift in the disaster management community from risk to resilience, as traditional risk assessment approaches are no longer suitable decision making tools in the face of a changing climate. As awareness and acknowledgement of climate change impacts grow in the scientific and political communities, there is an increasing demand for disaster resilience quantification methods and tools to provide additional insight into effective disaster management strategies. Although there is significant literature available on resilience concepts, research in this area has often been siloed within specific scientific fields. Therefore, resilience concepts are explored through a variety of scientific fields and are integrated to form a comprehensive definition of dynamic disaster resilience. The second part of this chapter introduces system dynamics modelling and simulation which is used to capture complex temporal non-linear feedbacks within systems.

Chapter 3 focuses on resilience theory and the resilience quantification methods. This chapter sets the resilience landscape and characterizes dynamic disaster resilience. One of the defining characteristics and strengths of the disaster resilience principle, as identified in this chapter, is its ability to represent dynamics in both time and space. To capture these dynamics, spatial and temporal modelling techniques are integrated into a novel resilience simulation tool (DRST). This tool captures the linkages and interactions within, and between, five model domains (physical, economics, engineering, health, and social) to simulate a city's response following a disruption (in this case, a flood). The end of this chapter provides a conceptual introduction to the DRST.

Chapter 4 focuses on the implementation of the dynamic disaster resilience quantification methodology and dynamic resilience mathematical concept. This chapter provides a detailed description of the DRST including a description of each of the models' systems and subsystems. The DRST consists of one input domain (physical hazard) and four integrated impact domains: economic, engineering, health, and social. The main structure of each of the four impact domains is similar, but the way in which resilience is characterized and quantified for each of these domains varies greatly. The development of each of the five domains, relative to the resilience focal scale, is discussed in this chapter.

Chapter 5 describes an application of the framework and implementation of the resilience quantification methodology using the DRST in a Canadian context for the region of Metro Vancouver in British Columbia, Canada. This application tests three different adaptation strategies: mobile health unit, managed retreat, and access to additional external funding to examine their effects on disaster resilience. The DRST provides insight into which of these adaptation options may provide the greatest opportunity to improve regional disaster resilience.

Chapter 6 summarizes the findings and limitations of the concepts and applications presented in this dissertation and provides recommendations for future research related to the refinement, modification, expansion, and continuation of the DRST and proposes recommendations for adopting resilience-based strategies in the disaster management community.

Chapter 2

2 RESEARCH MOTIVATION AND LITERATURE REVIEW

The climate is changing and subsequently so are the characteristics, patterns, and consequences of natural disasters. The Intergovernmental Panel on Climate Change (IPCC) is one of the leading international bodies responsible for the synthesis of climate change research. The IPCC Fourth (AR4) and Fifth (AR5) assessment reports (IPCC, 2007; IPCC, 2014) demonstrate that there has been significant global changes in the climate and that the rate of climate change continues to rise. Evidence supports that global average surface temperature is increasing; snow, mountain glaciers, and ice cover is decreasing; and global average sea levels are rising at alarming rates (Shepherd, et al., 2010; Radić and Hock, 2011; IPCC, 2014; Bathiany et al., 2016). All these global changes have far-reaching effects with long term consequences. There is general consensus in the scientific community (Cook, et al., 2016) and many internationally recognized scientific and governmental organizations including NASA, United Nations, World Economic Forum, and World Health Organization (among others) have issued public statements endorsing that the climate is warming and that this warming effect is extremely likely to be influenced by human activities (NASA, 2009; United Nations, 1992; IPCC, 2012; United Nations, 1997; WHO, 2003). In the past few decades, there has been mounting political, commercial, and academic awareness and recognition of the potential devastating impacts that climate change may have on natural, human, and manmade systems.

Climate change plays an important role in the characterization of natural hazards and extreme events. Climate change influences the magnitude, frequency, duration, and seasonality of hazards. This recognition, combined with the understanding that hazards are natural, unavoidable phenomena, generates a sense of urgency to find ways in which climate change-influenced hazards can be managed to provide a sustainable, disaster-resilient future. Failure to address current and future climate change issues will have negative ramifications for generations to come.

There are often high economic and societal costs of natural disasters. A communities' past actions shape the effects of natural disasters. Decision support tools provide an opportunity to explore the future consequences of disaster planning decisions before acting in the present. This practice may reveal unexpected interactions and consequences of planning decisions. Failure to properly plan for future climate-influenced hazards will likely end up costing more in the future. Therefore, it is critical that cities develop action plans and implement adaptation measures as the opportunities present themselves. One of these key opportunities is in the process of disaster recovery; not only because reconstruction and restorations need to take place, but also because this is when political and personal motivations are highest and when the lingering impacts from a disaster are still fresh in everyone's mind (Walker and Salt, 2012). It is also an opportunity to increase resilience by "building things right the first time" and balancing adaptation needs.

The resilience concept has recently been popularized in the media, touted by governments, and promoted in disaster management research. However, a gap remains in establishing a systematic way of identifying, describing, and gauging the performance of resilient systems. Despite widespread interest in resilience concepts, the diversity of its applications across various disciplines and research domains hampers agreement on methods of its quantification and measurement techniques. This has resulted in a universal need to develop a generic resilience analysis framework which includes the identification, quantification, and assessment techniques for disaster resilience to provide for the broader disaster management community.

To set a foundation for this research, the remainder of this chapter reviews literature pertaining to climate change influenced disasters and resilience theory with applications in disaster management and describes how these two fields are brought together using simulation techniques.

2.1 Research Motivation: Climate Change and Natural Hazards

The primary motivation in pursuing the research presented in this thesis is driven by the pressures of climate change and natural hazards. As the climate is changing and so are the spatial and temporal patterns of natural hazards (IPCC, 2012). Hazard characteristics (frequency, magnitude, intensity, and seasonality) are significantly affected by changes in the climate and it is anticipated that climate change will significantly alter the global water cycle through changes in temperature. As greenhouse gas emissions increase, more moisture can be retained by the atmosphere which will subsequently affect changes in precipitation (Sharma and Babel, 2013). To contextualize the urgency of climate change, the Intergovernmental Panel on Climate Change (IPCC) issued an urgent special report in October 2018 warning that humanity has only 12 years left before the globe reaches 1.5°C of warming – only 0.5°C less than the 2°C threshold or “tipping point” for warming that would cause irreversible changes and lead the world into a climate catastrophe (IPCC, 2018). Due to the lag between greenhouse gas emissions and global warming, continued warming is inevitable even if humanity immediately ceased all GHG emissions. Therefore, cities must be prepared to adapt to climate change impacts.

However, there are inherent spatial and temporal uncertainties in future climate change projections and therefore uncertainties in the frequency and magnitude of extreme hazard events. With these uncertainties, it is important to prepare for, and adapt to, a range of possible future climates.

Climate change influences many hazards; exacerbating some and diminishing others. Climate change is a hazard driver, rather than being a hazard itself. The complexities of the interactions between climate change, specific hazards, at specific locations, makes climate change influenced hazard projections challenging (Kelman, 2015). Even with this understanding, the potential changes in natural hazard patterns and characteristics are not inherently a problem; the problem is specifically when hazards interact with the surrounding natural and built environments in undesirable ways, creating costly and destructive disasters. Hazards routinely occur across the globe, but through complex interactions between physical systems, human systems, and the constructed environment, otherwise ordinary phenomena are resulting in serious disasters.

In the past decade, Canada has experienced numerous climate hazards which have had significant socio-economic impacts. Two of the most costly hydrometeorological disasters both occurred in 2013 on opposite sides of the country. On the West coast, a deluge of precipitation fell in the Rocky Mountains which ended up in streams and rivers. The steepness of the terrain caused flows to route quickly downstream and combine with a record-high 45 mm of daily rainfall. By June 20th, over 100,000 people had been evacuated and the city of Calgary was inundated with floodwaters up to 2 m high (Pomeroy et al., 2016). Flood waters caused widespread damage to telecommunications, transportation corridors, power utilities, properties, and caused four casualties. Two weeks later on July 8th 2013, the city of Toronto faced an intense thunderstorm which brought 126 mm of precipitation to the region causing flash flooding, catching most local residents unprepared (Environment Canada, 2013). The disaster caused wide-spread damages to properties, disruptions to transportation, and interruption of utility services. Since then, there have been a number of other major flooding disasters including the 2017 flooding of the Grand River and the most recent 2019 flooding of the Ottawa River.

These disasters highlight the catastrophic effects that hydrometeorological disasters can have, even in interior Canada. Climate changes and land use patterns are driving changes in Canada’s flood regime (Burn and Whitfield, 2016). The 2013 event in southern Alberta was determined to be a 1- in approximately 40-year event (Pomeroy et al., 2016). However, with the changing climate it is possible that what was historically the 1- in 40-year flood event may now be closer to a 1 in 25-year event; and looking to the future, it’s possible that the frequency of high precipitation events may increase even further (IPCC, 2014).

What’s more, Canadian cities at the confluence of riverine and ocean (delta) environments face additional hazards. Coastal cities along river deltas operate in complex hydrometeorological physical environments. They face pressures from: coastal hazards such as hurricanes, tsunamis, and storm surge; riverine and estuary hazards such as water salinization and fluvial flooding; and storm hazards such as pluvial flooding. At the global scale, many other cities are facing similar problems.

Coastal regions are highly dynamic and complex systems which respond in various ways to extreme weather events (Balica et al., 2012; Kerle and Muller, 2013). Coastal cities are exposed to multiple types of extreme climate hazards, particularly hydrometeorological hazards including storm surges, floods, hurricanes, sea level rise, and tsunamis. Recently, there have been disasters affecting coastal cities across the globe resulting in significant economic and social losses.

Since natural hazards are phenomena which cannot be entirely eliminated, it is necessary to take measures to reduce the impacts on populations exposed to extreme climate hazards through employing effective adaptation policy (Henstra, 2012). As adaptation mechanisms, communities should consider increasing their flexibility, resistance, and robustness to cope with the various impacts of extreme hazards (Godschalk, 2003) and integrate adaptive capacity into the fabric of society (Paton and Johnston, 2006).

Climate change modelling is typically employed to help improve the understanding of relationships and identify important feedbacks in the complex climate-earth system. Climate models provide estimates of how physical systems will respond under various carbon emissions scenarios. The IPCC AR4 (2007) and AR5 (2014) reports outline scenarios which range from a carbon emissions "reduction" future scenario to the less conservative "business as usual" carbon emissions scenario. These emissions scenarios are used in conjunction with Global Climate Models (GCMs) in climate modelling to provide estimates of potential future warming of the Earth's atmosphere. Although GCM outputs provide a reasonable estimation of future climate, their coarse spatial resolution is limiting in many local and regional applications. When a finer spatial resolution is required, statistical or dynamic regional climate model (RCM) downscaling techniques are used to bring GCM output to the local level (Masud et al., 2016).

Furthermore, to determine how greenhouse gas (GHG) emissions and atmospheric climate changes may modify hydrometeorological hazards, the GCM or RCM outputs are used in hydrologic and hydraulic modelling applications (Arnell, et al., 2001; Shrestha, 2014; Eum et al., 2010) to estimate how climate scenarios may modify streamflows, water levels, and flood extents. This research applies a similar methodology to estimate climate change influenced flooding. These floods represent future possible events under climate change. Even though the resilience framework and methodology presented in this research can be generically applied to any city, the climate change influenced hazards will vary according to future estimated regional hydrometeorological conditions of the basin.

Climate change and urbanization are considered the main motivations of this research. With increased urban pressures and catastrophic climate threats looming on the not-too-distant horizon, it is more important than ever for cities to make informed, long-term decisions and become more resilient.

2.2 Research Motivation: Megacities

Another primary driver of the research presented in this thesis was due to the pressures of rapid urbanization and the increasing size and complexity of the world's megacities. When it comes to the rapid urbanization of coastal megacities, the only constant is change. It's projected that 68% of the global population will be living in urban areas by 2050; an increase of approximately 30% from global urban population levels in 2011 (UN DESA, 2018). This anticipated increase may be attributed to the trend of increasing rural-to-urban migration as people abandon agricultural practices to seek out economic opportunities and prosperity in urban cities (Wenzel et al., 2007; Akanda and Hossain, 2012). This migration is causing many major cities to rapidly develop into megacities (Akanda and Hossain, 2012); defined by the United Nations as cities with populations greater than 10 million people (UN DESA, 2018). The number of global megacities is anticipated to grow to 43; most of them in developing regions. As supported by Figure 1, a majority of the world's current and projected megacities are located in hazardous low-lying coastal areas, particularly in developing countries (Akanda and Hossain, 2012; UN DESA, 2018). Therefore, millions of people are already exposed to coastal climate hazards. In addition, these megacities are often characterized by high population densities, destitute slum settlements, and inadequate life-sustaining infrastructure (Wenzel et al., 2007); conditions which exacerbate the impacts of climate hazards. Currently, 21% of the world's population lives within coastal zones and an average of 46 million people per year experience storm surge flooding. Some 189 million people presently live below the 1 in 100-year storm surge level. To exacerbate this problem, some coastal megacities are expected to experience more frequent, high intensity events in the future as a result of the changing climate. In addition to more immediate hazards that threaten coastal cities, it is expected that many coastal cities will see some degree of sea level rise (SLR) in the future (Hinkel, et al., 2014; Wong, et al., 2014; Jevrejeva et al., 2016; Bindoff, et al., 2007). Land subsidence combined with warming is causing SLR at unprecedented rates (Wong, et al., 2014). Even if global emissions were immediately reduced to zero, emissions retained by the atmosphere would cause the globe to continue to warm. Jevrejeva et al. (2016) estimates that with even 2°C of warming, more than 90% of coastal areas would exceed 0.2 m of SLR by 2040. If warming were to exceed this estimate (which is a distinct possibility), SLR levels would be even higher. These small changes in SLR play a significant role in the magnitude and extent of flooding due to storm surges. Higher sea levels are not just a problem of additional water, but also salt contamination. Salt water flooding has the potential to negatively impact agricultural land, groundwater, and freshwater ecosystems.

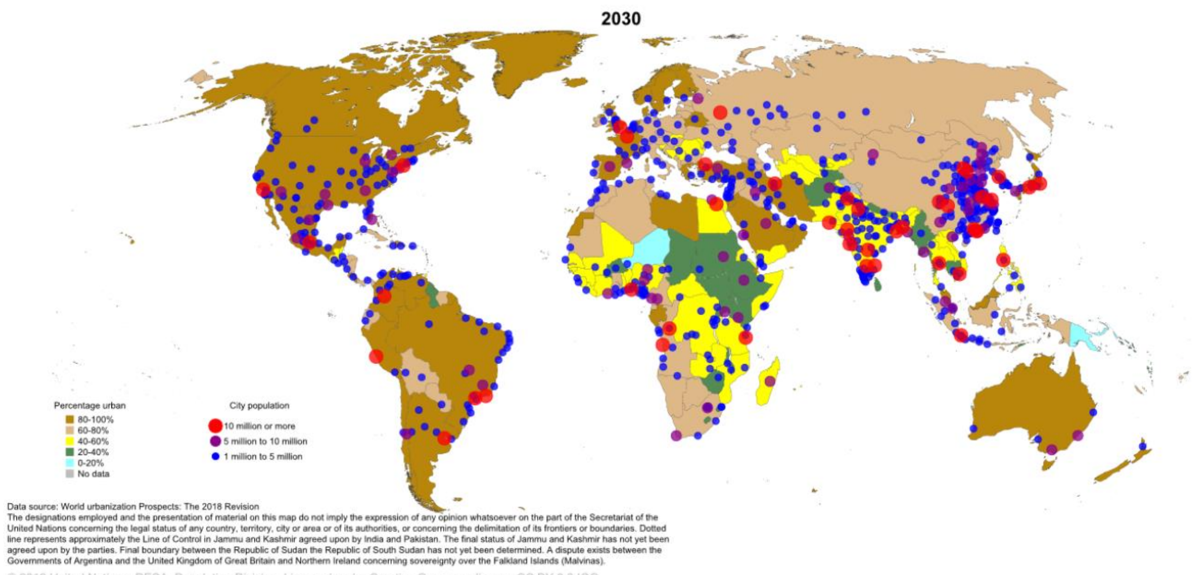


Figure 1: Projected population growth; red dots indicate megacities (≥ 10 million people) (image from: (UN DESA, 2018))

Megacities possess a diverse set of intellectual, technical, and financial resources that, when mobilized effectively, provide an opportunity to develop effective disaster resilient systems.

The many disaster management professionals still operate with a reductionist approach to handling complex systems by breaking them down into small, separate, manageable components. This approach enforces the perception that these components are unrelated to each other. A shift in thinking from a compartmentalized approach to a more holistic, interrelated way is required to tackle large-scale issues such as climate change and disaster management. The essence of systems thinking is wholeness. The objective is to look at the behavior of interrelated non-linear systems together to better understand those relationships which influence complex system behavior.

Orr (2014) suggests there are at least 6 ways in which systems thinking can help improve urban governance:

1. Help governments organize data to distinguish between information and noise
2. Educate the citizens
3. Improve forecasting and planning
4. Improve the quality of urban decision-making
5. Improve organizational behavior
6. Improve realism and precautionary public policies

Thus, systems thinking is a critical component to building sustainable and resilient cities. Cities can be thought of as systems of systems. That is, a city is made of many sub-systems, each consisting of its own components, but interacting dynamically with other city sub-systems to form the complex whole which allows a city to function. This approach brings up another important systems concept: that constitutive characteristics are not explainable from the characteristics of isolated parts. That is, merely adding up the components is meaningless as compared to the part-whole relationships and the collective behaviour of the system. Applying conventional thinking to complex problems, can lead to unintended consequences. Fixing isolated pieces without consideration for the whole may seem harmless, but also may be ignoring essential relationships that drive system behaviour and end up undermining the best efforts of the solution. In an ever growing, advancing, and globalized society, systems thinking is essential for developing effective solutions to complex real-world problems. The rise of cities in the world presents both opportunities and potential problems. The challenge for social system design is summarized in the second McKinsey Global Institute (MGI) report:

"Cities can be part of the solution to such stresses, as concentrated population center can be more productive in their resource use than areas that are more sparsely populated. But if cities fail to invest in a way that keeps abreast of the rising needs of their growing populations, they may lock in inefficient, costly practices that will become constraints to sustained growth later on. How countries and cities meet this rising urban demand therefore matters a great deal. Beyond the direct impact of the investment, their choices will have broad effects on global demand for resources, capital investment, and labor market outcomes" (Dobbs, et al., 2012, p. 2).

Systems analysis is an approach used to break complex systems into its constituents and study their interrelationships and function as part of the whole. The function of each component in a systemic context differs from how the component would function in isolation. Both cognitive (mental) and physical (mathematical) modelling techniques are useful for formalizing system architecture and exploring emergent system behaviour.

Cognitive models (e.g. causal loop diagrams) are mental models which help formalize and visualize complex system structures; readily recognize relationships between system elements; and identify feedback mechanisms that drive complex system behaviour. Cognitive modelling is an important step in formalizing system structures. Causal loop models are constructed based on research, personal experience, and in consultation with experts and stakeholders in the fields of the system (and sub-systems) of interest. Mental models are continually reassessed and refined as new information becomes available.

Mathematical and computer models (e.g. stock and flow diagrams) are idealized representations of physical systems expressed in the form of mathematical expressions and equations. Mathematical and computer models can simulate the complex relationships between various elements within a system and give rise to resulting emergent system behaviour.

2.3 Research Motivation: Disaster Resilience

Coastal urban development pressures, combined with increases in the magnitude and frequency of climate change influence on coastal hazards, place a particular importance on effective disaster management. It is imperative to estimate and reduce climate change influenced hazard impacts by understanding the risks, vulnerabilities, and capacities of people and the built environment to properly prepare for, and make informed decisions related to, disaster management.

Historically, traditional approaches such as vulnerability assessments and "hard" engineering mitigation measures, such as dikes, were the primary solutions to disaster management problems. In other words, to prevent flooding, solutions would revolve around building flood protection infrastructure stronger, bigger, and higher. However, it is becoming apparent that flood protection infrastructure is only part of the solution and that resilience approaches are key to finding more sustainable disaster management solutions.

The past two decades of disaster management have experienced a paradigm shift from traditional disaster mitigation and prevention strategies to disaster resilience. This more holistic approach has gained a lot of momentum in the disaster management community. The benefit of this transition to resilience-based approaches is reinforced by social scientists and psychologists who suggest that to tackle climate-related issues, the focus should change from telling "catastrophe" stories to focusing on potential opportunities and solutions; ways in which improvements can be made to new and existing systems to better prepare, respond to, and recover from disasters. The resilience of people, nature, and the built environment are all positive narratives which can drive constructive changes and help build better cities (Goldstein et al., 2015).

Resilience focuses on positive characteristics and opportunities to improve or (in some instances) transform a system. It is both a short-term response and long-term process which invites opportunities for growth and transformation through the power of knowledge, collaboration, preparedness, and flexibility. The concept of resilience appears in a variety of domains, but was formally introduced in the field of ecology, defined as a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variable (Holling, 1973).

Despite its origin in ecology, there is general consensus within the scientific community that the concept of resilience is multidisciplinary and that it has spread outside of its original disciplinary fields (Cutter, et al., 2008; Ayyub, 2015). Several well-known organizations have defined resilience in high-impact documents. Most notably:

- The United Nations Centre for Disaster Risk Reduction (UNISDR) (2016) has defined resilience as the ability to "recover" or "spring back" from a shock. It describes the resilience of a community in respect to potential hazard events as determined by the degree to which the community has the necessary **resources** and is capable of **organizing** itself both **prior to** and **during** times of need. "The **capacity** of a system, community or society potentially exposed to hazards to **adapt**, by **changing or resisting** in order to reach and maintain acceptable levels of functioning and structure."

- Public Safety Canada (2019) believes that enhancing resilience is a shared responsibility across all levels of government to deal with disruptions and ensure the continuation of businesses and essential services; and emergency management planning to **ensure adequate response procedures** are in place to deal with unforeseen disruptions such as natural disasters. It is seen as **the capacity of a system, community or society to adapt to disturbances** resulting from hazards by persevering, recuperating or changing to reach and maintain an acceptable level of functioning.

In scientific literature, resilience definition has also taken on multiple forms. Some of the most notable include:

- Cutter et al. (2013) defined resilience as "a **capacity** measure that can be views as sector-focused, **systems-based**, or, applied more broadly to a community, defined as systems of systems where the various components – environment, infrastructure, social, economic, institutional and so forth – are **integrated** and mutually supportive."

- Aven (2011) argues that resilience is closely related to the concept of robustness and that the key difference is that resilience is interpreted as the **uncertainty (probability) and severity of the consequences** of an activity given the occurrence of an event.

- Haimes (2011) defines the resilience of a system as a manifestation of the **states of the system** and a vector that is **time- and threat-dependent**. More specifically, resilience represents the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable cost and time.

Aven (2011) argues that the identification of critical uncertainty factors can alter a systems' resilience, rendering what would otherwise be considered highly resilient systems, less resilient. The work presents an alternative framework for the description of resilient systems driven by uncertainty, vulnerability (as a function of probability), and resilience (also a function of probability). The consequences and the system performance in general are affected by a number of performance influencing factors (PIFs), for example: resources, level of competence, and management attitudes. What's more, is Aven proposes a probability-based approach to resilience. That same year, Haimes published a response to Aven's article, wherein he criticizes Aven's interpretation of his original work (Haimes, 2011). Haimes (2011) goes on to explain resilience as a function of: time, a threat, inputs, decisions, and exogenous variables. Furthermore, consequences are described as functions of the states of the system (thus, by definition, they are also functions of resilience of the real system).

Ayyub (2015) defines resilience as follows: "Resilience notionally means the ability to prepare for and **adapt to changing conditions** and withstand and **recover rapidly** from disruptions. Resilience includes the ability to **withstand and recover from disturbances** of the deliberate attack types, accidents, or naturally occurring threats or incidents." This definition lends itself to measurement through metrics. The resilience measure offers a basis for quantification of:

1. System performance;
2. Uncertainty relating to events; and
3. Persistence, recovery, and/or resumption of performance.

It is evident that there have been various definitions of resilience and its widespread use in various fields has led to some ambiguity in its use and interpretation. In order to assess disaster resilience, first requires its definition. This definition should capture the essence or essential attributes of disaster resilience (Ayyub, 2015).

Therefore, drawing from the above literature and resilience literature in the fields of physics, ecology, and hazards, it’s possible to identify common elements in the definition of resilience (similarly identified in Simonovic and Peck, 2013) including: (i) minimization of losses, damages, and community disruption; (ii) maximization of the ability and capacity to adapt and adjust when there are shocks to systems; (iii) returning systems to a functioning state as quickly as possible; (iv) recognition that resilient systems are dynamic in time and space; and (v) acknowledgements that post-shock functioning levels may not be the same as pre-shock levels (and may actually even be higher). Resilience is the ability of a complex system to respond and recover from disasters and includes those conditions that allow the system to absorb impacts and cope with an event, as well as post-event adaptive processes that facilitate the ability of the system to re-organize, change, and learn in response to a threat (Simonovic and Peck, 2013); aspects of resilience are therefore influenced before, during, and after the occurrence of a disaster.

Governments around the world have begun to recognize that resilience-based approaches are effective as part of a more comprehensive, sustainable, integrated disaster management strategy. Traditional “hard” engineering solutions are being complemented by less-traditional “soft” solutions which consider effects in fields outside of engineering such as economics, health services, environmental science, and sociology. Strengthening community resilience is a complex process which stretches across many organizational, institutional, disciplinary, political, and geographical scales. With this understanding, the UNISDR released the Hyogo Framework for Action (HFA) which focuses on building community-level and nation-wide resilience to natural disasters (UNISDR, 2005). Priority actions identified within the framework promote disaster risk reduction with an emphasis on building resilient communities (UNISDR, 2005). In 2005, 168 countries adopted the HFA with a common goal of reducing disaster impacts and losses. This framework was a first step in international recognition towards identifying factors that contribute to disaster resilient urban communities. Since then, the World Bank has also highlighted the importance of resilience strategies as part of a comprehensive disaster risk management plan. World Bank manages the Global Facility for Disaster Reduction and Recovery (GFDRR) to promote collaboration on the HFA. The research in this dissertation is in-line with many of the priorities identified in the HFA (UNISDR, 2005), specifically:

Priority 2: Identify, assess, and monitor disaster risks and enhance early warning;

Priority 3: Use knowledge, innovation, and education to build a culture of safety and resilience at all levels;

Priority 4: Reduce the underlying risk factors; and

Priority 5: Strengthen disaster preparedness for effective response at all levels.

The HFA uses 22 core indictors in addition to a qualitative assessment administered by UNISDR to monitor the progress of disaster risk reduction in each country. The research presented in this dissertation could support these HFA initiatives in cities across the globe.

One of the strengths of the resilience concept is developing an understanding and acceptance that natural hazards will inevitably occur, but that these hazards do not necessarily need to become full-blown disasters. The ways in which hazards are prepared for, responded to, and recovered from, ultimately contributes in determining whether a hazard turns into a disaster situation.

There is an inherent coping capacity in human and physical systems which affect the way in which hazards, and disasters, are managed. These capacities vary from system-to-system and person-to-person based on a variety of factors. Physical system capacities may be influenced by location, building materials, and resource availability. Human system capacities may be influenced by cultural and societal values, access to resources, sense of community, and previous disaster experiences. People and communities around the world face different hazards, risks, and vulnerabilities; they also possess varying degrees of coping capacities and resilience. Capturing the differential elements of flood impacts and capacities is a prerequisite for developing adaptation policies that promote building resilience and avoid unforeseen negative consequences of policy implementation. To accomplish this, decision makers would benefit from understanding trade-offs and balance among adaptation options. The research in this dissertation seeks to address this challenge by simulating various responses in city systems to climate change and disaster resilience adaptation options.

After establishing a generally agreed-upon definition of resilience in the disaster management context, what constitutes a disaster resilient city? To begin answering this question, it is important to recognize cities as a combination of interacting systems including: transportation, health, emergency services, education, utilities, critical facilities, and more. Many of these city systems are interdependent; that is, if one system is affected it can subsequently lead to indirect effects in other city systems.

2.3.1 Resilience Quantification, Tools and Applications: How is disaster resilience being assessed?

Given the recent breadth of resilience literature published by academia, government, NGOs, insurance, and industry, it is evident that the concept of resilience is popular in the urban disaster management domain. The sheer number of disaster resilience publications is a sign of success in the disaster management field. For years, vulnerability and disaster risk reduction had dominated the disaster management field and only recently (in the past decade-or-so) has disaster resilience featured as a main topic of disaster management conversations. As a response, there have been a variety of proposed tools (Shaw et al. 2010, UNDP 2014; IFRC, 2014; NIST, 2015, Simonovic et al., 2016), frameworks (Joerin et al., 2012; Hammond et al., 2013; Henry, 2016), and guidelines (OECD, 2014; Watters, 2014) to “build resilience.” It is also evident through both scientific literature and the media that the concept of “building resilience” is being encouraged, particularly in the wake of some of North America’s most costly disasters (Dunlap, 2017; Grannis, et al., 2016). In response, insurance companies and emergency management agencies have started offering incentive programs to protect homes and improve floodplain management (FEMA, 2018). “Building resilience” has become the latest buzz phrase. In fact, the concept of resilience has become so popular that it’s challenging to keep up with all of the publications being released between the media, governments (all levels), organizations, scientific bodies, and academic institutions. Though it is evident that the concept of resilience has gained a lot of momentum over the past decade, there are limited examples of resilience-building measures being operationalized and successfully implemented. That is, in part, because there is limited research on measuring resilience and resilience quantification techniques are still in their infancy. Therefore, there is an increasing demand for improved resilience metrics and quantification methods (Bruneau, et al., 2003; Pant et al., 2014). One of the main goals of the research in this dissertation is to help bridge this gap by proposing an integrated space-time dynamic resilience measure for use in disaster resilience quantification and implementing it in a disaster resilience assessment tool.

Currently, multiple forms of resilience-based assessment tools exist. A few of the most popular methods for resilience assessment include: toolkits, indices, models, and scorecards.

Sharifi (2016) and Cutter (2016) both provide recent comprehensive reviews of resilience-based assessment tools. Cutter (2016) identified, described, compared, and contrasted 27 resilience assessment tools. She found that the tools offered multiple different solutions to resilience assessment which she attributes to the fact that (i) resilience is contextual, and (ii) people have different interpretations and motivations for assessing resilience.

Although focused on general resilience applications, Sharifi (2016) provides a critical review of 36 selected community resilience assessment tools and evaluates their performance based on the following criteria: ability to address multiple dimensions of resilience; consideration for cross-scale relationships, capturing temporal dynamics, addressing uncertainties, employing participatory approaches, and developing action plans.

Ultimately, Sharifi (2016) concludes that while progress has been made in the development of resilience-based tools, there has been limited success in accounting for resilience dynamics in time and space and in employing iterative processes that involve scenario-based planning to address assessment uncertainties. Further, he advocates that more attention needs to be paid to stakeholder participation in developing assessment tools. Of the 36 tools that were evaluated, most of the tools were developed for city-scale or community-based applications. Two-thirds of the tools considered some form of quantitative resilience assessment, less than a quarter considered temporal dynamics, and only five (5) offered some form of consideration for threshold behaviour. Sharifi advocates for the increased use of resilience illustration techniques, highlighting strengths and weaknesses of the resilience assessment process, maintained stakeholder engagement and communication, and identifying temporal resilience dynamics. He emphasizes improvement is needed in communicating temporally dynamic resilience assessment results in a digestible way.

Sharifi (2016) provides a comprehensive and thorough evaluation of resilience assessment tools, though he uses the term “tool” to mean any and all of resilience: frameworks, guidance documents, methodologies, and actual resilience implementation / application tools. To avoid duplicating the work, the remainder of this discussion will focus on four (of the 36) resilience assessment tools identified by Sharifi (2016) that consider the following characteristics: quantitative resilience assessment, temporal dynamics, and thresholds (Table 1).

Table 1: The basic characteristics of a subset of quantitative, temporally dynamic, threshold-based resilience assessment tools as originally identified in Sharifi (2016)

	Resilience Assessment Tools (per Sharifi, 2016)			
Author(s)	Shaw et al. (Academia)	UNDP Drylands Development Centre	International Federation of Red Cross and Red Crescent Societies (IFRC)	National Institute of Standards and Technology
Tool Name (if applicable)	CDRI2	CoBRA	FCR	NIST
Year	2010	2014	2014	2015
Source	Shaw et al. (2010)	UNDP (2014)	IFRC (2014)	NIST (2015)
Focal Scale	City	Community, household, city	Community	Community
Resilience Assessment Method [Qualitative, Quantitative, or Both]	Both	Both	Quant.	Both
Interdisciplinary [Y/N]	Y	Y	Y	Y
Temporally Dynamic? [Y/N]	Y	Y	Y	Y
Thresholds?	Y	Y	Y	Y
Format(s)	Toolkit	Toolkit	Toolkit	Toolkit

The Community Disaster Resilience Index (CDRI2) Tool by Shaw et al. (2010) is described by Sharifi (2016) as a toolkit which is quantitative, dynamic, and provides consideration for threshold behaviour, though it was challenging to find additional information supporting the development of this tool. Presumably, it is an extension of the more popular CDRI tool proposed by Peacock et al. (2010), with additional consideration for threshold behaviours. With the limited information on the development and use of this tool, it’s difficult to offer a fair assessment of its value.

The FCR Tool (2014) was developed by the International Federation of the Red Cross and Crescent Societies (IFRC) with a focus on knowledge, health, social connectedness, infrastructure, economy, and natural assets. The tool was developed using a mixed methods approach whereby an initial list of indicators is identified through a review of relevant literature supported by expert input. Weights are assigned to the list of indicators considering priorities of the public. While the FCR tool conceptually sounds valuable, there are no available illustrative examples of the toolkit in use and, as identified in Sharifi (2016), there is limited available information on its implementation.

CoBRA (2014) is a participatory resilience assessment methodology that considers financial, human, natural, physical (resources and infrastructure), and social factors that contribute to the resilience of households and communities facing different types of disruptive events (shocks). Its development was guided through bottom-up participatory consensus on what the stakeholders perceive to be a community and on indicators that should be included in the assessment framework (Sharifi, 2016). Stakeholders also participate in focus group discussions designed to examine if community performance has been perceived as improving over time through the set of resilience indicators. Though this tool can be used to assess community resilience over time, the evaluation is currently restricted to considering how resilience *has* changed and doesn't evaluate potential *future* changes in resilience. While this tool can therefore be valuable for evaluating changes in resilience, it doesn't provide the opportunity to project resilience changes into the future to "build resilience" to future disruptive events. Further, although Sharifi (2016) identified this tool as being both qualitative and quantitative, the tool is primarily qualitative. There is no explicit consideration of space in the resilience assessment process.

The NIST toolkit (2015) is perhaps the most comprehensive of the four tools. It provides a six step process for prioritizing resilience building measures to "build back better". The tool focuses on helping communities integrate resilience plans into their local planning activities that impact their built environment (i.e., infrastructure systems). The NIST Guide includes templates for assessing current system performance levels and setting future goals. The tool comprehensively addresses interactions between various resilience domains, but does not provision for financial aspects of community resilience nor does it explicitly consider spatial interactions. On a positive note, the tool continues to be treated as a "living document" for which materials continue to be released to support new initiatives and tool improvements, improving its longevity.

There are also resilience assessment tools which were not evaluated by Sharifi (2016), since they were released in the years following his review (Table 2). Looking at the characteristics of these additional tools, there has been a mix of qualitative and quantitative tools released. Most of the more recent tools do not provision for spatial dynamics nor do they capture the importance or influence of threshold-influenced resilience behaviour. The remainder of this section discusses these tools.

Joerin et al. (2012) presents a resilience framework (CDCRF) which addresses the various system states pre-, during, and post-disaster. They also advocate for more quantitative approaches to resilience assessment. However, the framework fails to identify thresholds as a significant contributor to resilience and recovery and offers a simplistic, incomplete example of resilience assessment. The study also points out one of its own limitations in operating on solely the household level and neglects the support between various other levels of stakeholders (e.g. governments, cities, etc.). The scope of the framework is limited to within two wards located next to the river and therefore does not capture the effects that flooding may have on households located outside the floodplain (external and indirect impacts) or influences across multiple scales. The case study focused on two regions in Chennai, India, however some useful information may be taken from the findings and extended to a more global whole; those which are "inherently human" and neither a function necessarily of place-based or interest-based communities.

The resilience concept is an effective way to bring multiple stakeholders, disciplines, and countries together to address both short and long-term challenges in the disaster management community. This practice is commonly referred to as "resilience thinking" and can be a useful way to help stakeholders conceptualize and formalize their own systems. However, resilience thinking without resilience assessment or resilience practice often leads to formidable system definitions, but ambiguous guidance for effective use of resilience in practical disaster management applications. With this understanding, a number of tools have recently been developed to for resilience assessment. Table 2 presents a list of some of the tools recently released by organizations leading resilience assessment techniques and tools.

The US Environmental Protection Agency (EPA) recently released a Water Network Tool for Resilience (WNTR) that analyses the resilience of water distribution networks to disruptive events (US EPA, 2017). The tool is Python-based, supported by an application programming interface (API). The API allows changes to be made to the structure of the distribution network and changes in network operations. While the tool is both an interesting and meaningful contribution to the field of engineering resilience assessment, it lacks the ability to represent or quantify cross-domain relationships important to holistic disaster resilience.

The CARE Resilience Marker tool (CARE, 2018) allows teams to self-assess how well resilience is integrated into their projects and provides a starting point for further reflection on integrating resilience throughout the project cycle. The Resilience Marker Tool is used across various CARE projects to provide insight into the overall performance of integrating resilience and provides for assessment and comparative analysis. The Resilience Marker Tool is implemented via a fillable form. The user is prompted to answer questions related to resilience concepts to develop a resilience profile and although the tool attempts to be temporally dynamic, it's actually more quasi-dynamic; the process needs to be completed by the user again at a different stages in the project to identify changes over time and approximate project resilience dynamics.

Infrastructure Canada released a guidance document called Climate Lens (2018) which is intended to act as a requirement for funding eligibility in Infrastructure Canada's Investing in Canada Infrastructure Program (ICIP), Disaster Mitigation and Adaptation Fund (DMAF), and Smart Cities Challenge. The document claims to be intended to act as an incentive to reduce the carbon footprint and/or consider potential climate change resilience of Canadian infrastructure projects. While the document provides some useful direction for infrastructure projects to begin considering mitigation and adaptation in otherwise traditional engineering projects, the extent of the climate change resilience assessment is essentially a risk assessment that includes analysis of future climate conditions and risk treatments. It appears to mention resilience, without fully describing what is meant by the term, and then continue to use it almost synonymously with risk.

The United Nations Office for Disaster Risk Reduction (UNDRR) released a Disaster Resilience Scorecard for Cities tool (UNDRR, 2017). The Scorecard provides a set of assessments that allows local governments to assess their disaster resilience, structuring around UNDRR's Ten Essentials for Making Cities Resilient. It can also be used to help monitor and review progress and challenges in the implementation of the Sendai Framework for Disaster Risk Reduction. However, this tool is not dynamic and although quantitative in a way, it relies solely on qualitative answers to construct quantitative measures.

RAND Corporation created a resilience toolkit that contains multiple tools primarily driven by qualitative resilience assessment with a focus on stakeholder engagement and education (Acosta et al., 2015; Acosta et al., 2016). These are useful tools for resilience discussion and public participation, but lack the ability to measure resilience and do not explicitly account for dynamics.

ResilSIM (University of Western Ontario, 2016) is a decision support tool which implements the space-time dynamic resilience measure as presented in this dissertation. It's designed to estimate resilience to flooding events in Toronto, Ontario and London, Ontario. It uses a simplified generation of flood inundation maps using the Modified Rational Method to compute effective flood depths and identify impacts. Resilience assessment is calculated for a period of time, and simulates temporal dynamic resilience. It tests resilience response to various adaptation options to assist decision makers (planners, engineers, government officials) select preferred options. Though the tool is similar in nature to the work presented in this dissertation, it claims to be dynamic in space while the resilience calculation is performed for only a single geographical unit. Furthermore, it does not provision for cross-boundary, multi-scale, or spatial interrelationships.

While the above tools are certainly important for provoking thoughtful discussions surrounding resilience concepts, establishing, characterizing resilience, most of them don't adequately address the temporal, nor spatial, dimensions of resilience. Any of the tools that consider threshold behaviour describe it in primarily a qualitative way.

Table 2: A list of recent resilience assessment and quantification tools to complement the resilience tools identified by Sharifi (2016)

	Additional Resilience Assessment Tools					
Author(s)	US EPA	CARE, CCRP	Infrastructure Canada	UNDRR	RAND Corporation	University of Western Ontario
Tool Name (if applicable)	Water Network Tool for Resilience (WNTR)	Resilience Marker	Climate Lens	Disaster Resilience Scorecard for Cities	Resilience Toolkit	ResilSIM
Year	2018	2019	2018	2017	2015 / 2016	2016
Source	US EPA (2018)	CARE (2018)	Infrastructure Canada (2018)	UNDRR (2017)	RAND (2015a,b,c) RAND (2016)	UWO (2016)
Focal Scale	Various; Water Distribution Network	Project-based	Project-based	City	Various	City
Resilience Assessment Method [Qualitative, Quantitative, or Both]	Quant.	Qual.	Both	Both	Qual.	Quant.
Interdisciplinary [Y/N]	N	Y	Y	Y	Y	N
Temporally Dynamic?	Y	N	N	N	N	Y
Thresholds?	N	N	N	N	Y (one of the tools)	N
Format(s)	Simulations via Python package	Self assessment scorecard (survey)	Risk evaluation exercise including risk matrices and narratives	Stakeholder workshops & assessment scorecard	Interactive Learn, Tell, Activities, and Videos	Simulation and Gaming

As identified in the comprehensive review by Sharifi (2016), and further supported by the review of additional tools in Table 2, there has been a surge in the production of resilience assessment tools over the past decade. These tools serve as good starting points and offer valuable insight into resilience behaviour, but at the same time, there are many remaining challenges and much room for improvement in disaster resilience quantification techniques and tools. The aforementioned tools have achieved limited success in effectively quantifying disaster resilience, capturing dynamics, and accounting for thresholds.

2.4 Summary of Motivation for the Research

Though the above review of existing literature and tools is not exhaustive, it’s evident that coastal cities face increasing pressure from urbanization, hydrometeorological hazards, and climate change. It’s important to estimate the potential impacts that climate change influenced hydrometeorological hazards may have on cities to make more informed decisions related to disaster management.

Viewing disaster management through a resilience lens can provide valuable insight into how systems, such as cities, respond to and recover from climate change influenced hazards. The resilience concept is crucial for developing sustainable disaster management strategies. However, despite the recent uptick in social, political, and scientific interest in resilience concepts, there remains a gap in in available systematic quantification methods and tools to implement disaster resilience in a practical, meaningful way. Through the review of existing literature and resilience assessment tools, the following three significant research gaps have been identified:

Issue 1: There is a growing recognition that resilience is temporally and spatially dynamic, however improvements are still needed to explicitly account for spatio-temporal dynamics in resilience quantification.

Issue 2: Most existing resilience tools fail to identify thresholds as a significant contributor to the expression and assessment of dynamic disaster resilience and provide no means for its explicit inclusion in resilience quantification.

Issue 3: Improvements are still needed to explicitly quantitatively account for spatio-temporal dynamics in resilience assessment tools.

The remainder of this dissertation presents research to help address these gaps. The theory behind the research presented in this dissertation and in developing a DRST is built on the fundamental concept that a resilient city is a sustainable network of physical (constructed and natural) systems and human communities (social and institutional) that possess the capacity to survive, cope, recover, learn, and transform from disturbances by: (i) reducing failure probabilities; (ii) reducing consequences; (iii) reducing time to recovery; and (iv) creating opportunity for development and innovation from adverse impacts. To deal with the shortcomings in existing resilience models and to provide a conceptual basis for establishing baselines for measuring resilience, this research introduces a space-time dynamic resilience measure (STDRM). This measure is implemented in a coupled spatio-temporal dynamic simulation model to capture the process of dynamic disaster resilience in both time and space. The ability to quantify disaster resilience offers an avenue for improved resilience assessment and the opportunity to enhance the resilience of systems through reducing the impact of disturbances and enhancing expeditious recovery.

Chapter 3

3 FRAMEWORK AND METHODOLOGY FOR RESILIENCE QUANTIFICATION

As identified in the review of scientific literature, presently the most common approaches to urban disaster management are focused on disaster risk reduction, but there is momentum behind identifying additional ways to quantify disaster resilience. Resilience is the ability of a complex system to respond and recover from disasters. It includes conditions that allow the system to absorb impacts and cope with an event which includes post-event adaptive processes that facilitate the ability of the system to re-organize, change, and learn in response to a threat (Simonovic and Peck, 2013).

To address some of the shortcomings in existing resilience models, a mathematical framework was developed to combine physical, economic, engineering, health, and social impacts and capacities for a more holistic, integrated form of disaster resilience. A schematic of the framework and implementation methodology is presented in Figure 2. Within this framework, a space-time dynamic resilience measure (STDRM) is introduced to characterize dynamic disaster resilience in both time and space.

As stated by Haines (2011), questions related to the resilience of a system are answerable only when the threat (disturbance event) scenario (or a set of scenarios) and its timing are specifically identified. Therefore, the aim of this chapter is to lay the contextual and methodological framework for dynamic resilience quantification which was implemented to assess the resilience of coastal cities to climate change influenced hydrometeorological disasters. As it relates to Figure 2, this chapter **sets the resilience landscape**.

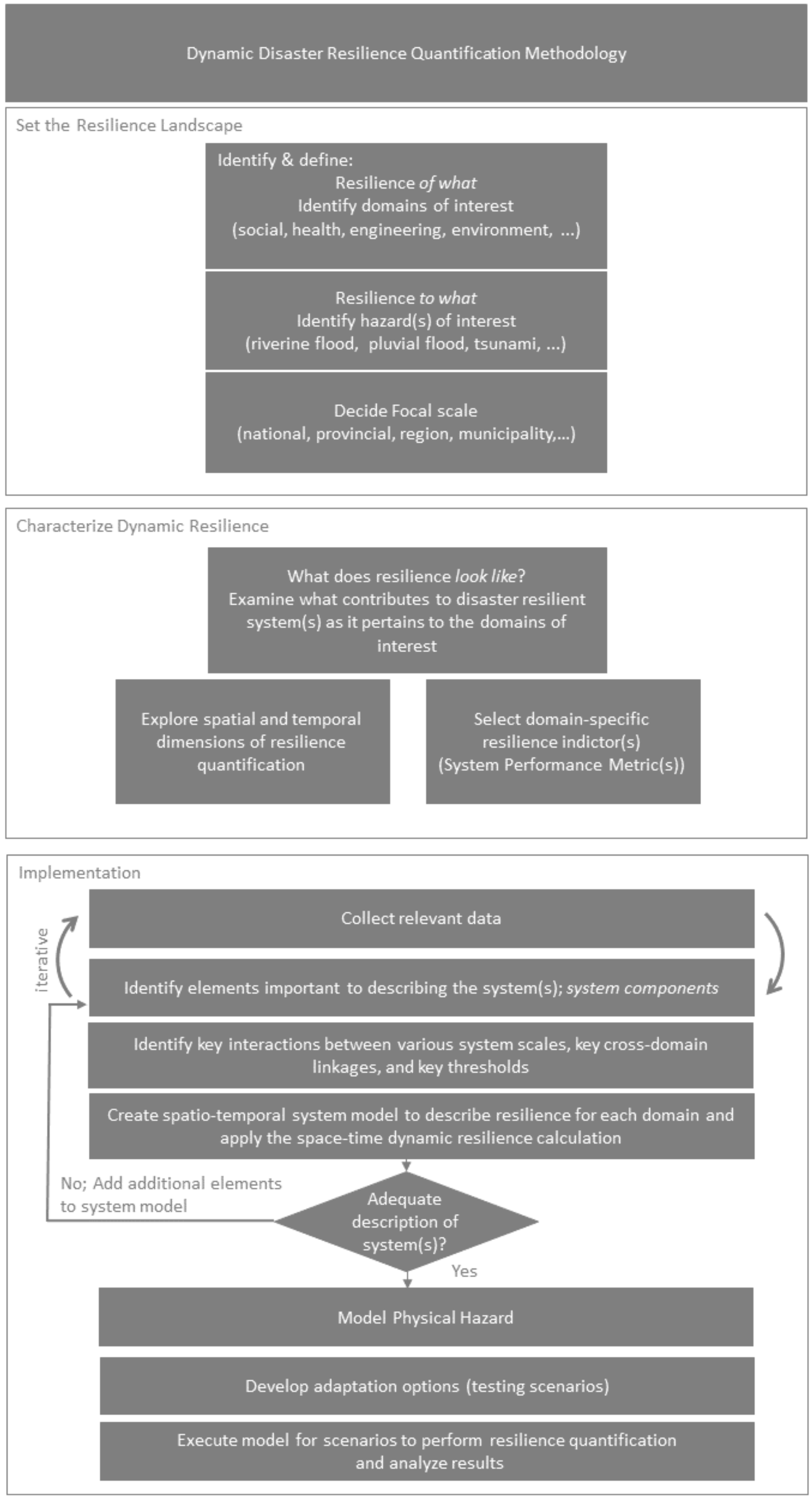


Figure 2: Framework for disaster resilience quantification and methodology for its implementation

3.1 Setting the Resilience Landscape: Resilience Definition

Drawing from resilience literature in the fields of physics, ecology, and hazards from Chapter 2, some common elements in the definitions of resilience include:

1. Degree of losses, damages, and community disruption;
2. Ability and capacity to adapt and adjust to shocks to the system;
3. Rate that systems return to a functioning state;
4. Is dynamic in time and space; and
5. Acknowledges that post-shock functioning levels may not be the same as pre-shock levels.

Disaster resilience as considered in this work can therefore be considered as a combination of these elements, and most importantly, this research considers resilience to be a dynamic process.

3.2 Setting the Resilience Landscape: Resilience Quantification

In this research, the method of resilience quantification is based on:

1. Dimensions of resilience;
2. System impacts and capacities;
3. Thresholds; and
4. Interdisciplinary resilience domains (health, economic, engineering, and social).

This method of resilience quantification is particularly unique to this research. Considering multiple dimensions of resilience (both space and time) means that the representation and calculation of resilience in this research is dynamic. While the literature has addressed the importance of capturing dynamic behaviours of resilient systems, very few methods explicitly include both spatial and temporal dimensions. The ability to capture both dimensions is one of the major contributions of this research. In addition, the resilience quantification method in this research considers system impacts and capacities. That is, there are various factors which may “take away” or “build” resilience. Impacts of a disturbance (such as a disaster) to a system are driven by that systems’ inherent vulnerability (or sensitivity) to suffering consequences as a result of the disruption. This level of impact will also be influenced by the physical magnitude and characteristics of the disturbance. Human, natural, and manmade systems all have various inherent capacities to cope with disturbances. These systems also have adaptive capacities which may result in additional mechanisms for coping with disturbances and building resilience. These system capacities are explored through what are herein referred to as “the four R’s of Resilience” (Robustness, Redundancy, Rapidity, and Resourcefulness) whose concept was originally proposed in Bruneau, et al. (2003) and has since been refined by Simonovic and Arunkumar (2016). Finally, the resilience quantification method in this research considers a comprehensive, interdisciplinary approach to capturing the resilience of a variety of interconnected systems. Economic, engineering, health, and social systems are fundamental to the overall functioning of a city system. The impacts, capacities, and relationships between these sub-domains are explored in this research.

The following sections provides further details on these three resilience quantification considerations and the important role they play in formulating a comprehensive definition of disaster resilience.

3.2.1 Dimensions of resilience

The starting point in the development of a new system framework for quantification of resilience is an engineering hazard-based definition of resilience as a static measure that reduces the probability of failure (Kjeldsen and Rosbjerg, 2004; Cutter, et al., 2008). The main shortcoming of the traditional engineering approach is that it often fails to capture important social and governance factors that occur at the local level, or to account for the resilience of the natural environment. Resilience has two qualities: inherent (functions well during non-crisis periods); and adaptive (flexibility in response during disasters) and can be applied to the physical environment (built and natural), social systems, governance networks (institutions and organizations), and economic systems (metabolic flows). To address some of the shortcomings in existing resilience models and to provide a conceptual basis for establishing baselines for measuring resilience, a space-time dynamic resilience measure (STDRM) is proposed. The STDRM is designed to capture the relationships between the main components of resilience. The STDRM is theoretically grounded in a systems approach, open to empirical testing, and can be applied to address real-world problems in urban communities.

Resilience is still a relatively new, but recently popular, topic in disaster management. As indicated in the literature review, much of disaster resilience research has focused on qualitative conceptualizations of disaster resilience with little attention to resilience quantification and implementation in the management of disasters. Attempts to quantify resilience thus far have evaluated resilience as a single state of the system. This approach does not adequately represent the real-world complexities or dynamics of disaster resilience drivers and barriers, whereas a system's resilience may fluctuate in time before, during, and following the occurrence of a disaster. The measure of resilience is also affected by the location in space. Therefore, the two important dimensions defining the STDRM are time (t) and space (s):

$$STDRM = f(t, s) \tag{3.1}$$

These dimensions are important to accurately represent real-world dynamic interactions between natural disasters and city systems. In mathematical form, the STDRM for various impacts (i) is represented by the area under the system performance graph between the beginning of the system disruption event at time (t_0) and the end of the disruption recovery process at time (t_r). The STDRM can be expressed in general terms by the concepts illustrated in Figure 3, where dynamic evolution of resilience (ρ) may result in one of three possible states:

1. Post-disturbance performance level equal to pre-disturbance level, represented by the area under the solid line ($P_0^i(t, s)$)

2. Post-disturbance performance level is insufficient to bring it back to a pre-disturbance level, represented by the area under the dashed line ($P^{t}_{e'}(t,s)$); and

3. Post-disturbance system performance achieves above the pre-disturbance level, represented by the area under the dash-dotted line ($P^{t}_{e''}(t,s)$).

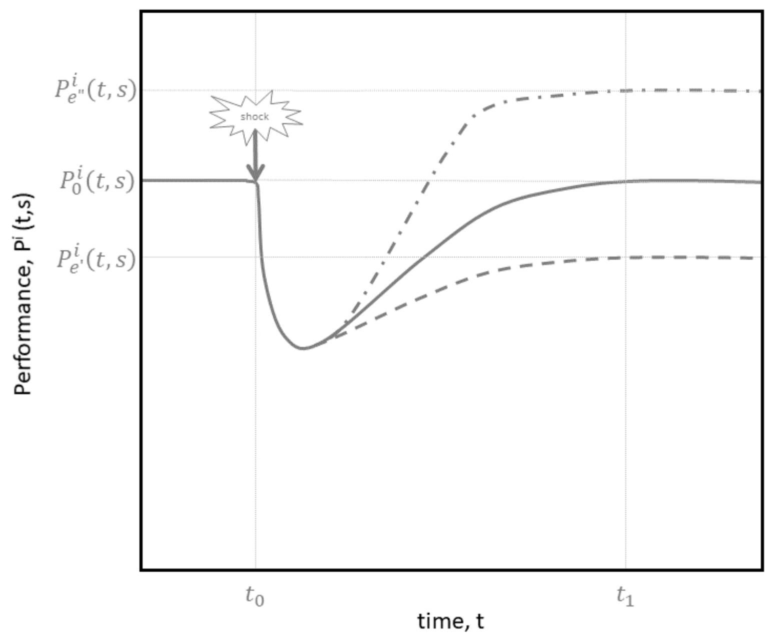


Figure 3: Conceptual definition of STDRM using system performance graph (modified after Simonovic and Peck, 2013)

3.2.2 Impacts and capacities

The STDRM is defining the level of system performance in time (t) and location in space (s). The measure integrates various domains (i) that characterize the impacts and capacities of disasters on an urban community. The five domains which are used to define disaster resilience in this work are: physical ($i = 1$), economic ($i = 2$), engineering ($i = 3$), health ($i = 4$), and social ($i = 5$). Measures of economic system performance may include number of businesses closed due to disaster [$no. businesses$], lost economic activity [\$] or municipal level GDP [$million$ \$]. Measures of engineering system performance may include length of road $[km]$ inundated during a flood, the residential area $[km^2]$ that is inundated during a flood, or the damages $[CAD\$]$ to municipal infrastructure. Measures of health system performance may include the number of local emergency shelters $[no. shelters]$, number of doctors available per capita $[no. doctors/km^2]$, or number of people afflicted by disease $[no. people]$. Measures of social system performance may include the number of people who lose their homes in a flood $[no. people]$, amount of time $[days]$ to receive insurance payments, or less tangible qualities such as the sense of community $[dmnl]$. Each system performance indicator used in the quantification of impacts may therefore be expressed in different units $[\$, days, people, etc.]$, but can be combined across domains for calculation of total resilience.

Changes in system performance, and subsequently resilience, can be represented mathematically as:

$$\rho^i(t,s) = \int_{t_0}^{t} \left[P_0^i(t,s) - P^i(t,s)\right] dt \tag{3.2}$$

$$where \;\; t \in [t_0, t_r]$$

Equation (3.2) will have the units of the selected domain impact indicator. Therefore, to calculate an integral resilience measure across different domain impacts, the value of $\rho^i(t,s)$ is normalized as follows:

$$r^i(t,s) = 1 - \frac{\int_{t_0}^{t} \left[P_0^i(t,s) - P^i(t,s)\right] dt}{\int_{t_0}^{t} P_0^i(t,s) dt} \tag{3.3}$$

This can be simplified to:

$$r^i(t,s) = \frac{\int_{t_0}^{t} \left[P^i(t,s)\right] dt}{\int_{t_0}^{t} P_0^i(t,s)\, dt} \tag{3.4}$$

When there is no degradation in performance, normalized resilience is one. When the resilience value is zero, the performance of the system has been entirely and immediately lost. In other words, when performance does not deteriorate due to disruption, $P_0^i(t,s) = P^i(t,s)$, the loss of resilience is zero, and the system is in the same state as at the beginning of disruption. When all of system performance is lost, $P^i(t,s) = 0$ and the loss of resilience is at a maximum. As illustrated in Figure 4, performance of a system which is subject to a disturbance (in this case a hazard event) at time t_0, could cause significant damage such that system performance is immediately reduced and takes time to recover (t_r). Disturbance to a system causes a reduction in system resilience from a value of one at t_0 to some value $r^i(t_1, s)$ at time t_1 (Figure 5). Duration of the recovery is usually greater than the duration of disturbance. Ideally, resilience should return to one at the end of the recovery period and the faster the recovery (based on the slope of the recovery line), the better. The system restores itself over time until t_r, the time at which it is completely repaired, indicated by achieving pre-disaster performance level. In this example, additional serviceability measures are incorporated into the repaired infrastructure which improves system performance and achieves higher than pre-disturbance levels. If the systems' performance is enhanced, it is possible that the time to recovery can be reduced and the resilience value may surpass the pre-disturbance level. However, it is entirely possible that if system performance is poor and improvement is slow, the recovery period will be longer and in some cases the system may never return to the pre-disturbance level.

By time t_r, system performance has exceeded the original system performance level. When the loss of system resilience (shaded area between t_0 and t_1) is equal to the recovery of system resilience (shaded area between t_1 and t_r), then the system resilience is equal to 1 at the end of the recovery period, t_r.

There are three potential outcomes of the resilience simulation:

1. Resilience returns to pre-disturbance level ($r^i = 1$) represented by the solid line in Figure 5;

2. Resilience exceeds pre-disturbance level ($r^i > 1$) represented by the dash-dotted line in Figure 5; or

3. Resilience does not return to pre-disturbance level ($r^i < 1$) represented by the dashed line in Figure 5.

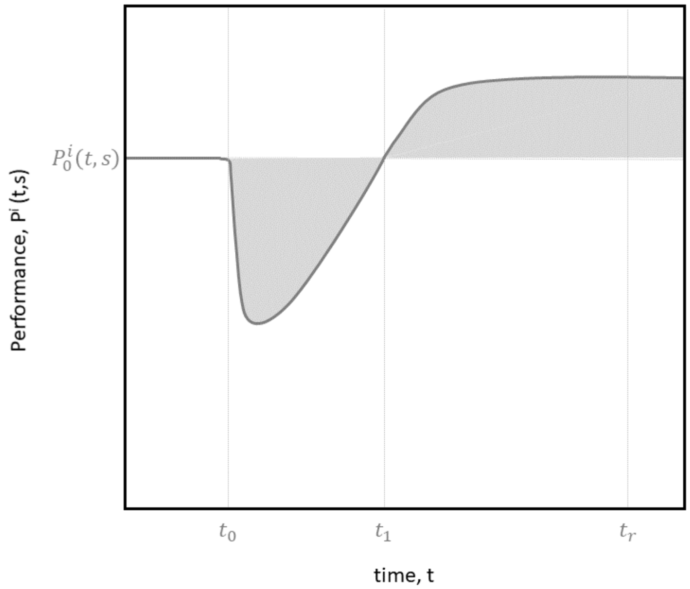


Figure 4: Illustration of dynamic system resilience in performance space

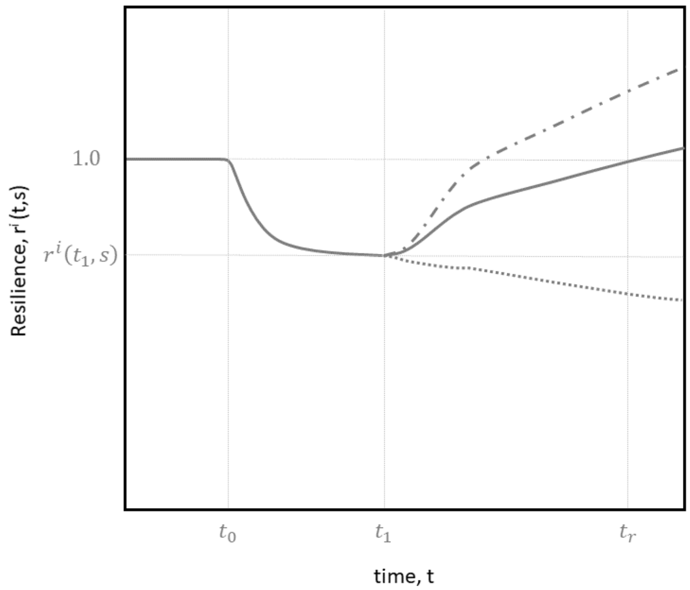


Figure 5: Illustration of dynamic system resilience in resilience space demonstrating examples of resilience which returns to pre-shock levels (solid line); exceeds pre-shock levels (dash-dot line); and does not recover to pre-shock levels (dotted line)

One way of integrating various impacts is to consider the integral STDRM over all impacts (i), calculated as:

$$R(t,s) = \left\{\prod_{i=1}^{M} r^i(t,s)\right\}^{\frac{1}{M}} \tag{3.5}$$

$$where\ M\ is\ the\ total\ number\ of\ impacts$$

Since the calculated value of $R(t,s)$ is dependent on time and location, the outcome of the STDRM computation is a dynamic map that shows change of $R(t,s)$ in time and space (Figure 6). This schematic presentation of the STDRM computational process illustrates different resilience values in space, indicated by the shades of red colour. Spatial units of the analysis are shown as grid cells for the simplicity of the concept illustration. The spatial resolution for resilience analysis may require aggregation or disaggregation of indicators selected for description of various impacts, (i). This is, in part, driven by the availability and resolution of resilience indicator data. For STDRM implementation in Canadian cities the dissemination area (DA) is a useful spatial unit for analysis. This area is defined by Statistics Canada (2018) as *"a small, relatively stable geographic unit composed of one or more adjacent dissemination blocks. It is the smallest standard geographic area for which all census data are disseminated"*. Any resilience indicator which relies on Statistics Canada data is readily available in this form and allows easy integration with other DA-level resilience data. Additional details pertaining to spatial resolution and scale of analysis are contained in Section 3.3 describing the development of the Resilience Simulator Tool (DRST).

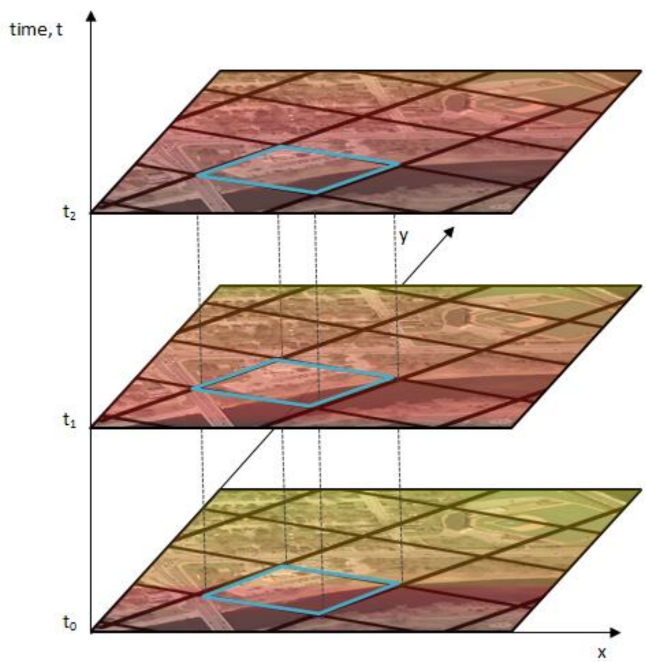


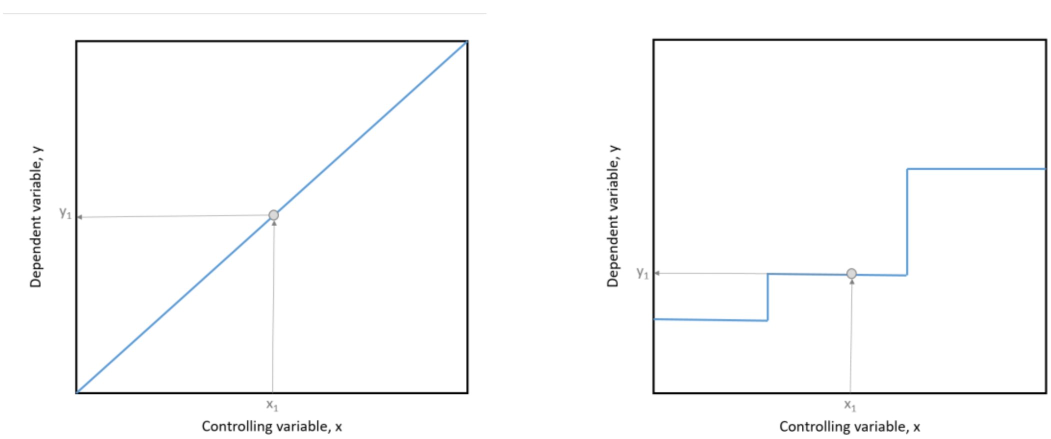
Figure 6: Illustrative dynamic resilience map in time (t) and space (x,y) using STDRM where the changing colours represent changes in resilience

3.2.3 Thresholds

Thresholds are important to the behaviour of systems and in defining and quantifying disaster resilience. Thresholds are used to define the limits of a system, the safe operating range for which a system will function as intended. Beyond these thresholds, a system may function differently, or not at all. Operating outside of thresholds can initiate or break critical feedback processes and can cause a system to operate under a different regime and exhibit different, often undesirable, system behaviour. Thresholds may represent limits to growth or tipping points of a system (Bennett et al., 2005). Walker and Salt (2012) suggest there are four (4) types of threshold-related behaviours as follows (illustrated in Figure 7):

1. No threshold effect;
2. Step-change;
3. Alternate stable state; and
4. Irreversible change.

(a) (b)



(c) (d)

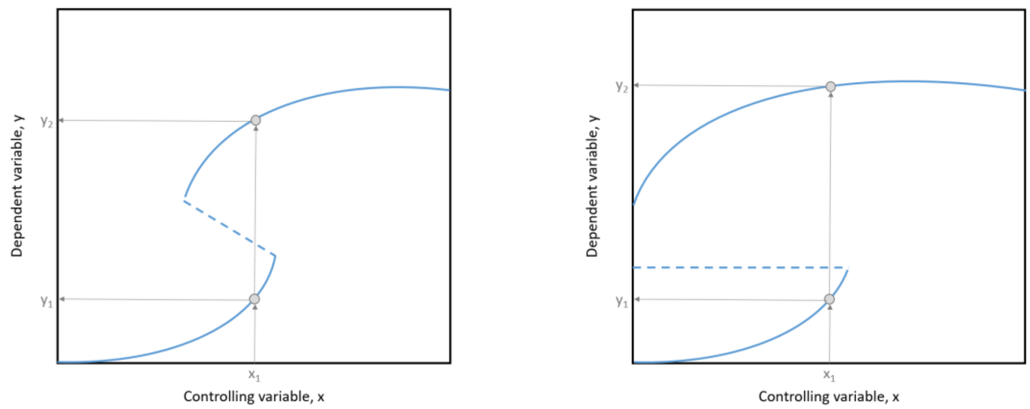


Figure 7: Four types of threshold responses including (a) no response; (b) step-change; (c) alternate stable state; and (d) irreversible change (adapted from Walker and Salt, 2012)

Once a threshold is crossed, it's possible that other system variables may also be influenced and undergo significant changes. Thresholds in one disaster resilience domain may influence thresholds in other domains. When a key threshold is crossed, it may also trigger (or accelerate) the crossing of multiple other thresholds. This type of behaviour is what often leads to cascading system failures.

Some thresholds are well understood, particularly in physical systems; for example, the conversion of water to ice at a temperature of 0°C. However other thresholds – particularly in social and health systems – are more difficult to identify and are not always well understood. Moreover, threshold values are often not apparent until they have already been crossed, which means they often go unnoticed until it's too late. This poses a challenge to defining reliable thresholds in a system model. The process often becomes iterative and, in many instances, the identification of system thresholds is based on expert opinions and/or previous experience.

To further add to the complexity of system behaviour, thresholds are not always fixed. That is, it's possible for certain thresholds to move (Walker and Salt, 2012). Changes in a system can move a variable threshold up or down, thereby increasing or decreasing a systems safe operating space (Figure 8). The shrinking or expansion of the safe operating space caused by the movement of thresholds has an impact on system resilience (Bennett et al., 2005). At any given time, it's important to know how far away a system state is from a threshold and how fast the variable is moving towards or away from the threshold. It's therefore important to know what defines the position of a threshold, and to determine whether it's possible for this threshold to move, in order to properly manage resilience.

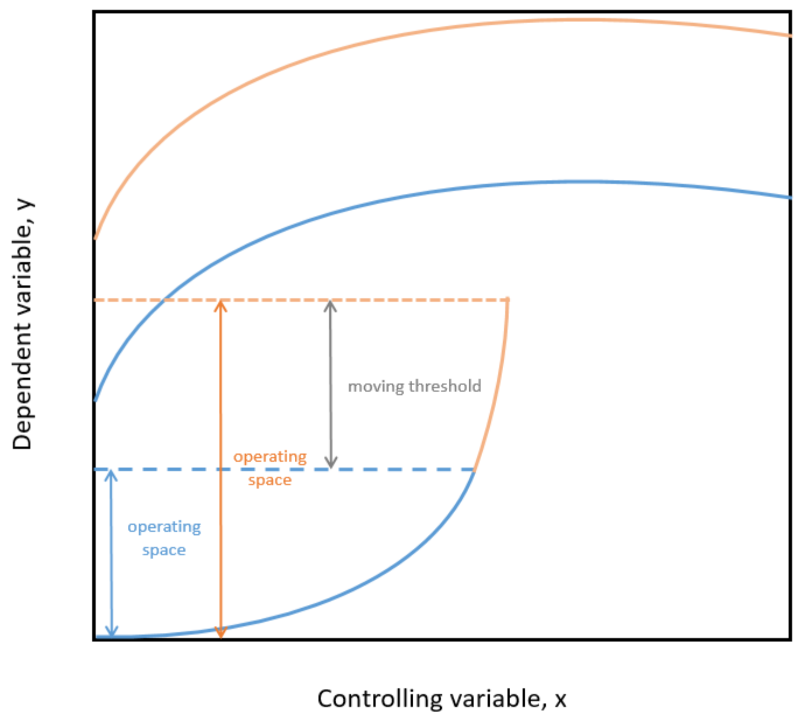


Figure 8: Schematic example of a moving threshold

Not all systems or system variables possess thresholds, but it's important to identify which ones do. The quantification of disaster resilience as included in this research relies on key thresholds to define domain (economic, engineering, health, and social) subsystem responses to hazards. These thresholds come in the form of various system elements that contribute to system behaviour and subsequently, to system performance. In fact, it's possible to have many relationships between controlling (*x*) and dependent (*y*) variables within system elements that defines a system's performance. However, it's also possible that thresholds be expressed as part of the description of system performance itself. In other words, a threshold can be expressed in the units of the performance indicator [*$*, *days*, *people*, *etc.*] and may be represented as a constant or function over time. The threshold acts as an indicator of *safe operating space* and has implications on system resilience. A system's proximity to a performance threshold is governed by:

1. The initial state of the system (how close the system is to a threshold to begin with); and

2. The rate at which the state of the system is approaching or receding from the threshold (the redundancy and resourcefulness of the system).

This means that even if a system's performance remains the same, the system's resilience can be increased (or decreased) by moving the threshold up or down within the performance space. For example, Figure 9 shows two conceptual scenarios of a system that has been shocked. The two scenarios have the same performance curve, the only difference is that the threshold in Figure 9a is higher than in Figure 9b. Scenario A has less safe operating space (i.e. the performance curve is closer to the threshold) than Scenario B. Therefore, Scenario B should be categorized as having a higher adaptive capacity – and higher resilience – than Scenario A, even though the impacts (after disturbance) were the same.

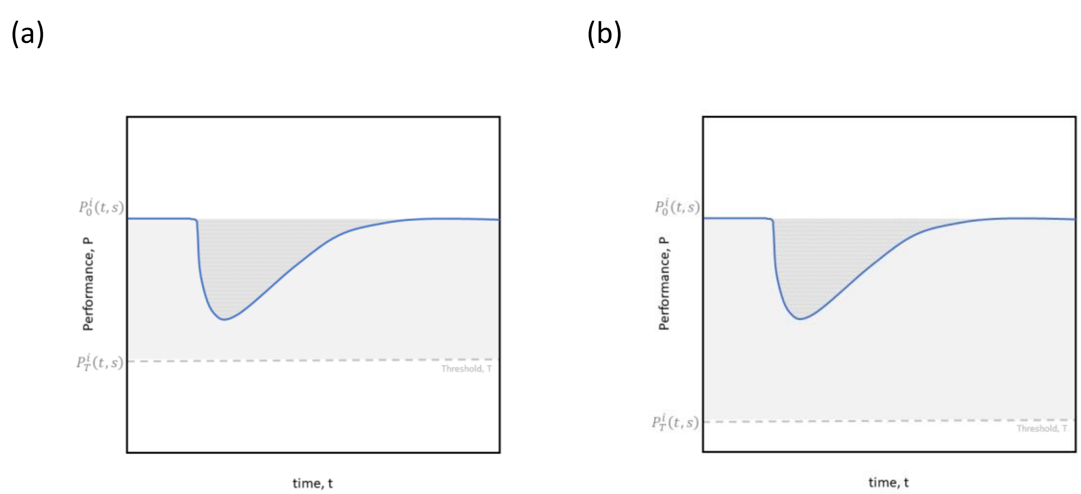


Figure 9: Schematic of conceptual thresholds in performance space for (a) Scenario A: higher threshold; and (b) Scenario B: lower threshold

The previous expression of resilience quantification in equations 3.2 and 3.3 did not account for the potential influence of thresholds on system performance. So, systems which have key thresholds (defined as constants) linked directly to system performance, may therefore require a modified description of system resilience as follows:

$$\rho^i(t,s) = \int_{t_0}^{t} \left[P_0^i(t,s) - P^i(t,s) - P_T^i(t,s)\right]dt \tag{3.6}$$

$$where \;\; t \in [t_0, t_r]$$

Resilience with the inclusion of a threshold can therefore be defined as:

$$r^i(t,s) = 1 - \frac{\int_{t_0}^{t} \left[P_0^i(t,s) - P^i(t,s) - P_T^i(t,s)\right]dt}{\int_{t_0}^{t} \left[P_0^i(t,s) - P_T^i(t,s)\right]dt} \tag{3.7}$$

Although it is likely that a threshold value may be specified as a constant, this general expression leaves the opportunity to capture the impact of a threshold as a function. Though in a more simplified form, it may still be represented as:

$$r^i(t,s) = \frac{\int_{t_0}^{t} \left[P^i(t,s) - P_T^i(t,s)\right]dt}{\int_{t_0}^{t} \left[P_0^i(t,s) - P_T^i(t,s)\right]dt} \tag{3.8}$$

Though it may be useful to express a system in terms of thresholds, they do present challenges in their practical implementation. Due to the inherent difficulties associated with identifying the presence and magnitudes of thresholds, any subsystem or variable identified as having thresholds may need to be iteratively incorporated in order to properly describe the system.

3.3 Setting the Resilience Landscape: Focal Scale

The concept of scale is important in the definition and behaviour of complex systems and plays an important role in disaster resilience modelling. There are various scales relevant to disaster management including: governance, political, and decision-making scales; information management and information dissemination scales; and geophysical boundaries or geographic scales. At any one time, disaster management is occurring at multiple scales across multiple systems. The complexity of disaster management necessitates an understanding of important systems and the scales that they operate within. An increased understanding of cross-scale relationships can enhance the coordination and effectiveness of disaster management efforts.

All complex systems, and their dynamics, are scale dependent. It's therefore important to identify the "scale of interest" at an early stage of system description. The scale of interest (the focal scale) for this research is the Regional scale (a collection of lower-tier municipalities). Regions, (and cities) can be described as complex systems of systems which operate over a large range of scales. Understanding what happens at one scale of the system is important, but offers an incomplete story, as each scale of a system influences another. For example, if considering scale from a bottom-up approach, individual people influence neighbourhoods, which influence communities, which influence cities, which influence a province or nation. The reverse is also true; nations can influence cities, and cities influence communities, which influence neighbourhoods, which influence individual people. Therefore, to appropriately understand a particular system is to acknowledge that there are influences from other scales above (larger scale) and below (smaller, embedded scale) the focal system scale that are constantly interacting (Figure 10). A system cannot be appropriately managed by considering only one scale.

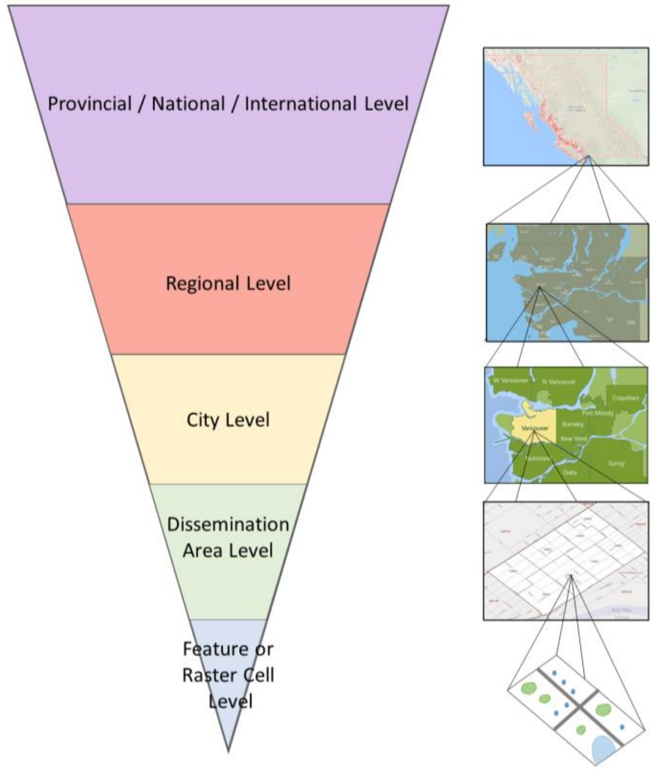


Figure 10: A non-exhaustive example of multiple (hierarchical/vertical) multi-level governance scales which may be involved in the mitigation, planning, response, or recovery decisions and/or actions in the event of a natural disaster

There is disaster literature which supports the notion that the most effective time to implement resilience measures is during the disaster recovery phase, when there is general agreement and motivation between the various scales of a system (Walker and Salt, 2012). This is the time when individual, local, provincial, and even national motivations are high, which is also often accompanied by a surge in financial and human resources.

Therefore, to appropriately capture disaster resilience at the Regional scale, consideration must also be given to how resilience is influenced by other scales. As further discussed in the Implementation chapter of this dissertation, conceptualizing the Region (focal scale) as a system of systems can help capture cross-scale dynamics. The implementation of which can be achieved using integrated spatio-temporal dynamic simulation models.

3.3.1 Characterizing Resilience: Interdisciplinary Resilience Domains

Quantification of disaster resilience requires **characterization of resilient systems**. It's necessary to define domains (systems) of interest and identify what contributes (or does not contribute) to resilient system behaviour. Presently, there is still a gap in the universal standardization of disaster resilience metrics and agreement even on qualitative measures of disaster resilience remains a challenge. For this research, four (4) domains were identified as significant to resilient city systems: economic, engineering, social, and health. This decision was based on relevant resilience literature and driven by external (project-based) factors.

The integrated resilience measure proposed in this research builds on the technical-organizational-social-economic integration concept by Bruneau, et al. (2003) by considering the resilience measure to be dynamic in both time and space. It also expands on the approach of Bruneau, et al. (2003) by considering the spatial interactions between physical, economic, engineering, health, and social domain responses to system disruptions and provides a more comprehensive representation of disaster resilience.

Chapter 4

4 IMPLEMENTATION: AN INTEGRATED CITY SYSTEM

The methodology in this chapter is predicated on the recognition and acceptance of cities as complex and dynamic systems made up of many smaller, multi-domain, integrated sub-systems. These sub-systems interact with each other in any number of ways, across multiple scales, and are managed and influenced by a number of various stakeholders including engineers, architects, land developers, public safety managers, transportation managers, council, committees, and community organizations.

The practice of trying to understand cities is not new. There are many professions and disciplines that have looked at various resilience indices and metrics; some of which were described in Chapter 2. With recent advances in the collection, organization, and management of Big Data, there is motivation and capability to understand complex systems and the methodological approach presented in this Chapter offers one way to represent the complexities of city systems and quantify disaster resilience.

System dynamics simulation modelling can help inform disaster management policies and decision making by providing insight into the underlying structure and behaviour of complex real-world city systems. In this research, a city is modeled using system dynamics as a network of interacting economic, engineering, health, and social subsystems. Everyday basic functioning of a city was simulated to provide a baseline scenario for comparison, and then this system was “shocked” by a climate change influenced hazard to estimate the potential impacts in each city domain. Resilience concept was used as the primary means of evaluating various adaptation options to help inform future disaster management practice.

The proposed methodological approach to modelling and quantifying dynamic space-time disaster resilience involves a systems approach. This chapter describes the implementation of the resilience methodology. With reference to Figure 2, this chapter focuses on **implementation of dynamic disaster resilience quantification.**

4.1 Implementation: Disaster Resilience Simulation Tool (DRST)

The basis for developing a DRST relies on the definition of a city as a sustainable network of physical (constructed and natural) systems and human communities (social and institutional) that possess the capacity to survive, cope, recover, learn, and transform from disturbances by: (i) reducing failure probabilities; (ii) reducing consequences; (iii) reducing time to recovery; and (iv) creating opportunity for development and innovation from adverse impacts.

The DRST combines system dynamics simulation and spatial analysis to understand the behaviour of complex city systems subject to climate change influenced disasters. This approach was selected to capture the dynamic characteristics of disaster impacts and disaster resilience behaviour of coastal cities. Adaptation scenarios are used to introduce potential adaptation strategies into the resilience model, observe the effects on model behavior, and identify areas where adaptation policy may be most effectively implemented. These adaptation scenarios may also be used to modify physical hazard inputs (e.g. increase in rainfall intensity) and simulate the impacts of multiple consecutive or concurrent hazards. The remainder of this chapter will describe the basic temporal and spatial concepts used to develop the DRST. The general implementation methodology is presented in Figure 11.

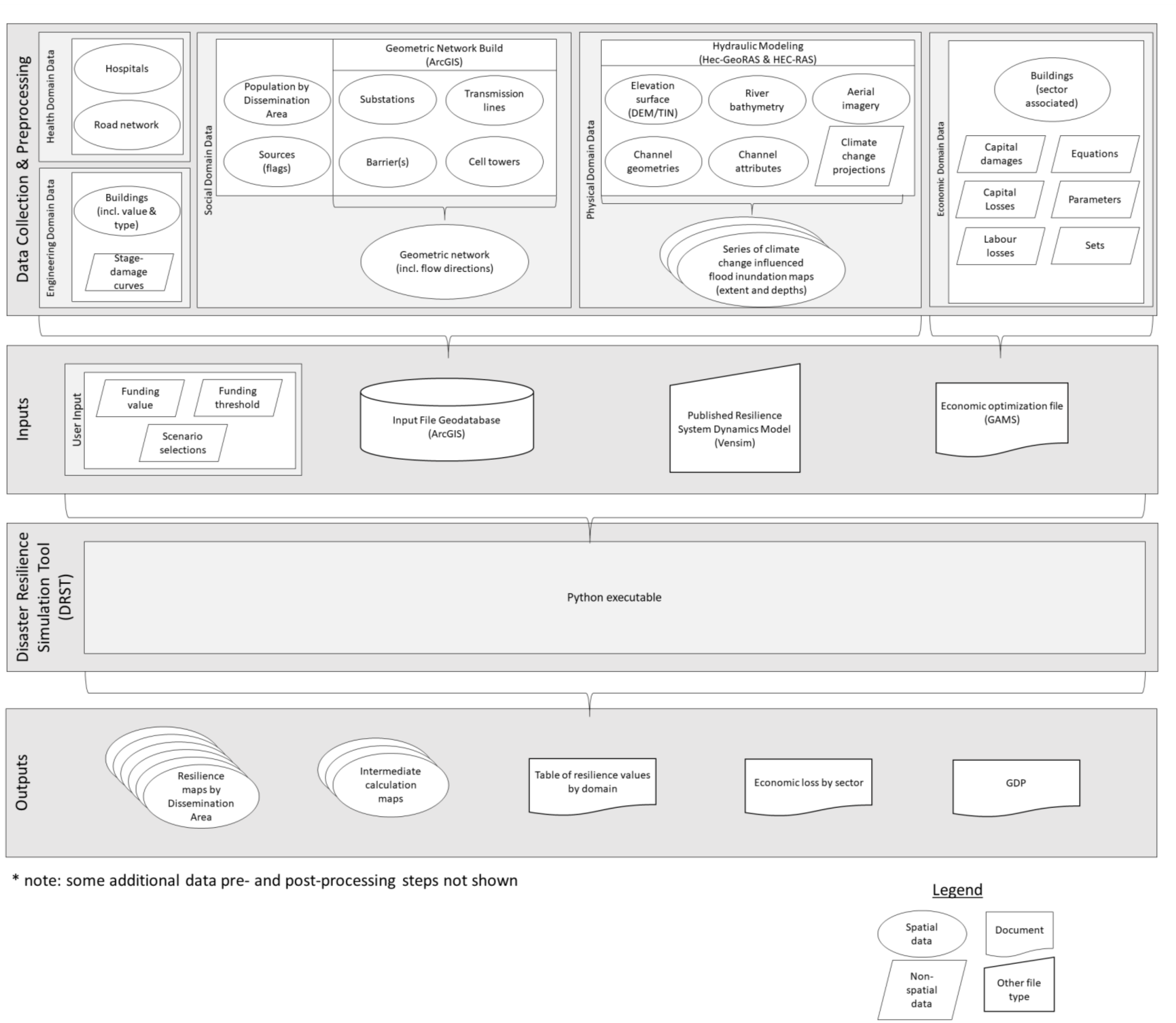


Figure 11: Generic implementation methodology

The quantitative resilience assessment calculation and methodology is implemented using system dynamics (SD). SD is a computer simulation technique with foundations rooted in the complex behaviour of dynamic, interdependent systems driven by feedbacks, commonly used for the purpose of gaining insight into real-world system behavior (Forrester, 1969). This approach was first introduced by Jay Forrester in the mid-1950s as a framework for the conceptual representation as well as the quantitative modelling of economic systems (Radzicki and Taylor, 1997). Since then, SD modelling has also been applied to study environmental processes, water resource management (Khan et al., 2009; Gastélumet al., 2010; Ahmad and Simonovic, 2000) and the energy resource domain. The ultimate goal is to provide insight into real systems behaviour and act as a decision support tool for stakeholders and policymakers.

"Disaster Resilience Simulation Tool" (DRST) is the name given to the Python script (and associated input files) which integrates and automates the functionality of three software programs:

1. ArcGIS, for spatial modelling;
2. Vensim, for temporal modelling; and
3. GAMS, for optimization modelling.

ArcGIS is used to display, analyze, and manage spatial data. The Python module ArcPy is used to provide a flexible way to automate geoprocessing tasks and spatial analysis tools. Vensim is used to model the connectivity and relationships between elements and to simulate the temporal behavior of city systems over time. GAMS software is used to model changes in the economy and subsequently, economic responses to disruptive shocks. The DRST connects this software and automates the spatio-temporal simulation of complex interactive processes within a city system. This integration makes the simulation process more straightforward, computationally efficient, accurate, and transferable.

The DRST is composed of five interacting resilience domains: physical, social, economic, engineering, and health. Each of these domains contributes to the calculation of disaster resilience to estimate disaster impacts and identify opportunities for improvements. The DRST is used to simulate the change in city resilience as a consequence of various adaptation scenarios. A set of adaptation scenarios represents one simulation scenario and provides one set of dynamic resilience maps and graphs. It is therefore possible to compare simulation outputs (in the form of resilience) relative to each other, to evaluate the performance of each adaptation option and create actionable items.

The DRST was developed for short term, event-based simulation to capture the more immediate impacts of event-based short and medium duration climate hazards such as flooding. This is captured in the physical domain of the DRST. This chapter provides a description of each model domain (physical, economic, engineering, social, and health) and presents resilience as framework for integration of impacts.

Water resources engineering practice needs to embrace the use of system dynamics simulation as a modelling technique useful for the management of disasters. The DRST uses system dynamics simulation modelling as a mechanism for dynamic resilience calculation. Since resilience is calculated using a system dynamics simulation model, the question of stationarity is left with the system inputs and not the system model. It's an effective approach for revealing temporal behavior of complex systems, such as cities. Although there have been recent developments in expanding SD to include systems' spatial dependencies, most applications have been restricted to the simulation of diffusion processes. Although SD research is trending in this direction, "the spatial dimension has not received a great deal of attention in system dynamics modelling. An intensive literature review showed that there are only a number of articles dealing with this subject" (Sanders and Sanders, 2004, p9).

System dynamics simulation is a mathematical modelling technique which formalizes the relationships between elements in a system. *System [structure]* refers to the patterns of interactions between various system elements. *Dynamics* refers to the changes in these patterns over time. *Simulation* involves the production of a system model, which is then used to study the behaviour of the system in response to various stimuli. Thus, system dynamics simulation links the dynamic behaviour of a system to its underlying structure

(Simonovic, 2009). It is a process-driven learning tool, which explicitly models the relationship and feedbacks between the components of a complex system. The overall objective of system dynamics modeling and simulation is to improve the understanding of key relationships within a system that drive its behaviour, rather than predict events.

System dynamics simulation models are primarily composed of stocks, flows, variables, and feedback structures (Figure 12) (Simonovic, 2009). Stocks are *accumulations* which characterize the state of the system. *Flows* are *rates* representing some form of activity. Flows drain and fill stocks. Both stocks and flows are necessary for generating dynamic behaviors in a system. *Variables* modify the activities (flows) in a system. These variables are used to break out the details of what would otherwise comprise a flow or may be used to represent external inputs. Unlike stocks, variables do not accumulate over time. Mathematically, stocks may be defined as:

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0) \tag{4.1}$$

Where s is any time between initial time t_0 and current time, t. Equivalently, the net rate of change of a stock can be described by the following derivative:

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \tag{4.2}$$

These two equations define the very basis of system dynamics simulation.

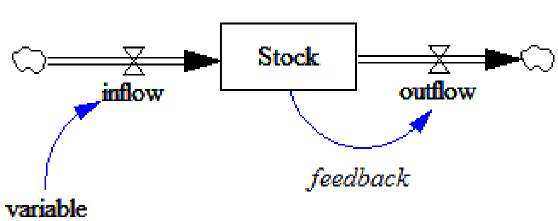


Figure 12: Generic stock and flow diagram

Forrester (1990) presents a set of principles that helps to define, understand, and implement system dynamics simulations as follows:

Principle 1: A feedback is a closed system

Principle 2: Every decision is made within a feedback loop

Principle 3: The feedback loop is the basic structural element of a system

Principle 4: A feedback loop consists of stocks and flows

Principle 5: Stocks are integrations

Principle 6: Stocks are changed only by flows

Principle 7: Stocks and flows are not distinguished by units of measure

Principle 8: No flow can be measured except as an average over a period of time

Principle 9: Flows depend only on stocks and constants

Principle 10: Stock and flow variables must alternate

Principle 11: Stocks completely describe the system conditions

Principle 12: A policy or flow equation recognizes a local goal towards which that decision strives

These principles form the basis for system dynamics simulation and are the governing principles which apply to the model developed in this work. In terms of methodology, the system dynamics simulation approach presented in this dissertation is well-suited for capturing the behaviour of complex city systems. It encourages holistic, “big-picture” thinking that makes it appropriate for disaster management applications.

A critical component of modeling and understanding complex systems is through a computer-based system dynamics simulation approach. Building a simulation model requires the creation of a mathematical-based model that represents the related real-world system that is being studied. Models of complex systems are often comprised of many components and interactions and therefore computers and system dynamics simulation software are typically used to facilitate the computations. Simulation models then form a basis for experimental investigations. This proves particularly useful to the field of disaster management where experimental investigations can take place in a simulation environment without the associated risks, consequences, time, and expense of changing actual systems. These simulation models can be used to assist decision makers and provide a set of tools to evaluate the performance of various decisions and help them understand and learn within complex environments.

4.1.1 System Dynamics Applications in Disaster Management

Although most of the system dynamics research in the past few decades has focused on applications in social studies, economics, engineering, healthcare, environment, and the military (Forrester, 2007), systems dynamics is gaining momentum in the field of disaster management. There are examples of system dynamics applications to model problems related to earthquakes (Xie and Rao, 2014; Ramezankhani and Najafiyazdi, 2006); tornados; and flooding, among others. The system dynamics approach is widely applicable to many problems because systems (and hazards) are prevalent across the globe. A systems approach can help clarify the problem being studied, reveal complex and sometimes counter-intuitive system behaviours, and test potential real-world solutions (Simonovic, 2009).

Ramezankhani and Najafiyazdi (2006) use a system dynamics model to simulate post-disaster management in Iran following the Bam earthquake. The model included simulating population, food supply, medical requirements and disease outbreaks, rescue teams, public perception and media coverage, building destruction, and debris removal. Five strategies (simulation scenarios) were tested to study the behaviour of model sectors and help answer critical questions related to disaster response and determine which strategies may reduce casualties. This simulation effort was valuable as part of post-disaster forensics, however, the real benefits of system dynamics simulation is being able to estimate potential disaster impacts before they happen in an effort to curb negative consequences. In addition, this example of system dynamics disaster management simulation only considered the post-disaster response phase of disaster management and did not consider other essential components of disaster management such as mitigation, preparedness, or recovery. This proposed research considers all phases of disaster management for a more holistic approach to improve disaster management decision making strategies at all stages.

Somewhat similarly, Khyrina et al. (2012) and Kuznecova and Romagnoli (2014) consider a more general system dynamics simulation approach to disaster management in the context of emergency preparedness which offers a valuable, but limited, investigation into potential disaster management solutions. Kuznecova and Romagnoli (2014) recognized cities as complex dynamic systems comprised of many components and feedback loops which necessitate a sophisticated understanding of city systems. The study links the concepts of cities (as urban metabolism and dynamics) and urban disaster resilience, going so far as to have produced a high-level causal loop diagram for urban resilience. The study appears to be limited to environmental and energy impacts on resilience and does not offer a quantification scheme for resilience assessment. The study does, however, identify a key relationship between communication and disaster resilience which will be further explored as part of this dissertation.

Since system dynamics lacks the explicit ability to capture the spatial dimension of dynamic resilience, the DRST also incorporates Geographic Information Systems (GIS) datasets and spatial analysis tools to capture both the temporal and spatial dynamics of resilience. The combination has the potential to solve a wide variety of problems (Grossman and Eberhardt, 1992). The groundwork for this integration was laid by (Neuwirth et al., 2015) where a Python program was used to tightly couple SD software to GIS. The approach provided the required capacities for handling bidirectional and synchronized interactions of operations between SD and GIS.

4.2 Implementation: Data Collection

Our world is inherently complex, but by modelling systems and their interactions, it is possible to learn something about the whole system that may not have been obvious within the original system complexities. By implementing dynamic disaster resilience using spatial and temporal modelling, it’s possible to layer multiple datasets together, exploring the interactions one dataset may have on another and exploring their contributions to the performance of the entire system. Spatial modelling and analysis can provide insight into what things are happening, where they are happening, and even help explain why things are happening. It can help provide solutions to data-intensive, large-scope spatial analyses problems.

Spatial data is often displayed visually using maps. These maps include location, topographical, and attribute data. Each feature on these maps has spatial information tied to it; usually as latitudinal and longitudinal coordinates. Historically, this spatial information was collected and displayed using hand drawn maps and tables. However, nowadays spatial information and maps are available in digital format using Geographic Information Systems (GIS). There are many useful examples of applications of GIS in water resources including the areas of flood recovery mapping, hydrographic analysis, and watershed protection. The resilience quantification framework and methodology presented in this research uses spatial data, spatial analyses, and spatial mapping in hazard definition and resilience assessment using GIS.

4.2.1 Implementation: Focal Scale and Geographic Scales in Spatial Resilience Modelling

The focal scale for resilience should be established early in the resilience assessment process. The focal scale will drive resilience quantification and assessment, and be used to identify key systems and their relationships. The selection of a focal scale will to some degree also impact the data collection efforts. However, at an implementation level, there are multiple contexts for use of scale in spatial resilience modelling. Three (3) of the most important ones include:

1. Scale as it refers to the relative size of an object or space as compared to its real size on Earth;

2. Scale as a resolution of data; and

3. Properties of data such as points, lines, or polygons.

For example, a small scale map on a computer screen may be 1:1,000,000 – or, one million times smaller than its actual size on Earth. On the other hand, a scale of 1:1 would be a very large scale representation – or, the same size on the screen as its actual size on Earth. The type of data and its properties often determine the resolution.

Data is collected at various scales and resolutions using various tools. These are typically not consistent between datasets, therefore one of the greatest challenges in spatial resilience modelling is analyzing and harmonizing spatial data to assess its fitness for use in spatial analysis. However, with sufficient pre-processing, the fact that spatial analysis can incorporate data at various scales and resolutions is one of its main benefits.

Selecting the focal scale for analysis is important because an area's boundaries will affect the values within that area. There is no single "correct" scale, but there are "appropriate" and "less appropriate" scales for resilience assessment. Selection of an appropriate scale is driven by problem definition and the intended use of results of resilience assessment. Perhaps most importantly, identifying a scale – whatever it may be – should be established early on in the resilience assessment process.

Some boundaries are seemingly arbitrary and invisible; others are political, topologically driven, or administrative. The criteria used to collect and represent spatial data and boundaries may evolve over time. Since boundaries modify spatial data, spatial analyses may require modification over time as different aggregation areas can modify the analyses and subsequently the results. Results will be a function of the spatial units used for the analysis making selection of scale important, especially since decision making and policies are often based on boundaries and data that are aggregated by area. Clearly identifying the focal scale can reduce the chances of misinterpreting resilience assessment results.

The representation of statistics (for Canadian Census) is provided at various resolutions of census units (e.g. CMA, CT, DA, etc.). These data provide a snapshot in time for various demographic and economic statistics across the country. These spatial units represent various levels of data aggregation commonly used in thematic mapping. The DRST uses data at various scales, but computes resilience at the DA level, but at the end of resilience calculation, the resilience calculation is provided Regionally (focal scale).

The remainder of this section provides details related to spatial analysis tools used in resilience calculations in the DRST.

4.2.2 Implementation: Spatial Analysis

Spatial analysis can help simplify complexities and solve geospatial problems. The results of spatial analyses can help inform policies and disaster management decision making. Spatial analysis relies on geographic data and the spatial relationships between data. It can be as simple as analysis of location, but usually includes characteristics of those locations and therefore requires knowledge of topography, geometric properties, and attribute data. It becomes especially important in dynamic spatio-temporal modelling where connectivity, adjacency, orientation, and containment are topological properties essential to properly capture spatial dynamics. Therefore, spatial analysis is critical in resilience modelling in the DRST.

It is important to select an appropriate spatial tool for the spatial relationship being modeled. Many spatial analyses are driven by (or limited by) the availability and access to high resolution spatial data. Similarly, the selection of tools used in a spatial analysis is driven by both the research question and data availability. The DRST uses multiple forms of spatial analysis toolsets in resilience quantification and assessment: extract, overlay, proximity, and reclassify. Each toolset performs specific spatial analysis of feature or raster data. A description of the tools implemented in the DRST is provided in Appendix A.

4.2.3 Implementation: Geographic Information Systems (GIS)

All spatial data can be mapped using a Geographic Information System (GIS). A GIS is a collection of components: hardware, software, data, people, and protocols. The remainder of this section focuses on the software aspect of a GIS, specifically as it relates to the DRST.

GIS is a useful computer tool for representing, processing, graphically displaying, and manipulating spatial data and preserving topology of spatial relationships. There are many advantages to using GIS as a tool for building resilience: easily updateable databases; intuitive graphical interface; statistical, mathematical and geometric tools available to preform spatial calculations; combining numerical attributes in a spatial format; spatial overlay capabilities; and the ability to handle multiple formats of data. Combining the temporal modelling of SD with spatial information in GIS is able to produce a time series of maps (dynamic mapping) of resilience. These maps can be used to target areas for effective capacity building. Maps are especially useful tools for representing and communicating the DRST results because they are visually interesting and spatial patterns are easily identifiable.

Datasets are the primary inputs and outputs for analysis, operations, and tools in a GIS. Before its use in GIS software, most data require significant pre-processing and quality review. The DRST uses ESRI's ArcGIS Desktop software (ESRI, 2011) for spatial data management, analyses, and mapping. This software is typically used to manage and represent large amounts of spatial data. However, the software also has the capacity to perform real-time data retrieval and spatial analysis. ArcGIS organizes spatial analysis tools in *toolboxes*. These toolboxes contain collections of data management and spatial analysis functions to modify geographic data. The DRST accesses these toolboxes and their tools to perform spatial analysis for resilience assessment.

Although ArcGIS provides a strong platform for spatial operations and visualization, the program is largely criticized for its limitations in modelling temporal dynamics of complex systems. Therefore, this research integrates ArcGIS with Vensim (Ventana Systems Inc., 2009) capabilities to consider combined spatial and temporal modelling.

4.2.4 Implementation: Integrated spatio-temporal modelling

The DRST uses a dynamic-link library (DLL) to access the temporal simulation and spatial analysis tools outside of SD modelling and GIS software. DLLs are modules which contain code that permits sharing between programs. They are collections of coded functions that can be called by other modules or applications. DLLs are unique in that they are only loaded at run time when an executable file loads them, thus the DLL can be updated independently without updating the executable itself. It is also possible for DLLs to be linked to other libraries and DLLs, thereby initiating cascaded loading of DLL files.

The Python module ArcPy (ESRI, 2011) is used to perform geoprocessing outside of the ArcGIS software. This module accesses multiple GIS DLL files and allows spatial tools to be accessed outside of the ArcGIS software which provides integration with other software for resilience modelling. The DRST combines ArcPy ArcGIS module (many *.dll* files) with a Vensim DLL (*vendll32.dll*) to access tools and functions from outside the programs. This allows the DRST to combine the temporal modelling and simulation capabilities of system dynamics with the spatial modelling and analysis capabilities of a GIS. The DRST also uses a DLL file to use the functionality of GAMS (GAMS Development Corporation, 1987) economic modelling software, which is discussed in future chapters. Combining these tools together is the technical development of the DRST (Figure 13). The foundation for this coupling is further described in a report Peck et al. (2014).

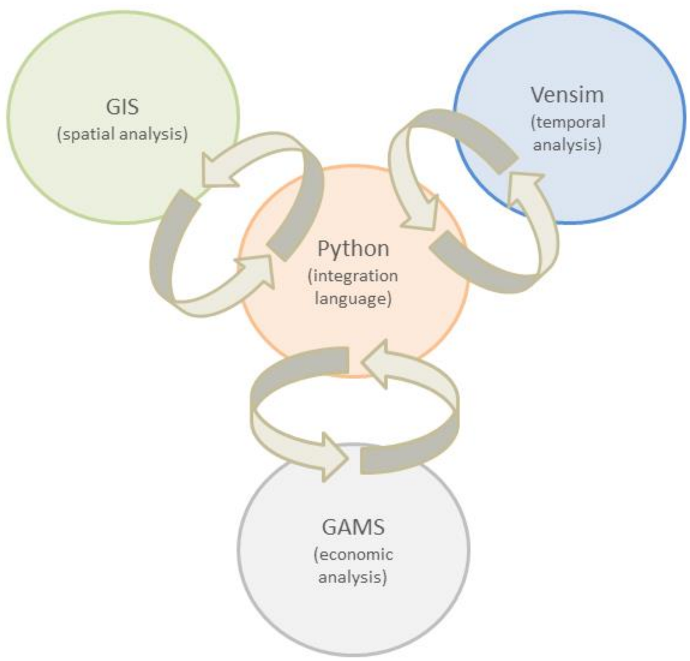


Figure 13: Technical implementation schematic for the DRST

In summary, the DRST uses multiple spatial datasets of various types, spatial reference, and scale as input into resilience simulation. The DRST is a combined spatio-temporal resilience modelling tool using temporal modelling capabilities of SD combined with spatial analysis tools supported by a GIS to support disaster management decision making processes.

4.3 Implementation: Systems Model

In the DRST, resilience is calculated for each of the model domains and then combined into a dynamic integrated resilience measure. To quantify resilience, a set of resilience indicator variables was identified for each of the five resilience model domains based on first hand experiences, expert knowledge, scientific literature, industry standards, and data availability. These indicators are from different domains and are characterized in different units. Their relative changes over the course of a flood event are used to characterize resilience in time and space.

Each of the domains is based on the same generic model structure (Figure 14). This conceptual model structure contains input variables, impact variables, adaptation variables, and resilience calculation variables. The main inputs into each domain of the model are climate change factors, vulnerability factors, and hydrometeorological hazard.

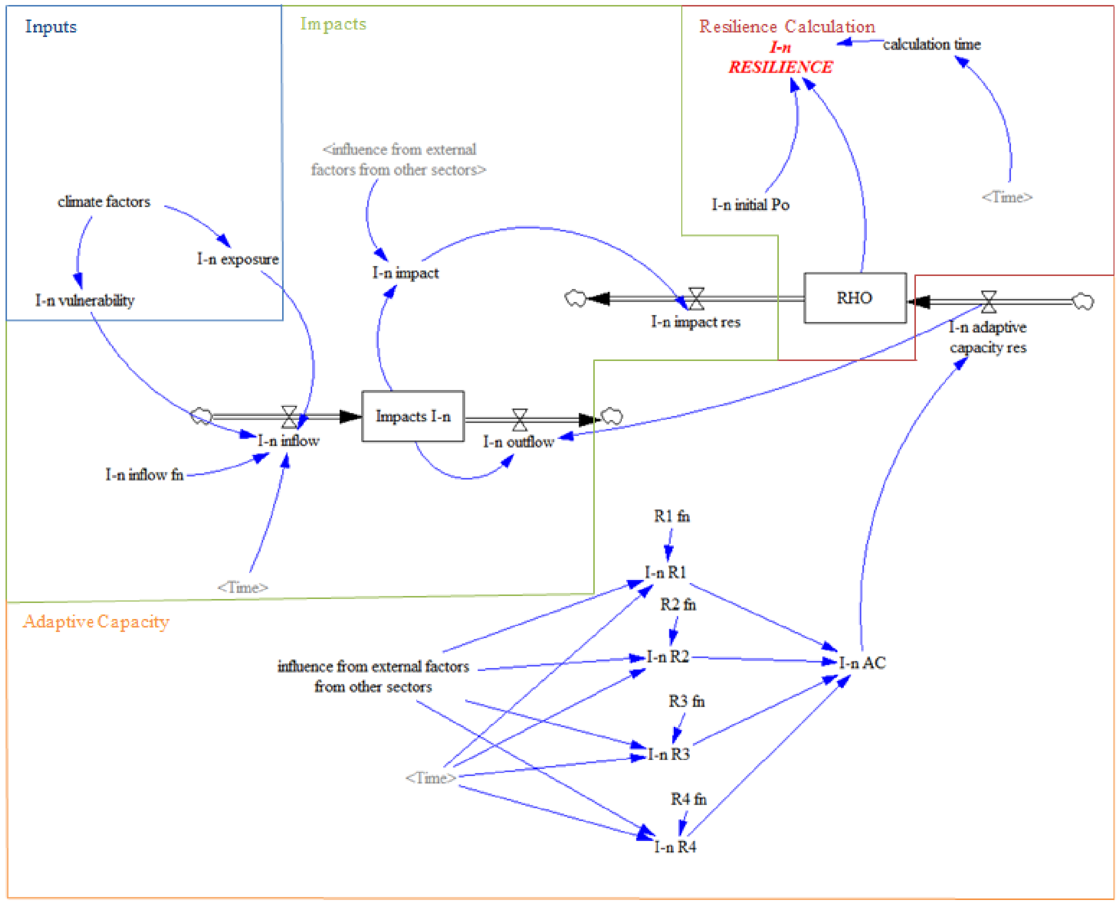


Figure 14: Generic model structure for each domain (I-n)

Each of the domains (I-n) uses climate factors, vulnerability, and physical hazards exposure as the main *Inputs* into resilience model simulation. *Impacts* elements consider the variables from *Inputs* and simulate the resulting consequences on the system. These impacts, however, are tempered by the capacity of the existing system to absorb, resist, and quickly recover from, the impacts. This effect is captured by variables in *Adaptive Capacity* elements of the model. The variables in *Impacts* and *Capacities* are then used in *Resilience Calculation*. Although the actual system variables may vary depending on the implementation of each resilience domain, in the most generic form, key stock (level) variables may be expressed as:

$$Impacts\ I - n = \int (inflow - outflow) \tag{4.3}$$

$$RHO = \int (adaptive\ capacity - impacts) \quad (4.4)$$

The flood Impacts (I-n) variable could be represented by resilience indictor variables from multiple domains. These impacts can be categorized into four types: direct tangible (e.g. damages due to contact with floodwaters), indirect tangible (e.g. business interruptions), direct intangible (e.g. loss of life) and indirect intangible (e.g. psychological suffering) (Bubeck and Kreibich, 2011). Ideally, each domain's model (I-n) would capture an estimate for all four types of impacts. However, not all domains may identify impacts for all four types. Future work could consider expanding the number of flood impacts considered in resilience assessment.

However, Figure 14 is more of a generic structure to guide the development of application-specific implementations of resilience quantification. Its expression in Figure 14 is not meant to encapsulate a complete representation of all specific elements that constitute dynamic resilience but to guide the incorporation of key aspects into disaster resilience assessment. Further details pertaining to this generic structure can be found in the report by Peck and Simonovic (2013).

The remainder of this chapter describes one example of the main impacts from each domain from Figure 14, driven by the hydrometeorological climate hazard (flooding) from the physical domain. It starts by describing how climate change may influence flood hazards and describes how the DRST incorporates these changes. Following which, the remainder of this chapter describes the development and implementation of the impacts and adaptive capacity measures (Figure 14) for the remaining four (economic, engineering, health, and social) resilience model domains.

4.3.1 Physical Hazard Domain: Description

Extreme riverine flooding events are one of the most frequent and costly natural hazards in the world (IPCC, 2012; Burn and Whitfield, 2016). This research is interested in exploring the impacts and capacities of urban communities to adapt to these hazards now and into the future. As such, this research focuses on climate change influenced flooding as the primary physical hydrometeorological hazard in resilience assessment.

Coastal environments are hydrodynamically unique from inland hydrological environments. Coastal stream networks have upstream freshwater flow like most other riverine networks. However, the downstream end of the river network outlets at the ocean which results in a portion of the downstream river network to be heavily influenced by tidal patterns. The upstream river reaches are often characterized by sections of the stream network which behave similarly to any other comparable river system. However, since the main river channel outlets at the ocean, there are distinct differences in the behaviour of the downstream ends of these river networks in terms of flow dynamics, flow properties, and river geomorphology. The confluence of riverine and ocean gives rise to special estuarine environments; the zone where mixing of fresh and salt water occurs. The dynamics of estuary environments are more complex due to the variability in salt water stratification and mixing, wave dynamics, and the heavy influence of tidal action (Stenström, 2004; Guha and Lawrence, 2013). Although the DRST physical domain does not explicitly consider all the unique properties of these environments, it does use tidal action and sea levels as part of hazard definition. Future work is recommended to determine the potential additional impacts that estuary dynamics and physical system plays in the role of flooding and disaster resilience.

Traditional floodplain maps are derived through modelling techniques which apply hydrologic and hydraulic modelling using historical physical data. The hydrologic model converts rainfall to runoff taking into consideration land surface characteristics such as vegetation, permeability, and soil. The runoff (discharge) is then used as input into a hydraulic model which is used to estimate water surfaces along the river channel. These water surface profiles are typically used to delineate the extent and depth of flooding in floodplain maps. These maps represent flood prone areas and spatial data which form essential support for disaster management. However, one of the shortcomings of traditional flood modelling and floodplain mapping studies is the underlying assumption of stationarity; that the climate, weather and runoff processes and patterns of the past will operate the future (Shrubsole, et al., 2003). However, hydrologic impact assessments have found that precipitation patterns are changing due to climate change, which impacts other significant hydrological processes (Eum et al., 2010). Changes in precipitation have propagating effects throughout the hydrological cycle and can influence the quality, quantity, and timing of runoff volumes, runoff peaks, streamflows, inundation extents and depths. This research attempts to address this gap by offering one approach to incorporate climate change projections into the traditional process of flood hazard estimations and floodplain mapping. Ultimately, these climate change influenced inundation mapping projections serve as the primary input into the DRST.

4.3.2 Physical Hazard Domain: Implementation

To begin this unique climate change influenced hazard assessment, it was necessary to estimate the potential effects that climate change will have on future extreme flood events. Therefore, the methodology incorporates climate change projections with traditional engineering simulations of physical phenomena to generate new, climate change influenced hazards.

The physical hazard domain is the only domain which has a direct influence on all four of the other model domains. The output generated from the physical domain of the DRST is used as input into each of the other four resilience model domains (economic, engineering, health, and social). The climate change influenced riverine flood hazard extents and depths influence impact calculations in each of the DRST model domains. The physical hazard domain produces a time series of climate change influenced flood inundation maps generated from future climate change projections, river characteristics, and detailed spatio-temporal data. The general process for incorporating climate change and deriving these flood maps and data is described in the remainder of this section.

The process for generating the climate change influenced inundation maps for the physical domain of the model is completed in a series of tasks (Figure 15), which follows common inundation mapping techniques used by the US Army Corps of Engineers. However, because the DRST is interested in the impacts of potential *future* flood disasters, the methodology is modified by introducing climate change parameters to modify hydrologic and hydraulic modelling and simulation inputs, thereby generating modified inundation mapping results. To capture both the spatial and temporal dynamics of a flood event, required as input into the DRST, it was necessary to obtain climate change information and apply it to precipitation and ocean levels to create climate-modified input data for hydrologic and hydraulic analysis in the form of climate-modified discharges and sea level rise. These climate-modified parameters were then used to perform 1-D unsteady hydraulic flow analysis. The unsteady (dynamic wave) flow simulation uses numerical solutions for the equations of gradually varied flow. The discharge in the river moves downstream and computes water surface profiles across the duration of the simulation to generate a time series of water surface profiles. These water surface profiles can then be used in conjunction with topographical information to generate climate-influenced inundation (floodplain) maps.

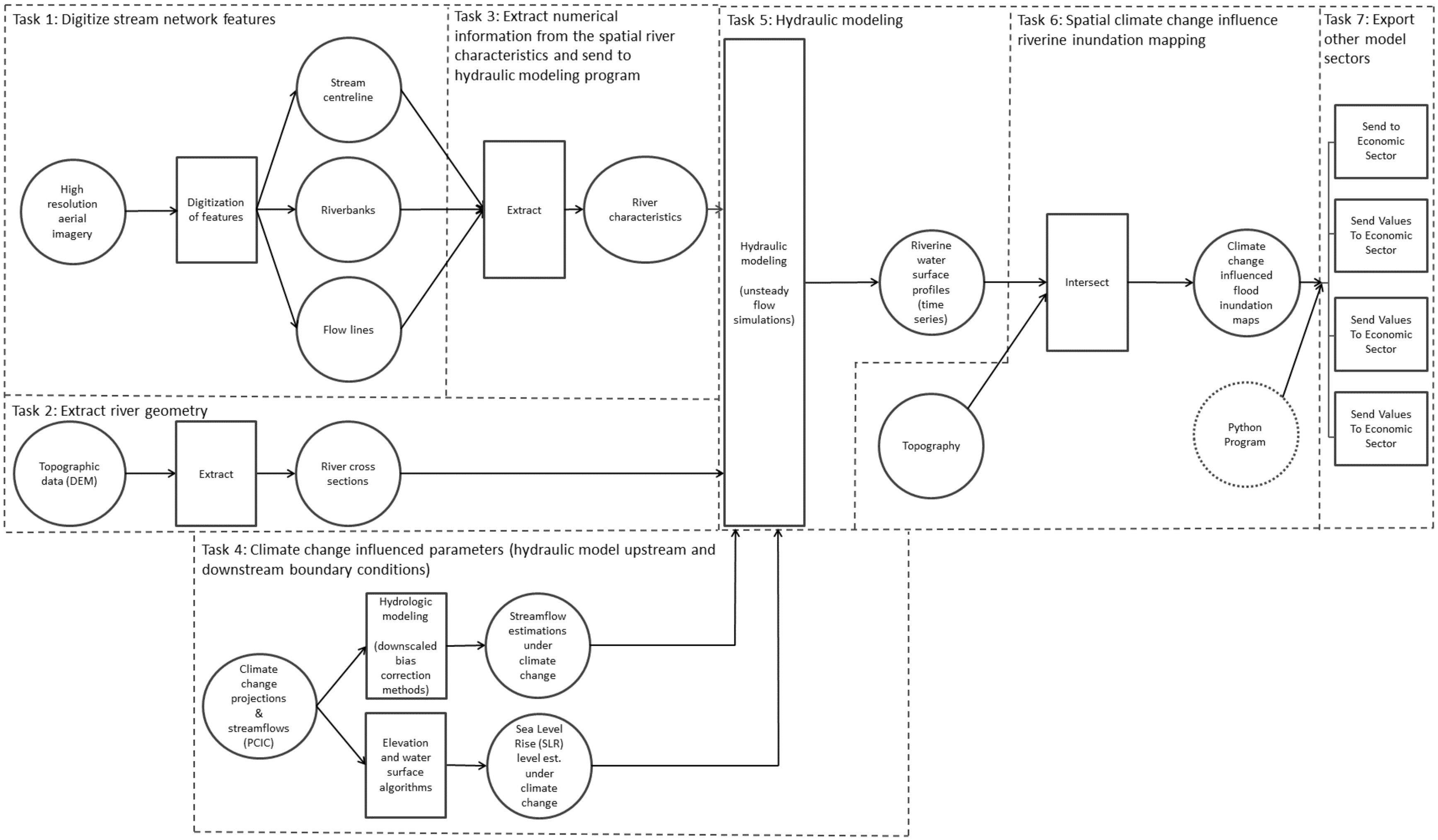


Figure 15: Physical domain workflow diagram; tasks 4, 5, and 6 are completed for each unsteady flow simulation scenario

Defining Stream Characteristics

Automatic and semi-automatic characterization and description of hydrological features (e.g. catchment delineation, slope profiling, flow direction, and stream network identification) has become a popular technique among hydrological engineers, saving time and often improving accuracy over traditional manual (hand-calculated) methods (Steinfeld et al., 2013; Gopinath et al., 2014). The technological advancements, growth of the GIS field, and improvement in high-resolution Digital Elevation Model (DEM) data has enabled automatic extraction of important drainage network parameters useful for hydrologic and hydraulic modelling (Lin et al., 2006). The characteristics of the extracted stream network depend extensively on channel definition over the digital landscape and so although the process has improved efficiency for hydraulic modelling and simulation, the procedure is still data intensive and computationally demanding. This thesis suggests a general digitization procedure similar to the one outlined in USACE's HEC-GeoRAS (2011) manual for extracting stream network features and characteristics for hydraulic modelling (Figure 16). These features are required for use in hydrological and hydraulic modelling and simulation to produce inundation maps for the DRST.

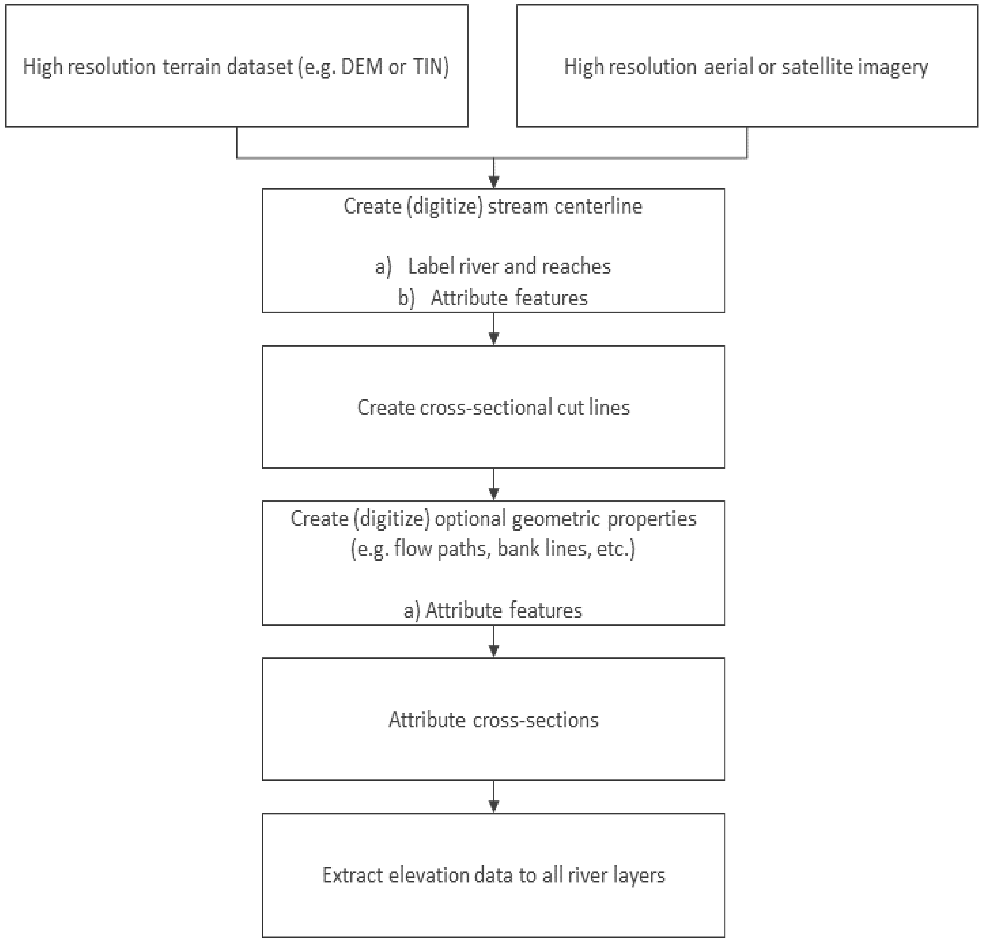


Figure 16: General river network digitization scheme (based on USACE (2011))

Climate Change Scenarios

Concentrations of GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and water vapor (H_2O) in the atmosphere play a large role in the warming of the planet, which in turn, plays a significant role in many hydrological processes. The concentration of GHGs in the atmosphere varies over time and space as a result of both natural (plant decomposition, volcanic eruptions, ocean evaporation) and anthropogenic (burning of fossil fuels, deforestation, agricultural and industrial activities) causes. According to some of the latest insights into projected GHG emissions provided by the Intergovernmental Panel on Climate Change (IPCC) (Figure 17), CO_2 emissions will likely continue to increase over at the next few decades. NASA's modelling and simulation of CO_2 concentrations retained by the atmosphere, suggest that this could particularly significant for the Northern Hemisphere (Figure 18).

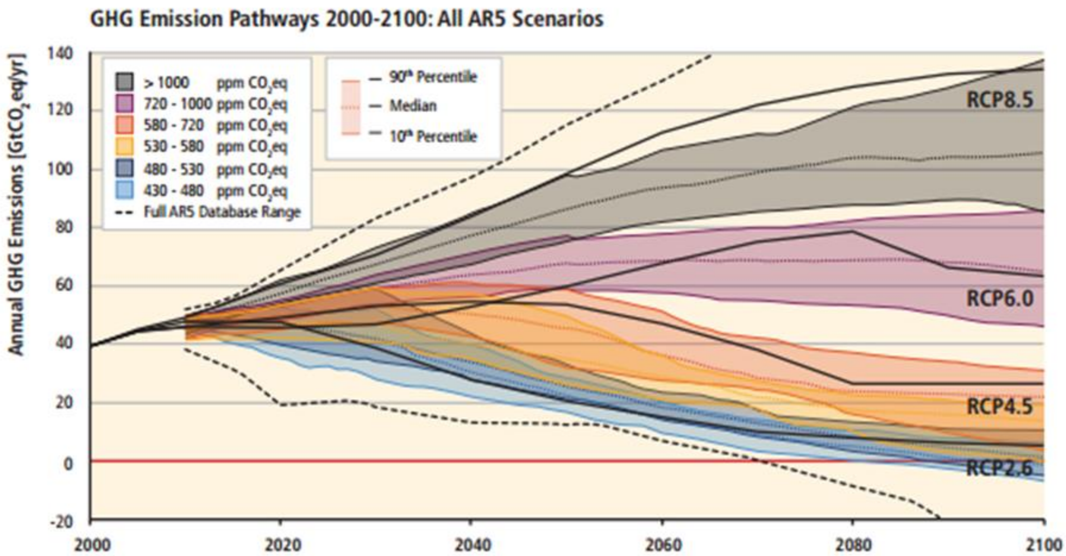


Figure 17: Pathways of global CO_2 concentrations for AR5 emissions scenarios (from IPCC (2013))

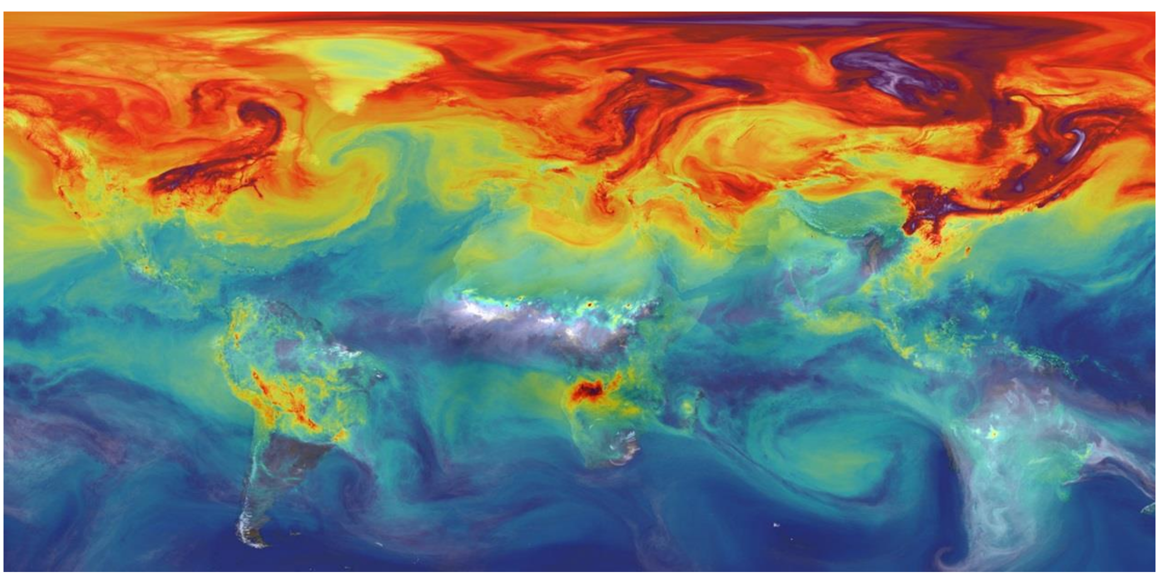


Figure 18: Simulation results of CO_2 in the atmosphere if the land and ocean can no longer absorb close to half of all climate-warming CO_2 emissions (from NASA (2015))

The IPCC is one of the leading scientific bodies on climate change research and in 2007 they released their fourth Assessment Report (AR4) on the physics and science of climate change. As part of this work, they developed four narrative emission scenarios representing alterative futures, covering a wide range of the main driving forces which could be used as a basis for climate change assessments. These emissions scenarios (A1B, A2, B1, and B2) are outlined in an IPCC Special Report on Emissions Scenarios originally published in 2000 (IPCC, 2000). The A1 family of scenarios represent a future of rapid economic growth, global population peak and decline, and introduction of efficient technologies; A2 family represents a heterogeneous world with regional economic growth, rapid and steady population growth, and slow technological development; B1 family represents a future of economic equity and sustainability, global population peak and decline, and clean technologies; and finally B2 family of scenarios represent intermediate levels of economic growth, slow and steady population growth, slow and diverse technologies. These scenarios offer a range of climate changes in response to emissions, which the most optimistic B1 scenario having projected a warming of by 1.8°C by 2100. Two of these climate scenarios (A1B and B1) were used to generate climate change modified streamflows in hydrologic modelling, which are subsequently used in hydraulic modelling and flood inundation mapping inputs for the DRST.

The IPCC Fifth Assessment Report (AR5) was released in 2013 with updated emissions scenarios called Representative Concentration Pathways (RCPs). There are four scenarios (RCP2.6, RCP4.5, RCP6 and RCP8.5), each representing a different emissions scenario future. RCP2.6 represents a mitigation scenario with low forcing; RCP4.5 and RCP6 are stabilizing scenarios and RCP8.5 is the scenario with high GHG emissions (IPCC, 2013). However, one thing remains common between the scenarios; total atmospheric CO_2 concentrations are higher in 2100 than they are in present day.

The DRST uses gridded hydrologic modelling results driven by AR4 SRES A1B and B1 emissions scenarios as upstream boundary conditions in hydraulic modelling to capture the potential changes in riverine flooding because of changing precipitation and runoff volumes. The DRST uses sea level rise estimates generated using the AR5 RCP2.6 and

RCP8.5 emissions scenarios as downstream boundary conditions in hydraulic modelling to capture potential changes in riverine flooding as a consequence of rising sea levels.

Sea Level Rise

Sea level rise (SLR) is a hazard threatening the world's coastal cities. SLR can lead to more severe storm surges, flooding, salt water intrusion and flood inundation resulting in severe damage to coastal communities and environments. The two primary concerns related to SLR, are the steady rise in the global mean sea level (GMSL) and the increased frequency and magnitude of ocean wave events. SLR is caused by an increase in global ocean volume caused primarily by two physical processes: thermal expansion of the ocean and the melting of glaciers (IPCC 2013). These two phenomena are estimated to be responsible for more than 80% of GMSL rise. The rate of GMSL has actually been rapidly increasing since the 1900's. The observed GMSL rise rate from 1901 – 1990 was 1.5 mm per year (IPCC 2013). This value then skyrocketed to over double the observed rate to 3.2 mm per year from 1993 – 2010 and it is anticipated that SLR rates will continue to increase well into the future, under all climate change scenarios (Figure 19) (IPCC 2013). There is inherently high spatial variability in the magnitude of SLR estimations, due to factors such as oceanic circulation patterns, salinity levels, and regional wind effects, but interestingly, it is very likely that sea level will rise in more than 95% of the global ocean area, with 70% of coastlines experiencing changes within 20% of the GMSL change (Figure 20) (IPCC 2013).

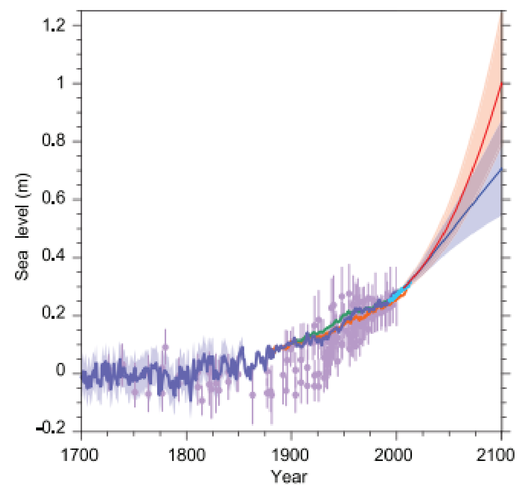


Figure 19: Projected SLR for RCP 2.6 (lower, blue projected line) and RCP 8.5 (higher, red projected line) (IPCC, 2013)

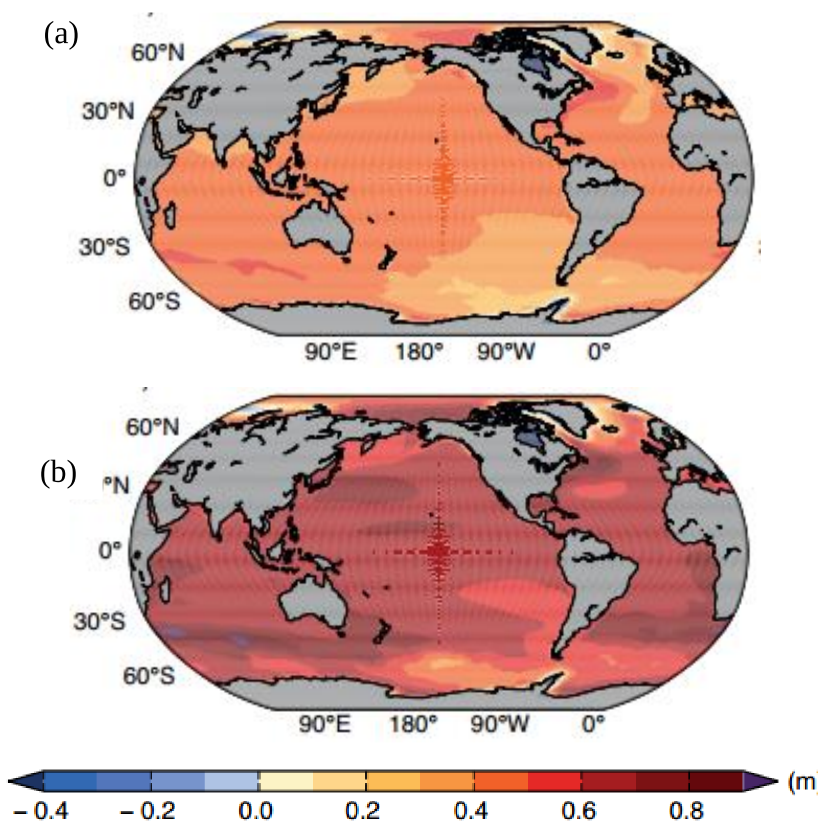


Figure 20: Climate model ensemble mean relative sea level change (m) (between 1986-2005 and 2081-2100) for (a) RCP 2.6; and (b) RCP 8.5 (adapted from IPCC (2013))

The most common way to understand the potential impacts of SLR is to visualize potential inundation extents by generating probabilistic or deterministic inundation maps (Gesch, 2009; Agam, 2014; Lentz, et al., 2016; NOAA, 2017). Deterministic methods use GMSL rates and factors for regional considerations such as localized tidal data and vertical land movements. Probabilistic methods use extreme value analysis in conjunction with local tidal data to estimate the frequency of extreme SLR events. Deterministic SLR projections were better suited for use in resilience assessment. However, SLR is a much slower inundation phenomena than riverine flooding and so SLR inundation mapping in itself is not appropriate as direct input into the DRST. Therefore, SLR is incorporated into the physical domain of resilience assessment by specifying climate change influenced sea levels as downstream boundary conditions in hydraulic modelling, thereby influencing the flood inundation maps.

Hydrologic Modelling: Rainfall-runoff simulations

Hydrologic modelling uses a mathematical model to simulate hydrological processes in watershed systems to estimate how watersheds respond to precipitation. In natural systems, much of the water that falls as precipitation is returned to the atmosphere through evaporation and transpiration processes. However, during storm events these processes are limited and most of the rainfall becomes runoff. From there, runoff may pond on the surface, infiltrate into the ground, or flow over land directly into a river channel. Ultimately, river channel flow is the result of overland flows, precipitation which falls directly into the channel, interflow (from vertical and horizontal movement of water in the soil subsurface layers), and baseflow (from groundwater aquifers).

Hydrologic models can be stochastic or deterministic. Stochastic models are black box systems which use mathematical and statistical concepts to relate rainfall to runoff. Examples of stochastic modelling techniques include regression analysis and neural networks. Deterministic hydrologic models represent real world physical processes and are able to model more complex relationships between flows. Hydrologic models can be simple (direct runoff) event-based models and can provide results in the form of peak flow volumes or runoff hydrographs. Alternatively, models can be more complex (full moisture accounting) continuous models which can provide results in the form of long duration runoff records. The degree of hydrologic model complexity required to model these processes is driven by the type engineering application and level of detail required in model outputs. Some of the popular hydrological models include: variable infiltration capacity (VIC) model developed by Liang et al. (1994) at the University of Washington; MIKESHE developed by DHI Group; and soil water assessment tool (SWAT) developed by the Texas Water Resources Institute at Texas A&M University. Although there is a variety of models available, most traditional hydrologic modelling and simulation computations involves the following constituents: state variables, parameters, boundary conditions, and initial conditions. Basic data requirements often include: delineated watershed areas, site-specific hydrological basin parameters (such as land use, soil cover, vegetation, and antecedent moisture conditions, among others), simulation settings, and meteorological (precipitation, wind, temperature) forcing data. Precipitation data may be specified as observed historical precipitation data from rain gauges, frequency-based hypothetical rainfall events, or as precipitation extremes (maxima).

This research used outputs from the VIC hydrologic model to generate runoff volumes which are subsequently used in hydraulic modelling and simulation. The VIC model is a macro semi-distributed hydrologic model originally created by Liang et al. (1994). It is a gridded land surface model which uses parameter files, basin delineation, and a time series of daily or sub-daily meteorological forcing data when coupled with statistically downscaled GCM projections driven by future emissions scenarios (IPCC SRES climate change scenarios A1B and B1) is able to simulate climate change influenced runoff. (Figure 21). It was developed for use in coupled land surface model – global circulation model (GCM) simulations. It’s based on a large grid cell size so it is intended for use is in large (> 10,000 ha) sized basins to be coupled with GCMs to estimate stream flows and atmospheric fluxes. The routing of streamflow within the channel is performed separately from the land surface model using the model of Lohmann et al. (1998). Basic mathematical relationships behind the VIC model are provided in Appendix B. Although this model was selected primarily for its applicability to the case study area (Metro Vancouver / Fraser River Basin) presented in Chapter 5, it may similarly be used to estimate climate change influenced streamflows for other regions. There are a few of the benefits of the VIC model that could extend its applicability to other regions across the globe. One of the key benefits of the model is its ease of accessibility and availability of the open source code, allowing researchers the option to run their own simulations. Open source code can also stimulate feedback and model improvements from the research community. Additionally, there is fairly detailed documentation on the development of the VIC model to support researchers in understanding and using the model. Although this model was used, other ways of estimating climate change-influenced hazards may be used as simulation models evolve and improved ways of capturing potential climate change influences emerge. What's important at this stage in the resilience framework is identifying how climate change may influence a hazard and identifying ways to represent these changes so they can be made a part of dynamic resilience assessment.

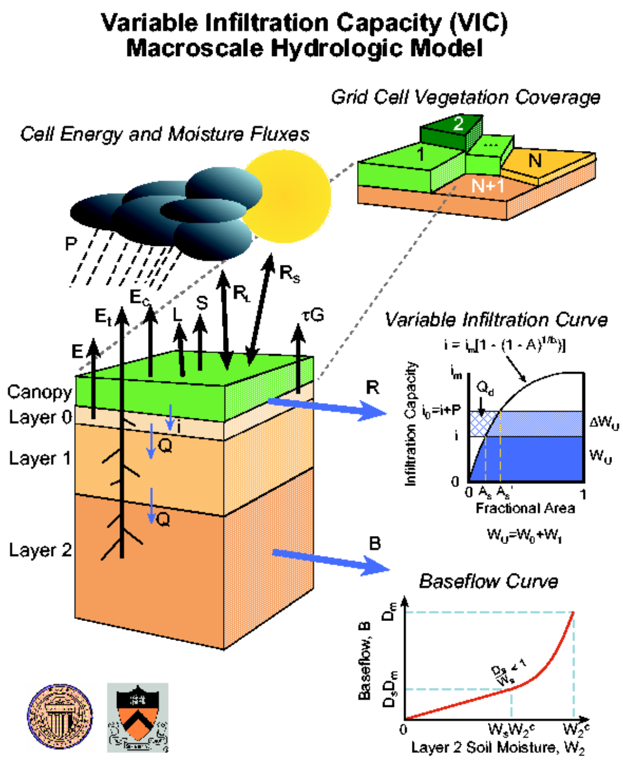


Figure 21: VIC hydrological modelling schematic (from Liang et al., (1994))

Hydraulic Modelling: Unsteady flow simulation

Hydraulic modelling uses a mathematical model to simulate hydraulic processes within river networks to estimate the response of a river system to a set of flow conditions in order to produce a set of water surface profiles. There are two types of approaches to simulating flows and water surface profiles: steady flow modeling; and unsteady flow modeling. Steady flow modeling refers to steady state conditions which are constant over time, and therefore not time dependent. Whereas unsteady flow modeling refers to time-dependent flow. The computational procedure is based on the solution to the 1-D momentum and energy (steady flow) or continuity (unsteady flow) equations (USACE, 2010). The effects of various obstructions and water control infrastructure (such as bridges, culverts, weirs, gates, levees, and dams) can also be modelled in hydraulic simulations.

Unsteady flow hydraulic analysis was used to generate a time-dependent series of inundation maps and time-dependent flood data. Unsteady flow modelling provides a dynamic solution for generating stage and flows throughout a river network. The use of an unsteady flow simulation model requires significantly more effort than a steady flow simulation (USACE, 2010), however the DRST requires dynamic spatio-temporal physical data to produce dynamic spatio-temporal resilience assessment so unsteady flow modelling is more appropriate than steady flow modelling. The basic data requirements for simulation include: river system geometry, flow characterization, simulation settings, and specification of boundary and initial conditions.

Unsteady flow simulations are more complex than steady flow simulations and requires a great deal of data and computational effort. Unsteady flow simulation requires a time-series of inflow data (discharge hydrograph). Common sources of these data include: historic stage-flow hydrographs; computed synthetic floods; peak discharges with assumed time distributions; and rainfall-runoff modelling. Historic records are insufficient for this analysis, as modelling climate change impacts implies that historic streamflow stationarity does not apply. Therefore, this analysis used hydrograph estimation based on computed peak discharges over an assumed time distribution, using the United States Army Corp of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS)'s interpolation routine. Unsteady, dynamic hydraulic modelling and simulation is governed by the principles of the conservation of mass (continuity) and momentum (all variables are described in Appendix C):

$$\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} - q_i = 0 \tag{4.5}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (VQ)}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{4.6}$$

The program then performs calculations to establish flows and water levels in the cross sectional profiles. Additional equations essential to the computational procedure are provided in Appendix C.

Hydraulic Modelling: Boundary conditions

Hydraulic modelling of a river network requires the specification of boundary conditions (BCs). There are upstream, interior, and downstream BCs. Upstream BCs are required for all reaches (main channel and tributaries) which are not connected to other reaches. Upstream BCs for unsteady flow analysis are specified as flow hydrographs (discharge vs. time). Interior BCs are required to specify the relationship between reach connections. They occur at junctions between tributaries and at places in the network where the flow splits. These locations either apply the continuity of flow, or the continuity of stage equations during hydraulic simulation. Downstream BCs are required at the end of all reaches not connected to another reach. Unsteady flow downstream BCs may be specified as either stage hydrographs, flow hydrographs, rating curves, or normal depths.

The climate change influenced streamflows are specified as flow hydrographs which were introduced into the hydraulic modelling and simulation as upstream BCs (Figure 22). The climate change influenced SLR projections are introduced into the model as downstream boundary conditions (Figure 22). These BCs are specified at the edges of the model and help define how the flow responds in the entire river system.

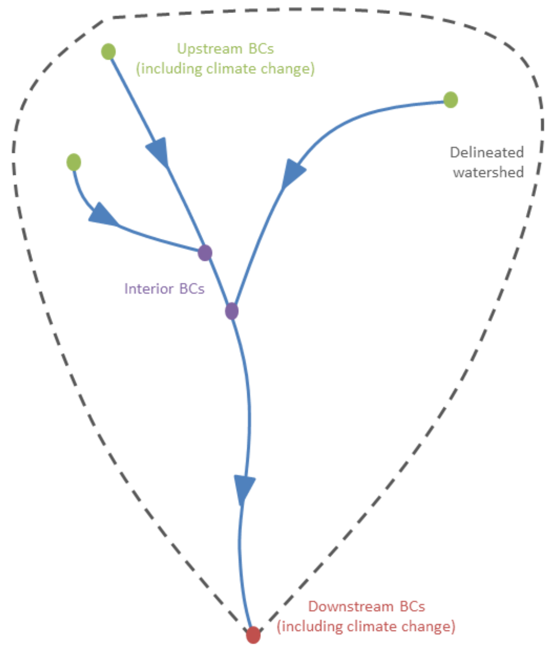


Figure 22: River schematic identifying locations which require the specification of boundary conditions and where climate change is incorporated into the hydraulic modelling process

Hydraulic Modelling: Output

Hydraulic simulation is time-dependent for dynamic unsteady flow. The unsteady HEC-RAS computational procedure uses many of the same inputs and hydraulic calculations as steady flow simulations, however the solution of the continuity and momentum equations uses a unique solver (USACE, 2010). The unsteady flow simulation can be considered a three-step process, and generates a collection of output files (Figure 23a) including a DSS file containing a time-series of stage-time and flow-time plots. If the optional Post Processor module is run, an output file is created containing detailed hydraulic results. When the spatial water surface extents are exported from HEC-RAS to GIS and intersected with spatial topographic data, it's possible to generate a time-series of climate change influenced inundation maps (Figure 23b). These are the maps used by the DRST to determine domain impacts.

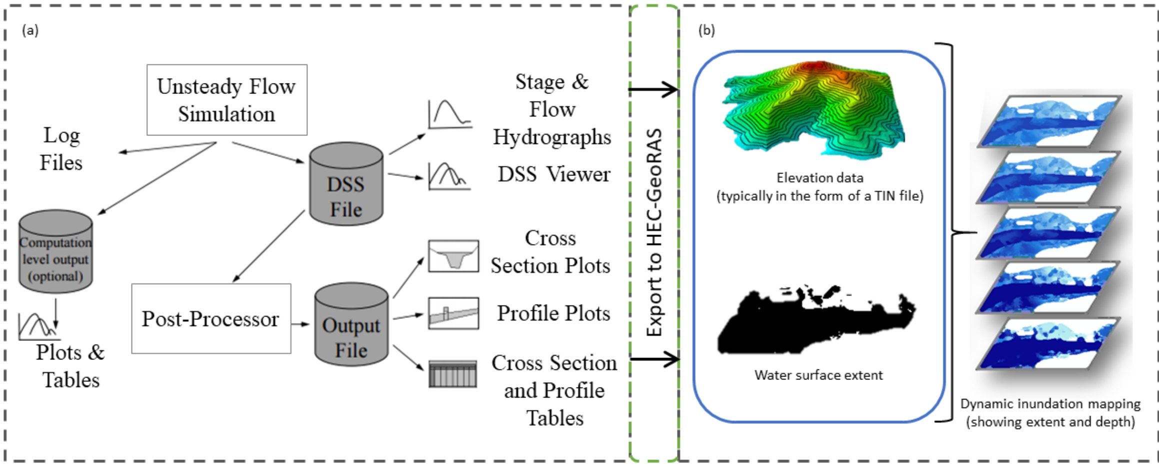


Figure 23: Schematic of physical domain output (a) generated from hydraulic unsteady flow simulation; (b) when combined with spatial topographical information to generate a time series of inundation maps (adapted from USACE 2010)

4.3.3 Economic Domain: Description

Natural disasters can have severe and long-lasting economic consequences. Typically, economic damage-and-loss assessments are conducted as part of post-disaster recovery activities (European Union, United Nations Development Group, and The World Bank, 2013). These assessments are reactive measures intended to coordinate recovery efforts and guide recovery planning. However, it would be valuable to be able to estimate these damages and losses before an event occurs. Although progress has been made in modelling the potential economic impacts of disasters, this area of research is still relatively new.

Gertz (2015) identifies three main approaches used to quantifying the economic impacts of disasters: econometric techniques, input-output modelling, and computable general equilibrium (CGE) models. Traditionally, input-output modelling was the most common way to estimate the economic impacts of both man-made and natural disasters (Cochrane, 1974; Hallegatte, 2008; Rose, 2017). The popularity of this technique lies in both its ability to reflect regional economic interdependencies and its methodological simplicity. However, the rigidity and linearity of the input-output modelling approach which makes it desirable also limits its effectiveness in adequately capturing the complex dynamic behaviours of the economy in the event of a disaster. As such, CGE models have become an increasingly popular way to model the impacts of disasters on the economy (Carrera et al., 2015). CGE models are more flexible in their approach to modelling the elasticity of economic supply and demand activities. Moreover, they are able to respond to price changes, handle production processes, and incorporate goods substitutions into the analysis, which better mimic real world disaster responses and more accurately captures disaster dynamics. Therefore, the DRST uses an innovative, dynamic, regional CGE model to estimate the economic impacts of a disaster.

4.3.3.1 Economic Domain: Implementation

The performance of the *economy* was identified as one of the indicators of economic disaster resilience. Engineering resilience quantification was implemented in the DRST considering the performance metric *GDP* as a proxy for the *economy* resilience indicator. Therefore, economic system performance can be described as a function of the following:

$$P_{economy}^{economic} = f(GDP)$$

The economic domain of the DRST is based on a multi-sector balanced growth CGE model, used to capture the dynamic impacts of hydrometeorological disasters on the regional economy. The CGE model used in the DRST was developed by Gertz (2015), with minor modifications made by the author. The CGE model builds on work done by (Hallegatte, 2008), but innovates by allowing the patterns and speed of recovery to be determined endogenously. Herein, reference to the CGE model is assumed to be this version in the DRST developed by (Gertz, 2015).

The CGE model is based on the optimization behavior of individual households and firms (government) within a region. Each sector in the GCE model uses capital, labour, and intermediate goods as inputs to production. The good produced by each sector is combined with an imperfectly substitutable import to create an Armington good (Armington, 1969); an elasticity substitution parameter for similar products produced in other countries. The assumption is that imports are used as imperfect substitutes for domestic goods. The Armington goods can then be consumed, invested, used as an intermediate in production, or exported. The households and government then each optimize their stream of consumption over time. A flood hazard is modeled as a shock to the capital stocks of various industries. The economy slowly rebuilds the capital stock over time and converges back to balanced growth. This optimization model is used to simulate the dynamic impacts that a flood (a shock) may have on the economy (in the form of damages to capital stock).

Objective functions, decision variables, constraints, and parameters characterize an optimization problem. A CGE model is an optimization model and can therefore be described using conventional optimization modelling terms. The objective functions for the DRST CGE optimization model includes the maximization of household and government profits and utility; subject to model constraints. The representative household chooses its stream of consumption and investment to maximize utility subject to budget constraints. Mathematically, this process is described as:

$$\max_{\{c_t, i_t^i\}_{t\in[0,\infty)}} \sum_{t=0}^{\infty} \beta^t u(c_t) \tag{4.7}$$

subject to

$$\sum_{t=0}^{\infty}\left[p_t(1+\tau_C)c_t + \sum_i p_t^{I^i}(1+\tau_I)i_t^i\right] = \sum_{t=0}^{\infty}\sum_{i=1}^{N}\left[\left(w_t^i - \tau_L\right)l_t^i + \left(R_t^i - \tau_K\right)k_t^i\right] \tag{4.8}$$

$$k_{t+1}^i = \left(1-\delta^i\right)k_t^i + i_t^i \tag{4.9}$$

where β is a discount factor, i_t^i is sector-specific investments, and $u(c_t)$ is the household utility function; where p_t is the price of the composite consumption good, $p_t^{I^i}$ is the price of the investment good, , τ_C is rate of sales tax on consumption goods, τ_I is rate of sales tax on investment goods, w_t^i is sector-specific wages, τ_L is tax rate on labour income, τ_K is tax rate on capital income R_t^i is sector-specific return to capital; and where k_t^i is capital, and δ^i is the depreciation rate. The government maximizes utility over its stream of consumption subject to budget constraints. Mathematically, this is:

$$\max_{\{G_t\}_{t\in[0,\infty)}} \sum_{t=0}^{\infty} \beta^t v(G_t) \tag{4.10}$$

subject to

$$\sum_{t=0}^{\infty} p_t^G G_t = \sum_{t=0}^{\infty} [T_t^L + T_t^K + T_t^{Sales}] \tag{4.11}$$

where β is a discount factor, and $v(G_t)$ is the government utility function; and where p_t^G is price of government consumption, T_t^L is labour tax revenues, T_t^K is capital income taxes revenues, and T_t^{Sales} is sales tax revenues. The decision variables are prices and quantities of the goods, capital, labour, and trade markets. All objective functions must satisfy model constraints.

To determine share parameters for sector-specific production, the consumption bundles, the investment goods, tax rates and trade shares, the CGE multi-sectoral model requires a social accounting matrix (SAM). A SAM is a comprehensive economic accounting system that captures all the transactions and transfers taking place between agents in a system over a period of time. It provides details on sector-specific intermediate inputs, labour, capital, taxes, and final demand (private consumption, government consumption, investment, imports and exports). Unlike simple input-output models, a SAM is capable of modelling inter-sectoral impacts by incorporating a complex household sector (Siddiqi and Salem, 2012). A well designed and disaggregated SAM provides insight about the structural features and interdependencies of an economy. It represents a snapshot of the transactions taking place during a period of time. The starting point for constructing a SAM is a regional input-output table and a regional final demand table. Since the DRST was designed to operate at the regional level, Gertz (2015) regionalized the provincial input-output and demand tables using sectoral municipal-level employment data from Statistics Canada. The SAM also requires a regional demand table which Gertz (2015) derived from detailed final demand tables in industry accounts. In this way, a SAM was derived for use in the CGE model.

The capital and labour sectors of the economics model are industry specific. Therefore, the CGE model considers 20 different industry classifications (Table 3). Each building in the spatial model is given one of these industry-specific classifications. The CGE model uses this information, combined with flood hazard extent and depths to estimate the damages to the capital stock in the form of damages (Figure 24). The maximum cumulative damages by sector are sent from the spatial and engineering domains of the model to the CGE model and then optimization operations are executed. In this way, it is possible to observe the effects that a flood hazard will have on the economy.

Table 3: Industry-specific economic model sectors

Economic Code	Economic Sector Description
B11	Agriculture, forestry, fishing, and hunting
B21	Mining, oil and gas extraction
B22	Utilities
B23	Construction
B31-B33	Manufacturing
B41	Wholesale trade
B44-B45	Retail trade
B48-B49	Transportation and warehousing
B51	Information and cultural industries
B52-B53, B55	Finance, insurance, and real estate
B54	Professional, scientific, and technical services
B56	Administrative and support
B61	Educational services (private)
B62	Healthcare and social assistance (private)
B71	Arts, entertainment, and recreation
B72	Accommodations and food services
B81	Other services (except public administration)
G61	Educational services (public)
G62	Healthcare and social assistance (public)
G91	Public administration

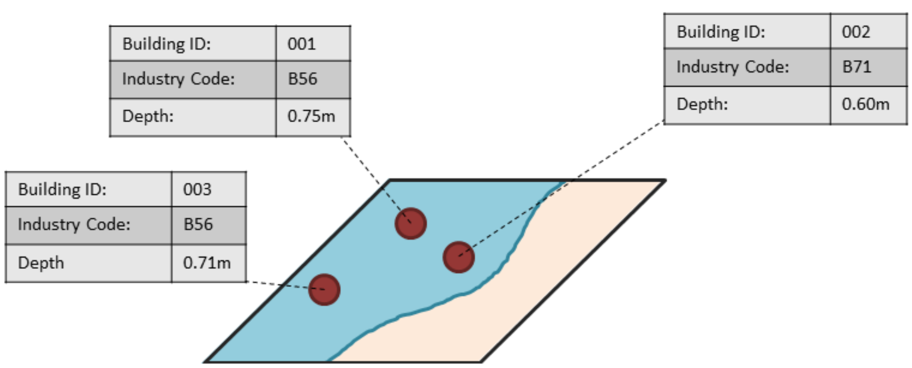


Figure 24: Schematic of spatial overlay and infrastructure attributes contributing to economic CGE model

Additional details pertaining to CGE model development, including additional model equations and assumptions can be found in Gertz (2015) with further refinement provided in (Gertz et al., 2019).

Contrary to the other domains of the DRST, the economics model runs analysis at the city-wide spatial scale. A shock, such as a flood, causes damage to industries that become inundated, resulting in damages to the capital stock. The impact of the flood is reflected in the regional GDP losses. Over time the capital stock rebuilds, and ultimately the solution to optimization converges towards a balanced growth path. Since a regional economy does not act independently of national or even global economies, there are additional parameters within the economics model which include out-of-bounds influences such as importing and exporting, and national GDP values, exogenous to the regional-level model.

The General Algebraic Modelling System (GAMS) software (GAMS Development Corporation, 1987) was developed in partnership with the World Bank to provide a system structure and programming language which maintains portability, generality, and ease of implementation for mathematical optimization models. It supports multiple optimization techniques including: linear programming; mixed-integer programming; non-linear programming; constrained nonlinear systems; non-linear programming with discontinuous derivatives; and quadratic constrained programs. The economic domain of the DRST uses GAMS software for CGE modelling and optimizing complex economic activities during a disaster. The generic organization of the economics domain GAMS program is provided in Figure 25. The Municipal Level GDP and Loss by Sector optimization results are outputs produced by the GAMS model. *Municipal Level GDP growth rate* is used as the performance metric for the *economy* in Economic Resilience calculation in the DRST. A more detailed description of the GAMS program and code is provided in Appendix D.

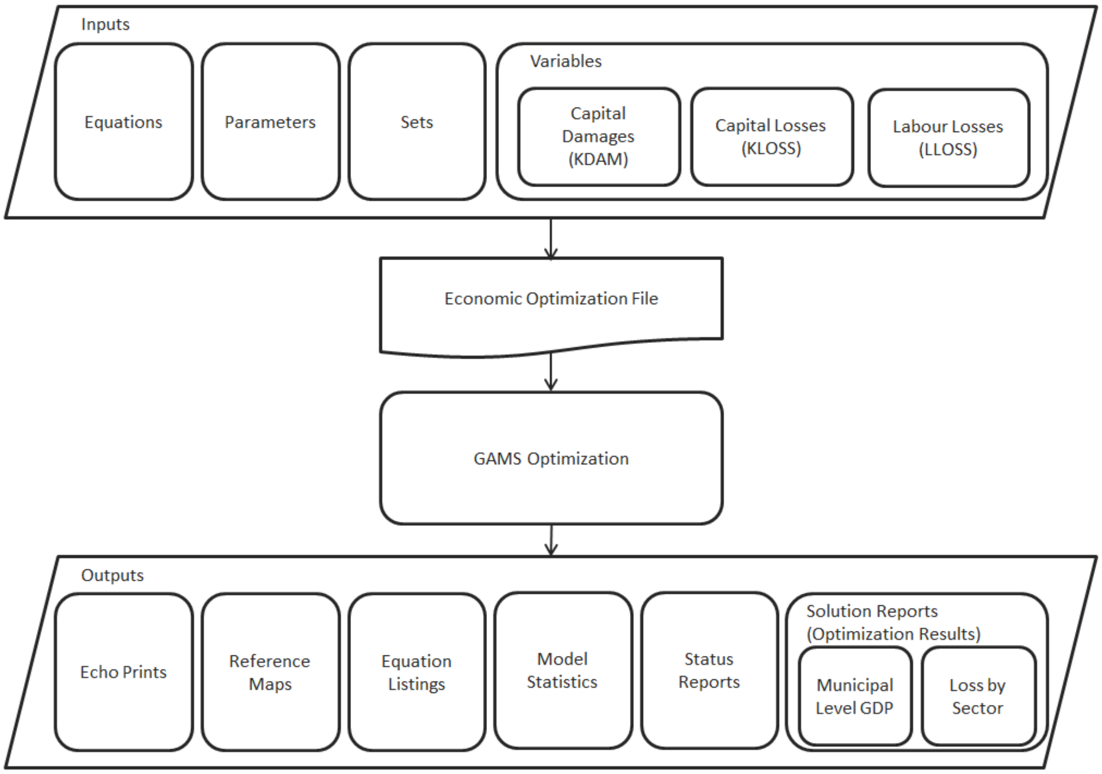


Figure 25: Schematic of the economics domain GAMS modelling and optimization; this process is completed only once, at the end of the simulation

4.3.4 Engineering Domain: Description

Engineered infrastructure provides services to people and places within a city. Maintaining the functionality and performance of this infrastructure often plays a critical role in disaster management. Rarely are infrastructure systems independent of each other; typically, they rely on each other to properly fulfill their intended purpose. These interdependencies increase system complexities, which means well-intended decisions may result in unforeseen adverse consequences. It is therefore important to consider these cross-connections and interdependent system linkages.

Nan and Sansavini (2017) recently proposed a metric for resilience quantification of interdependent infrastructures. They provide a multi-layer hybrid approach to capture interrelationships between various infrastructure components as applied to an electric power supply system. Each infrastructure (system) is broken down into its layers (subsystems) and their components. Interactions occur both horizontally (within layers) and vertically (across layers). The failure of any individual component could therefore cause cascading failures which could affect the operations or functionality of the entire system. The authors implement an Agent Based Model (ABM) to simulate the interactions of agents (i.e. system components) [acting in accordance with pre-defined physical laws and interaction rules] in the event of a disturbance – in their case study, a winter storm in the central region of Switzerland. Three "resilience strategies" are compared to determine which option may provide the best strategy for restoring power to pre-disaster levels. This application is suitable for individual infrastructure resilience assessment; however, it would be very complex to model using ABM across multiple infrastructure types and it does not provide a substantial enough foundation for incorporating non-infrastructure-type systems into resilience assessment. The DRST can estimate physical damages to school buildings and contents under various flooding conditions.

4.3.5 Engineering Domain: Implementation

Building stock was identified as one (of many) indicators of engineering disaster resilience. Engineering resilience quantification was implemented in the DRST considering the performance metric *structural and content damages* as a proxy for the *building stock* resilience indicator. Therefore, engineering system performance can be described as a function of the following:

$$P_{bldg\ stock}^{engineering} = f(water\ depth, building\ type, value\ of\ structure, value\ of\ contents, flood\ proofing, reconstruction\ rate)$$

The amount of damage directly depends on the depth of water in the area and therefore, the performance of this system is highly spatially dependent. When a disturbance occurs (such as a hazard event), it's possible that buildings get damaged by floodwaters and the *building stock* becomes impacted. As flood waters encroach on an area, the depth of water increases. As the depth of water increases, inundated infrastructure sustains additional damages. Once the building is no longer flooded, it's possible for recovery actions to begin and the building begin repairs.

Damages are quantified using stage-damage curves. These curves provide an estimate of damages based on the depth of flood waters. A schematic of the procedure for a single infrastructure element is shown in Figure 26.

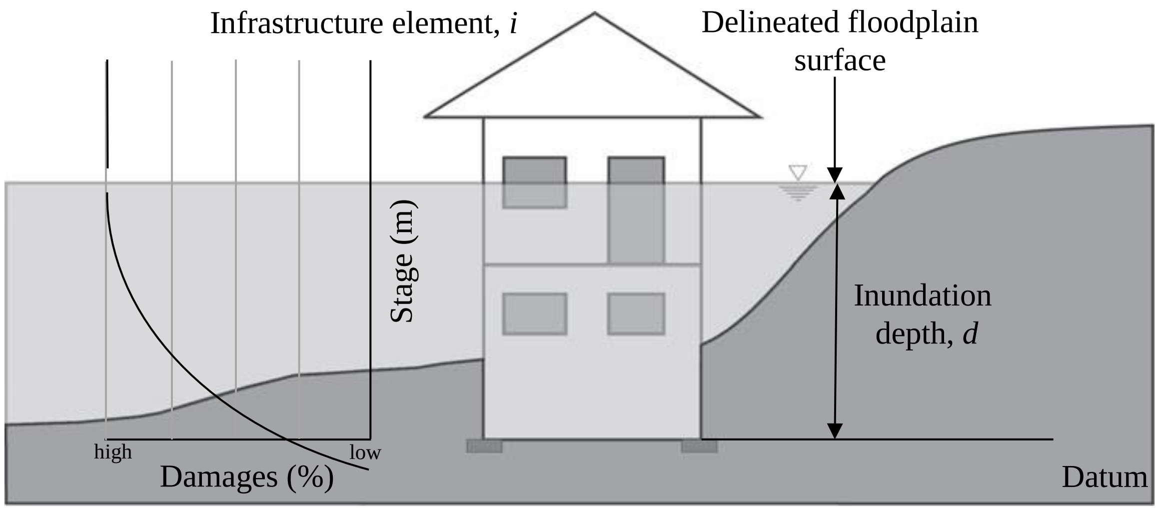


Figure 26: Schematic of engineering domain calculations for a single infrastructure element (adapted from Nastev and Todorov (2013))

As can be seen in the schematic, damage to any infrastructure element is dependent on its inundation depth and the type of structure (which drives selection of the appropriate SD curve). Since there will be losses to structure contents, these values are estimated as a proportion of the damage to the structure (typically around 30%).

Water depth, infrastructure type, and stage damage curves are the main requirements for engineering resilience assessment. The engineering resilience assessment process is completed in 7 steps (Figure 27). Estimating engineering resilience begins with spatial intersection of the flood inundation map and infrastructure layers. After identifying each element of inundated infrastructure (i), the depth of inundation (d) is extracted at each infrastructure location. This depth is then used with infrastructure-specific stage-damage (SD) curves to interpolate the corresponding damage percentage ($D_{i,\%}$). Mathematically this can be described as:

$$D_{i,\%} = f(d_i, type) \tag{4.12}$$

The damage percentage ($D_{i,\%}$) is then multiplied by the reconstruction value ($V_{i,\$}$) of the infrastructure to obtain a dollar damage value ($D_{i,\$}$). Mathematically, this is simply given by:

$$D_{i,\$} = D_{i,\%} \times V_{i,\$} \tag{4.13}$$

This process is repeated for every infrastructure element and then all of the damage values are summed together for a total estimated damage value ($D_{T,\$}$).

$$(D_{T,\$})_t = \sum_{t=0}^{i} (D_{i,\$})_t \tag{4.14}$$

This entire process is repeated for each time step. The damage at each time step $(D_{T,\$})_t$ is sent to engineering resilience calculations. The maximum summed damage value ($D_{T_{max},\$}$) is sent to the economic domain for use in economic resilience calculations.

$$D_{T_{max},\$} = \max((D_{T,\$})_t) \tag{4.15}$$

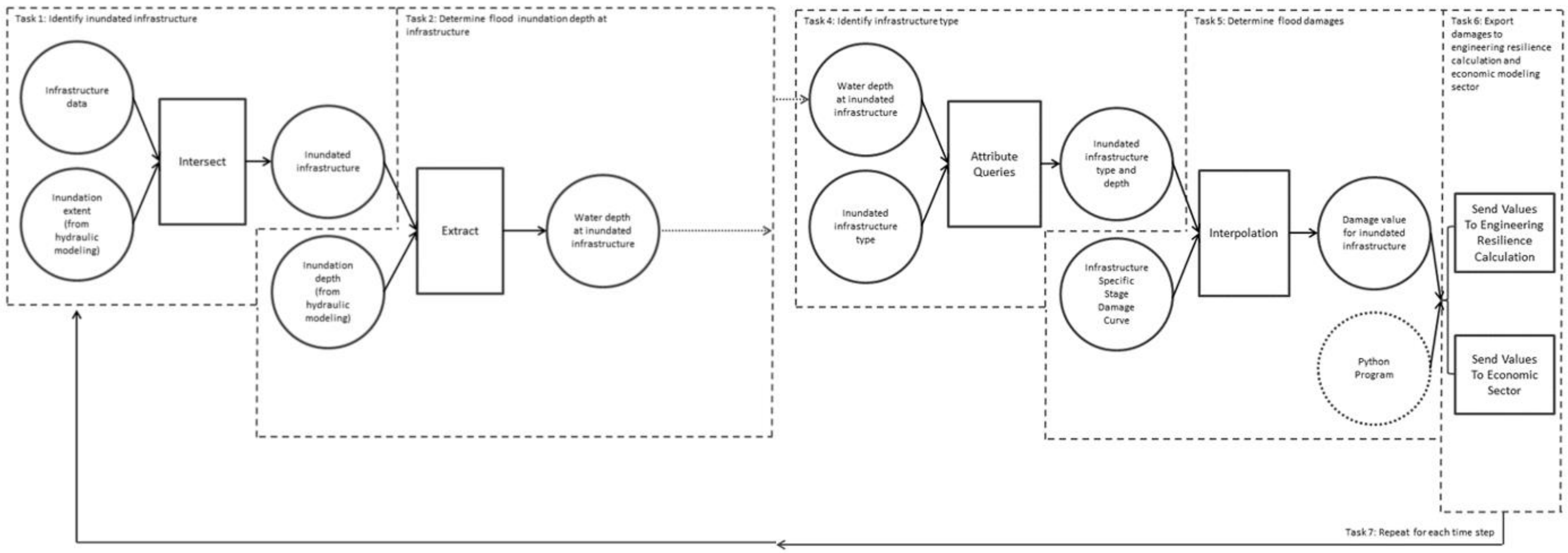


Figure 27: Engineering resilience spatial implementation, direct damages workflow diagram this process is completed for each time step (t) in the simulation

Since this process involves the use of spatial data, engineering resilience value will also be spatially (and temporally) dynamic. At each time step, engineering resilience values are aggregated up to the DA level, to achieve meaningful and compatible spatial resilience results.

4.3.6 Health Domain: Description

Public health and wellbeing are inextricably linked to climate change (Patz et al., 2014). It is therefore important to identify where the most climate hazard vulnerable communities are and what reprioritization of health resources may be needed to help address future health impacts. These resources may include improved disaster prevention, better communication systems, quicker disaster response, or even stronger food and water security. Intentional design in the public health domain is needed to build more resilient health systems for the future.

Traditional health disciplines include medical (physical) health, behavioral health, and social services. Although all three disciplines are important for comprehensive health management and health resilience, the DRST considers only medical health in resilience assessment. This choice was driven by available data and expertise in the medical field. Therefore, the remainder of this section focuses on health resilience in the medical (physical) health context.

Public health impacts due to natural disasters are inherently difficult to predict. Human health is a complex phenomenon and the relationship between climate change and the impacts it will have on human health is even more complex. This prediction is made even more difficult by the challenging spatial and temporal dynamic characteristics of diverse types of diseases. Data collection is difficult because diseases are not always reported nor diagnosed correctly. This difficulty is exacerbated by data collection methods which are dependent on both the human and financial resources of individual institutions. To complicate issues, where data are collected, records are often protected by patient confidentiality which limits the accessibility to health data.

Research suggests that public health capacities and consequences vary more by severity of the disaster than the type of hazard (FEMA, 1996; Frumkin, 2010), although geophysical disasters usually cause a greater number of injuries than meteorological disasters. The DRST simulates the impacts due to flood events of various magnitudes, which is consistent with these findings.

Injuries

Across all types of hazards, injuries are the primary cause of death (Luther, 2008; Luther, 2011); and drowning is the number one cause of death during a flood hazard (Malilay et al., 1997; WHO, 2018). Possible types of injuries during a disaster include: electrocutions, puncture wounds, falls, and carbon monoxide poisoning. Most of these injuries occur in the response and recovery phases of a disaster when contact with floodwaters and debris is highest. All sorts of debris can be carried by floodwaters, and when people come into contact with this debris, it can impact their health. Intermixed debris from the hurricane Katrina flood event included: municipal solid waste, vegetation, construction waste, asbestos, hazardous waste, white goods (such as refrigerators, stoves, etc.), electronic waste, and vehicles (Luther, 2008). This debris can cause serious injuries and propagate the spread of communicable diseases.

Diseases: Infectious Communicable

Infectious diseases are caused by microorganisms. Infectious diseases most commonly observed after a disaster include: acute respiratory infections, malaria, cholera, typhoid, hepatitis, measles and meningitis. However, many of the most serious infectious diseases are not commonly observed in North America. Malaria is a potentially life-threatening disease caused by parasites, transmitted through the bite of female mosquitoes. It’s most prevalent in sub-Saharan Africa, South-East Asia, Latin America, and the Middle East. Cholera is an acute infection of the intestines caused by the bacteria *Vibrio cholerae* found in the feces of infected people. It is commonly transmitted through consuming contaminated food or water. Cholera is not a concern in Canada, but regions with inadequate sanitation, poor hygiene, and overcrowding are at higher risk for infection. Cholera is a health problem in many developing countries in parts of Africa, Asia, Central and South America. In the Canadian context, measles and hepatitis do not have high prevalence in the general population due to vaccinations administered to children at a young age. However, children who have yet to receive the vaccination at the time of a disaster are more vulnerable to experiencing negative health impacts. There's also been reported links between malnutrition and infectious diseases. In cases of prolonged post-disaster food shortages, clinical malnutrition is a significant contributor to cause of death (Watson et al., 2007). Flood waters can contain Campylobacter, Giardia, Cryptosporidium, noroviruses, and enteroviruses associated with gastrointestinal illnesses caused by flood-induced sewage overflows (Patz et al., 2014). Meta-analysis of global waterborne communicable disease outbreaks have shown Vibrio and Leptospira were the pathogens most often cited (Cann et al., 2013).

Those infectious diseases which can be transmitted from one source to another through bacterial or viral organisms can be classified as communicable diseases (Heymann, 2016). Meteorological disasters are only rarely associated with epidemics of communicable disease (Keim, 2008), though many of the disaster-related disease deaths occur in displaced populations, likely due to high-density shelter conditions and high incidence of person-to-person transmissions. The displacement of populations (e.g. evacuations) is problematic for the spread of communicable diseases, particularly in developing countries where there are pre-existing conditions which contribute to the transmission of communicable diseases. Types of communicable diseases include: water-borne, respiratory, mosquito-borne, and rodent-borne. Sources of these diseases include: the built environment, freshwater organisms, and ocean water organisms. Common modes of transmission of infectious diseases include person-to-person, feco-oral, and vector-borne. Particular post-disaster conditions may influence the person-to-person and feco-oral transmission of infectious diseases post-disaster including: population characteristics, environmental conditions, endemic organisms, pre-hazard condition of the public health system, and type, duration, and magnitude of the hazard event. Furthermore, changes in the climate can influence the transmission of vector-borne diseases through multiple mechanisms including:

- Geographic shifts in the presence of vector-borne diseases;

- Rates of development, survival, and reproduction; and
- Increased biting and prevalence of infection.

The potential impacts of disasters on the spread of infectious diseases include: degradation of water quality; population displacement and subsequent population shelter densities; poor sanitation; increased sewage overflows; disruption of health services; decreased access to public healthcare facilities; and loss of major lifeline utilities.

Wet, bog-like post-disaster conditions create environments that are favourable for disease carrying insects (mosquitos carrying Malaria and Leptospirosis) and rodents (carrying vector-borne disease strains) (Watson et al., 2007). To reduce the spread of these diseases, it is good to reduce the favourable environment by increasing drainage (to reduce stagnant water), debris and garbage removal, improve sanitation, practice safe food storage and handling, and select dry shelter regions. In addition, improved infrastructure management and proper infrastructure design can reduce the number of sanitary overflow events, thereby reducing the spread of waterborne diseases.

Diseases: Non-communicable

There are also non-communicable diseases associated with the impacts of disasters. However, these types of diseases are more difficult to track and specific disaster-related impacts are particularly difficult to assess as they often go unreported or are diagnosed as aggravations of pre-existing diseases and not necessarily associated as a consequence of the disaster. Non-communicable diseases include: diabetes, neuropsychiatric (schizophrenia), cardiovascular (rheumatic heart, hypertensive cardiac), respiratory (asthma), and digestive (cirrhosis).

Other public health issues

Other post-disaster public health-related issues include: pollution (Zelenakova et al., 2016), malnutrition (Datar et al., 2011; Global Nuitrition Cluster, 2008), mental health and trauma disorders (Goldmann and Galea, 2014), and epidemics (rapid spread of infectious communicable diseases). The detailed impacts that flood disasters have on human physical and mental health are still not well understood (Chemtob et al., 2002), but qualitative evidence suggests that at an individual level, full recovery may take many years to achieve and financial, emotional, and mental costs related to health impacts may persist well into the future.

In summary, the overall risk of communicable disease outbreaks after natural disasters is relatively low, particularly when there is no substantial population displacement (evacuation). They are more likely to occur in in displaced populations that struggle to provide basic needs such as clean water, sanitation, and primary healthcare services (Watson et al., 2007). Disaster-related deaths are overwhelmingly caused by the initial traumatic (psychological and physical) impacts of the event (Watson et al., 2007) however drowning, and other more immediate flood-related causes of death were not explored as part of this work. Not only because these incidents are difficult to predict, but also because flood-related deaths by drowning are relatively uncommon in a Canadian context. Instead, the focus of health impacts was on treating people with injuries and/or continuing to provide traditional health care services to the community in the event of a disaster. Therefore, the implementation of the health domain focuses on restoration of access to primary care facilities in the wake of a disaster.

4.3.7 Health Domain: Implementation

It is apparent that there is high spatial and temporal variability in health impacts since each disease is active in different parts of the world and each has its own symptoms, onset time, and latency period. This makes diseases inherently difficult to monitor, track, and treat. During a disaster, it is particularly important to treat the injured and maintain adequate healthcare function. Therefore, *access to healthcare facilities* was identified as one (of many) indicators of health domain disaster resilience. Health resilience quantification was implemented in the DRST considering the performance metric *cost distance* as a proxy for the resilience indicator *access to healthcare facilities.* Access to healthcare facilities during a non-flooding situation is dependent on road type, local traffic, and road network connectivity. At the fundamental level, access to healthcare facilities during a flood is due to the same factors, which are then influenced by the extent and depth of flooding across the road network. This, in turn, is driven by the magnitude of the flood event and any structural and non-structural measures in place to protect the road network. For the research presented in this dissertation, health system performance was described as a function of the following:

$$P^{health}_{access\ to\ health\ care\ facilities} = f(distance\ to\ facilities, road\ type, road\ surface, road\ accessibility)$$

Since the provision of health services relies on the availability of roads (i.e. roads that are safe to drive), the performance of this system is contingent on the road network and its degree of flooding:

$$road\ availability = f(flood\ depth)$$

When a disturbance occurs (such as a hazard event), it's possible that the provision of emergency services is disrupted and *access to healthcare facilities* is disrupted when a road becomes flooded and is no longer accessible.

The DRST uses this principle and spatial analysis tools to calculate a cost-distance metric to public healthcare facilities at each time step during the simulation. This analysis implements an algorithm which combines a cost-surface profile, flood inundation extent, and water depth to calculate a cost-distance surface from public healthcare facilities to every point in space. Essentially, this is a raster-based algorithm which assigns a penalty factor to inundated roads; and the higher the depth of flooding, the greater the penalty (or "cost") would be to take that path to the hospital. The cost-distance algorithm determines the shortest weighted distance from each cell to the nearest "source" (hospital) location. Therefore, the output from this metric is a raster surface of cost units, not geographic distances.

The cost-distance algorithm requires an input source raster file (in this instance, it would be a raster dataset of hospital locations) and a single input cost-surface raster file (in this instance, an aggregate cost-surface raster created from combining multiple cost raster datasets (such as the road network combined with an inundation map). The source raster file is a raster file representing the location of hospitals. The cost-surface raster file is a raster file which is an aggregate-cost of all the input cost-surface raster files (road lanes; road type; road surface; and flood depth). The following outlines the cost-distance algorithm implemented in the calculation of health resilience in the DRST. This step-by-step description of the process is supported by Figure 28.

Step 1: The algorithm assigns a value of zero (0) to the source (hospital) cells

Step 2: The neighbouring cells to the source cells are activated.

Step 3: The travel cost between the neighbouring cells and the source cells is calculated. The travel cost between these neighbouring cells and the source cells depends on their spatial orientation and connection. The cost of moving from one of the activated cells to the source cell is calculated using one of the following cost formulas:

If the cell is adjacent, the cost to move to the neighbouring cell is calculated as:

$$a1_{adj} = \frac{cost1 + cost2}{2} \tag{4.16}$$

If the cell is diagonal, the travel cost is:

$$a1_{dia} = \sqrt{2} * \frac{(cost\ 1 + cost2)}{2} \tag{4.17}$$

Step 4: The costs are then arranged in a list from lowest to highest.

Step 5: The lowest cost cell is selected from the list and the value is assigned to the final cost-distance output raster file.

Step 6: The list of active cells expands to include the new neighbouring cells, as they now have a path to the source cell(s) (only cells with a route to the source cell(s) can be in the active list).

Step 7: The cost to move from the neighbouring cells to the source cells is calculated using the cost-distance formulas previously introduced and then the cumulative cost for nodes that are multiple cells away is calculated as:

$$cumulative\ cost = a1_{adj\ or\ dia} + a2_{adj\ or\ dia} + \cdots + an_{adj\ or\ dia} \tag{4.18}$$

where *n* is the number of adjacent or diagonal cells from the source cell. An accumulative cost is then assigned to each neighbouring cell; cumulative costs are placed in a list; the lowest cost cell is selected and added to the final cost-distance output raster; and the list of active cells expands. This algorithm continues until all eligible cells have received a cost value. When the growth patterns meet, cells will be able to reach another source or have a cheaper growth path available; if so, they will be reassigned to the new source or path.

Step 8: When all cells have been chosen from the active list and assigned to the output cost-raster, the process stops and the final cost-distance raster file is complete.

The final cost-distance raster file is used as one of the metrics for health resilience calculation where cost-distance is the performance indicator, and the units are dimensionless cost-units.

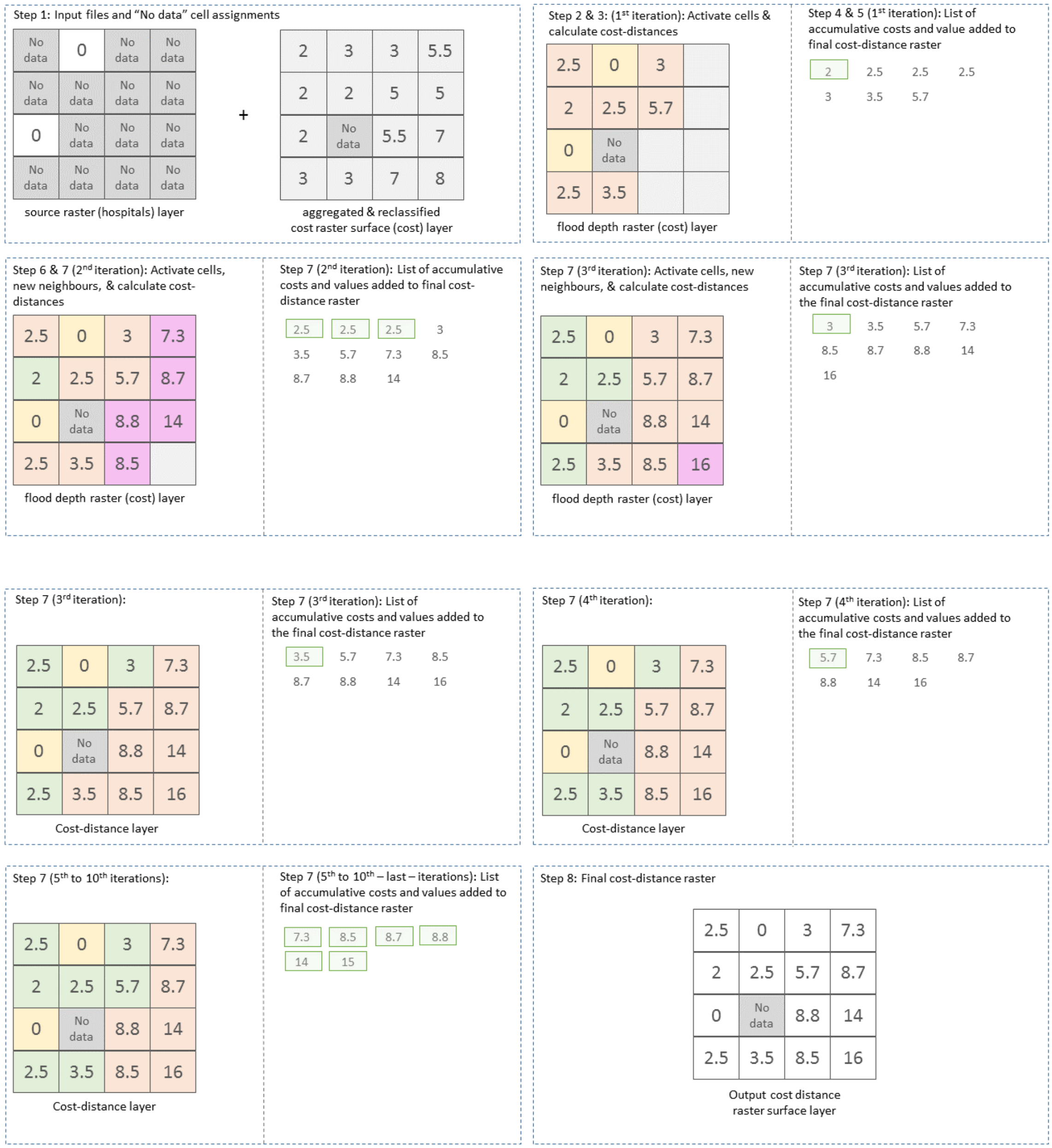


Figure 28: Implementation of the spatial health domain cost-distance algorithm

This spatial cost-distance algorithm is implemented at each time step in the DRST calculation, therefore capturing the spatio-temporal dynamic changes in access to public healthcare facilities. The final cost-distance values are then reclassified and aggregated to the DA level to provide a high-level indication of each regions' health domain resilience before, during, and after a flood event.

The results of the health domain spatial analysis (Figure 29) is combined with regional estimates of burden of disease and health impacts to provide a more complete estimate of health domain resilience.

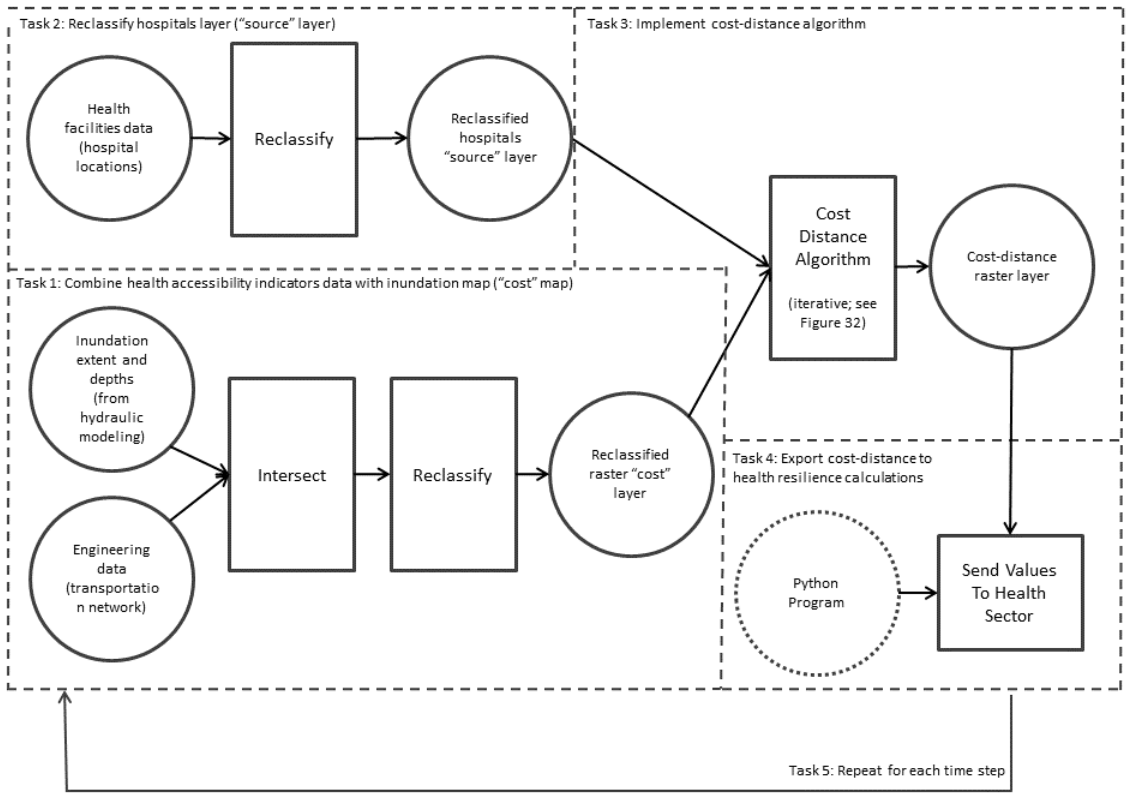


Figure 29: Health resilience spatial implementation, cost-distance workflow diagram; this process is completed for each time step (t) in the simulation

Since this process involves the use of spatial data and spatial analysis techniques, health resilience value will also be spatially (and temporally) dynamic. At each time step, health domain resilience values are aggregated to the DA level, to achieve meaningful and compatible spatial resilience results.

4.3.8 Social Domain: Description

Disasters have both tangible (relating to physical) and intangible (relating to emotional) impacts on people. Therefore, it's important to consider social resilience domain as part of integrated disaster resilience assessment. Socially resilient populations demonstrate the ability to adapt to a disturbance to better prepare for, respond to, and recover from disaster circumstances. These populations may recover and emerge more resilient than they initially were before the event occurred. Norris et al. (2008) suggested the following factors influence social resilience: citizen involvement in mitigation efforts, ongoing psychosocial support, strong civic leadership, and effective horizontal and vertical organizational linkages. O'Neill et al. (2016) substantiate these claims through a review of available social resilience literature, interviews with citizens, and through the author's personal experiences. They determined that the social resilience factors proposed by Norris et al. (2008) were consistent with their findings in a case study following the 2009 flooding in Fargo, North Dakota. They also propose that the community's "identity" (in this case a "floodplain identity") heavily influences its social resilience in the event of a disturbance (in this case a flood). These "identities" reflect a community's attitudes, responsibilities, and expectations of the government, relief organizations and individuals in the event of a disturbance. It's also been proposed that resilience of disaster management systems also relies heavily on interorganizational and social networks, effective communication, trust, and social capital (Kapucu and Demiroz, 2017). However, traditional disaster management approaches, such as performance measurement tools, have faced challenges in evaluating the relationships in – and between – these networks.

Disaster resilience at an individual level draws on knowledge gained from education, previous experiences, personal interactions, and the media. The information from these sources combines to formulate a perception which subsequently drives pre-disaster or post-disaster actions (or inaction). In North America, people typically desire to live near the coast; the close proximity to water makes it an attractive, popular, and hence expensive location to live; coastal communities are often affiliated with affluent residents. In developing countries however, people who have been displaced or rely on proximity to water as a means of survival, live closest to the water, which makes them particularly susceptible to impacts of hydrometeorological hazards. The disparity between these scenarios can be captured by considering a spatio-temporal integrated disaster resilience.

The relationship between poverty, environmental degradation and hazard vulnerability is a vicious, mutually reinforcing system of feedbacks (Kesavan and Swaminathan, 2006) especially prevalent in developing countries. The degree to which persons may experience physical, emotional, or psychological distress impacts is influenced by their tolerance and coping capabilities in stressful situations.

4.3.9 Social Domain: Implementation

Based on literature and informal feedback collected during resilience building workshops, *connectivity* was identified as one (of many) indicators of social disaster resilience. Social resilience quantification was implemented in the DRST considering the performance metric *number of people with cellular service* as a proxy for the *connectivity* resilience indicator. Therefore, social system performance can be described as a function of the following:

$$P_{connectivity}^{social} = f(no. of\ people\ serviced, operational\ towers, proximity\ to\ tower, tower\ capacity)$$

Since the provision of cellular service relies on the number of operational towers in the area and subsequently depends on adequate power supply, the performance of this system is also contingent on the power transmission network:

$$operational\ towers = f(operational\ substations, transmission\ network)$$

When a disturbance occurs (such as a hazard event), it’s possible that the provision of power is disrupted and *connectivity* is affected when a substation is no longer operational and fails to deliver power to transmission lines, therefore rendering the cell towers not operational. The implementation of the social sector is shown in Figure 30, an adapted version of the methodology proposed by Andre et al. (2000)

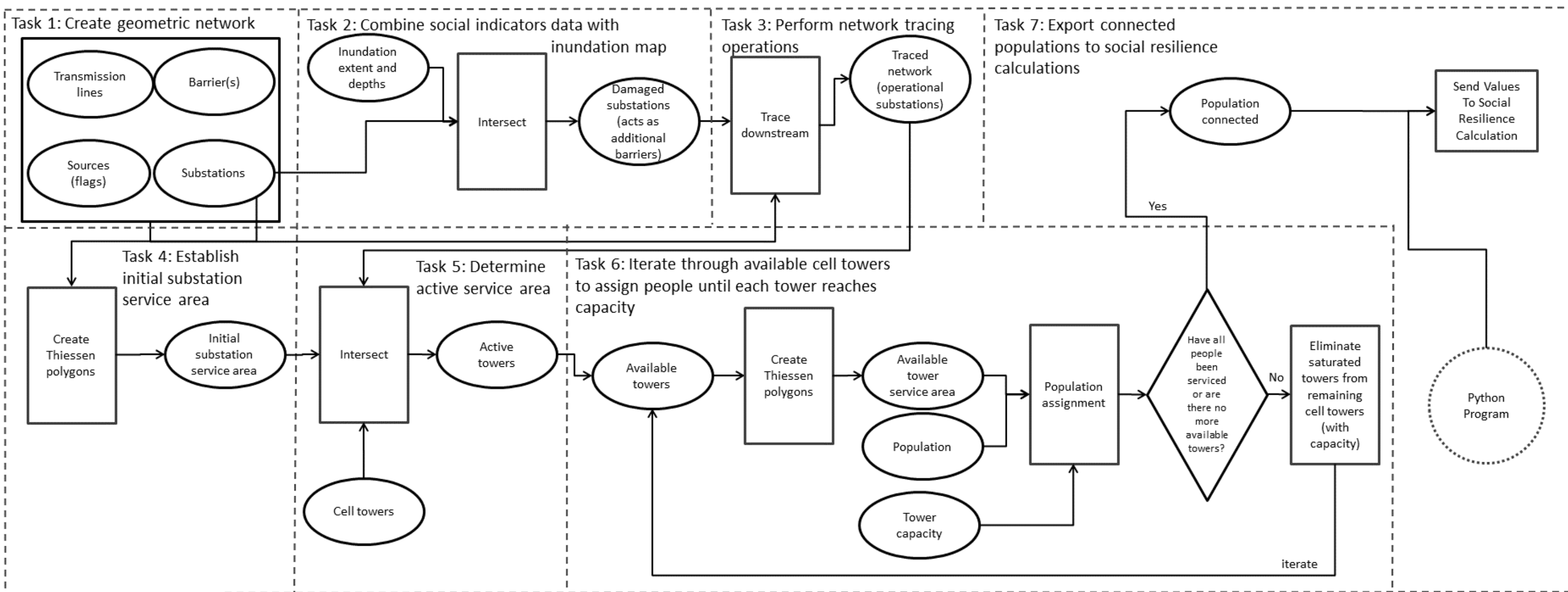


Figure 30: Social resilience spatial implementation, communications workflow diagram this process is completed for each time step (t) in the simulation

Connectivity was the social resilience indicator selected to be implemented in this research, however it's possible as part of future work to include other social resilience indictors as part of resilience quantification.

4.4 Integrated Resilience

The physical domain produces a times series of inundation maps which are used as input into the DRST and directly influences economic, engineering, health, and social domains. The engineering domain also provides input into the economic domain. These domains are connected in spatial and temporal analysis via a middleware program created in the Python programming language. This middleware program forms the crux of the analysis, linking together GIS spatial datasets, spatial analysis, system dynamics simulation, and economic optimization capabilities.

The proposed methodology currently integrates resilience measures from each domain (economic, health, physical and social) into a single Resilience Index (RI) measure at each time step (*t*) for each area (*A*), mathematically as:

$$RI = \sum \alpha_i R_i \qquad (4.19)$$

Where α_i is a weighting factor, R_i is each domain's resilience value, and *i* is the domain (physical, economic, health, and social). Expanded, this is:

$$RI = \alpha_i R_i + \alpha_2 R_2 + \alpha_3 R_3 + \alpha_4 R_4 \qquad (4.20)$$

The weights, α_i, were included to provide an opportunity to influence the resilience calculation and could be adjusted to reflect decision maker priorities. Priorities could be established through stakeholder workshops, discussions, or surveys. However, no additional research into the selection of resilience weightings is provided as part of this thesis.

4.5 DRST Programming and Simulation

The above relationships and model equations were implemented in a spatio-temporal dynamic simulation tool called the Disaster Resilience Simulation Tool (DRST). The resilience calculation is performed for each time step, for each domain, in the DRST. The system dynamics simulation model is set up as a gaming simulation, which allows the user to interact with the model to input model parameter values (from GIS) and make decisions as the simulation progresses. The user can therefore participate in decisions that affect the outcomes of the simulation. The next logical step would be to identify potential simulation scenarios (various combinations of input variables) to see the potential impacts on disaster resilience.

4.6 Adaptation Options

Implementing dynamic quantitative disaster resilience in a simulation tool provides an opportunity to test various adaptation options. To inform the disaster management community, it is necessary to conceptualize various opportunities and options for increasing resilience through both structural and functional adaptation measures. Adaptation options are best designed when they reflect local political and governance structures whilst factoring in public perceptions and preferences. Therefore practical, implementable options are best developed in consultation with local stakeholders.

Adaptation policies are incorporated into the model by considering adaptation scenarios as part of the DRST. These scenarios are a combination of values assigned to a set of model variables. The purpose of these scenarios is to observe changes in the city system resilience as a result of implementing specific adaptation policies. The purpose of adaptation scenario simulations is to help develop climate change adaptation policy, aid in resource allocation decisions and prioritize disaster management investments.

The adaptation scenarios modify particular elements within the DRST to represent policy actions. A scenario may modify initial values of input variables, or modification may be implemented at another point during the simulation time horizon. For example, a scenario may involve allocating additional financial resources to a particular model domain in the period of response during a disaster. Another scenario may consider the effects of allocating additional financial resources to a particular model domain in the period of recovery after a disaster. These scenarios can be simulated separately in the DRST to observe their effect on model subsystems and on overall resilience behaviour. Another example of an adaptation scenario is designating additional emergency shelters before a disaster in anticipation of coastal population growth and increased frequency of extreme climate events. The expected system behaviour from this action would be an increase in the STDRM and overall city resilience; the addition of emergency shelters would decrease shelter crowding and likely reduce the spread of communicable disease in the event of a disaster. However, this is an example of a direct, more obvious relationship associated with the scenario; there may be other indirect relationships in the system that may be negatively affected by this action. For example, increasing emergency shelters requires more coordination and communication during disasters, increased funding for adequate maintenance of buildings and possibly the employment of additional emergency support personnel. The scenarios change input conditions which have cascading effects and can modify subsystems of the resilience model. The results may be unforeseen consequences in other domains that are less obvious than initially thought. The resilience system is complex and the comprehensive DRST can help identify these direct and indirect relationships and obvious and nonobvious system behaviour. It is desirable for adaptation scenarios to be probable, realistic, and robust. Therefore, the three scenarios used to test the DRST were selected in collaboration with experts familiar with the social-political landscape in BC, Canada. Ultimately, the value in of this approach is not in providing a single solution, but in providing an avenue for comparison between suites of different scenario options, given the best information available.

Chapter 5

5 APPLICATION IN METRO VANCOUVER, BRITISH COLUMBIA, CANADA

The following Chapter describes an application of the DRST in Metro Vancouver, British Columbia. It closely follows the framework originally presented in Chapter 3, Figure 2. The chapter begins by identifying the primary motivation for resilience quantification application in Metro Vancouver region and then goes on to **set the resilience landscape, characterize dynamic resilience, and describe the implementation of dynamic disaster resilience quantification** specific to Metro Vancouver. The end of the chapter presents results and discussion.

5.1 Primary Motivation for Disaster Resilience Quantification Application in British Columbia

Metro Vancouver region is situated on the west coast of Canada on the Straight of Georgia, near the Pacific Ocean. Metro Vancouver Regional District (herein referred to also as “the Region”) is a collaborative governance federation which consists of 21 member municipalities, one electoral area, and one First Nations group (Figure 31). The Region consists of over 3000 unique Dissemination Areas (Figure 32), covering an area of almost 2,900 km^2 (Statistics Canada, 2018). It operates as a political and corporate entity under provincial legislation as a “regional district” that acts on behalf of its members to develop, plan, and deliver essential water, wastewater, and solid waste services and management. The Metro Vancouver region was selected as a case study for implementing the DRST because of its coastal geography, diverse economy and demographics, and its riverine delta hydrological environment in addition to the increasing pressures faced by urbanization and coastal and riverine climate change influenced hazards.

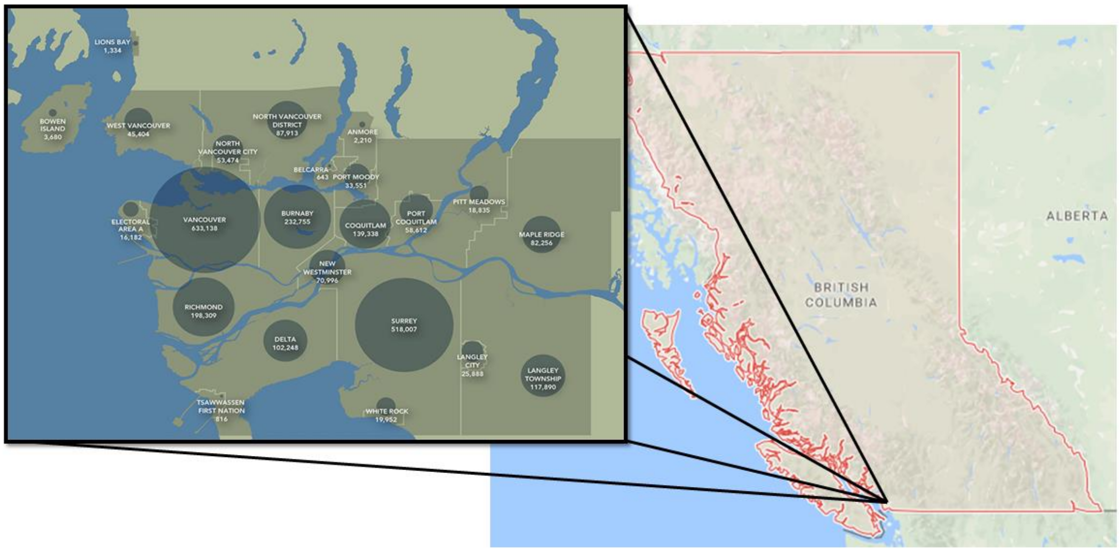


Figure 31: Region of Metro Vancouver (and population estimates) in the province of British Columbia, Canada (inset image courtesy of Metro Vancouver (2017))

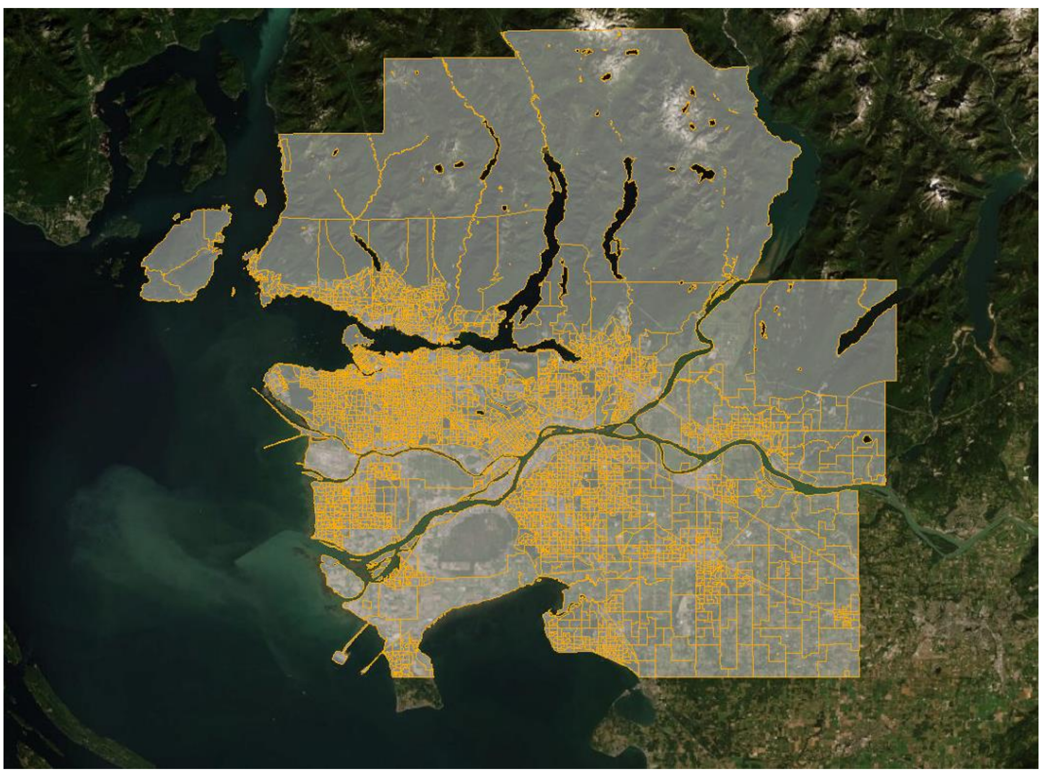


Figure 32: Dissemination Areas (orange boundary lines) in the Region of Metro Vancouver (white shaded area)

The province of British Columbia has experienced an average temperature increase of 1.4°C in the last century (higher than the global average of 0.85°C), and temperatures across the province are expected to continue to climb (BC Ministry of the Environment, 2016). The years 2015 and 2016 were two of the hottest years on record since 1900 due, at least in part, to climate change combined with El Nino conditions and increased warm nights due to increased cloud cover (Anslow, 2017). These changes in the climate are also causing changes in the distribution, frequency, and intensity of precipitation events over the region (Anslow, 2017). The region faces the combined threat of changes in peak flows and flooding from the Fraser River and the threat posed by increasing sea levels from the Pacific Ocean. Fortunately, the Region has recognized the threat of climate change and as such, has developed a Corporate Climate Action Plan (Metro Vancouver, 2010). Two of the most relevant Plan strategies to this work include “adapting existing infrastructure and operations” and “planning and building resilient new infrastructure and facilities” in the anticipation of climate change. Since then, the Region has also released a Strategic Framework focused on ensuring infrastructure, ecosystems, and communities are resilient to the impacts of climate change (Metro Vancouver, 2018). This framework explicitly identifies the need to develop methods and approaches for measuring resilience to climate change. Methodologies and tools such as the ones presented in this thesis, could help guide the Region in prioritizing spending and developing effective climate change adaptation policies in accordance with the strategies outlined in the Climate Action Plan and in support of the guiding principles of the Climate 2050 Strategic Framework. It could also be useful at the local scale for municipalities within the Region to help adapt to climate change impacts.

Therefore, the primary motivation for applying the disaster resilience quantification framework and methodology to the region of Metro Vancouver is two-fold:

i) To act as a proof-of-concept example for the work presented in this thesis; and
ii) To develop a tool that aligns with the Region’s climate initiatives and provides a foundation for effective disaster management in Metro Vancouver.

5.2 Setting the Resilience Landscape: Research Questions and Problem Definition

In addition to acting as a proof-of-concept, the purpose of applying this research to the Metro Vancouver region in British Columbia was to help answer climate change adaptation-related questions that the local communities would be interested in resolving, such as:

1. How are climate change influenced hydrometeorological hazards affecting Metro Vancouver?;
2. How can municipalities in Metro Vancouver better plan for, and adapt to, future climate change-influenced hydrometeorological hazards?; and
3. How resilient is Metro Vancouver to climate change influenced hazards?

In order to address these questions, the following research objectives were conceived for the Metro Vancouver-specific application:

1. Identify climate change influenced hydrometeorological hazards which effect communities in Metro Vancouver and incorporate climate change projections into hazard modelling and inundation mapping;
2. Identify and simulate local disaster resilience adaptation options; and
3. Propose how outputs from the DRST could be used to improve climate change mitigation and adaptation strategies at the local and regional levels.

The methodology from Figure 2 was implemented for the case study in order to simulate disaster resilience, discover answers to the research questions, and achieve application objectives:

1. Identify disaster resilience quantification system and metrics which are important at the Regional scale;
2. Collect spatial and temporal data related to physical, economic, engineering, health, and social disaster resilience domains;
3. Pre-process the data for use in the DRST using spatial and numerical tools;

4. Create a hydraulic model and simulate region-specific physical hazards including climate change influenced SLR of the Pacific Ocean and climate change influenced flooding on the Fraser River;
5. Identify potential local climate change adaptation strategies and use them to develop corresponding climate change adaptation options for the DRST;
6. Modify DRST inputs and/or structures to represent adaptation options, as necessary;
7. Simulate base case plus climate change and adaptation options using the DRST;
8. Post-process simulation results;
9. Compare adaptation option simulation results and identify times and areas of high and low resilience.

The remainder of this chapter considers the case study specific application of resilience quantification and the DRST at a Regional focal scale.

5.3 Implementation

The methodology behind resilience quantification was implemented in a primarily Python-based DRST. This tool is able to extract spatial and attribute data from ArcGIS and use it in combination with other numerical data as input into dynamic resilience calculations by integrating it with Vensim and GAMS software. The following chapter describes a specific application of the DRST and climate change influenced dynamic resilience assessment for the region of Metro Vancouver in British Columbia, Canada.

5.3.1 Implementation: Data Collection and Identifying Key Elements to Describe Systems

Before fully implementing the STDRM and resilience quantification scheme, it was necessary to establish what data were available to help describe the engineering, economic, health, and social domain system models. Since resilience is dynamic in both time and space, multiple data types were required to build the spatio-temporal model.

Spatial and numerical data were collected from various sources for use in the Metro Vancouver DRST (Appendix E). Most of the data used in developing the Metro Vancouver

DRST were publicly available, with the exception of detailed economics and engineering data which was provided by BC Assessment Corporation (BCA) and hydraulic modelling validation data which were provided by the Ministry of Forest Lands and Natural Resource Operations (MFLNRO).

Data for each resilience domain were collected in various formats including spatial and numerical, and at various resolutions including city-wide, Dissemination Area (DA), and feature-level (Figure 33). Therefore, significant effort was required to prepare data for input into the DRST. Some of the necessary pre-processing was completed using query statements and algorithms within a GIS environment; other data was modified manually. The data collection process was intensive and the preprocessing of data (particularly spatial data) required significant time investment. If data collection methods and formats were to remain consistent in future versions of the tool, the DRST would benefit from automation of these data preparation tasks. The preprocessed data files as used for input into the DRST are included as part of the dissertation electronic submission. More details are provided in Appendix F.

With a working knowledge of the available data and its limitations, the conceptual-level generic DRST originally presented in Figure 14 was customized for an application specific to quantifying disaster resilience in Metro Vancouver. A presentation of the system dynamics simulation Vensim temporal model is provided in Figure 34. The model looks a little sparse since many of the model relationships and dynamic feedbacks are spatial and occur in the GIS (ArcPy) component of the DRST, however the use of system dynamics simulation software, Vensim, provides an opportunity to expand the existing model and incorporate additional disaster resilience indictors, domains, and systems. The current version of the DRST system dynamic simulation model represents two key components of the overall disaster resilience quantification scheme: (i) emergency disaster funding; and (ii) disaster resilience calculation. Supporting model simulation equations are described in this section.

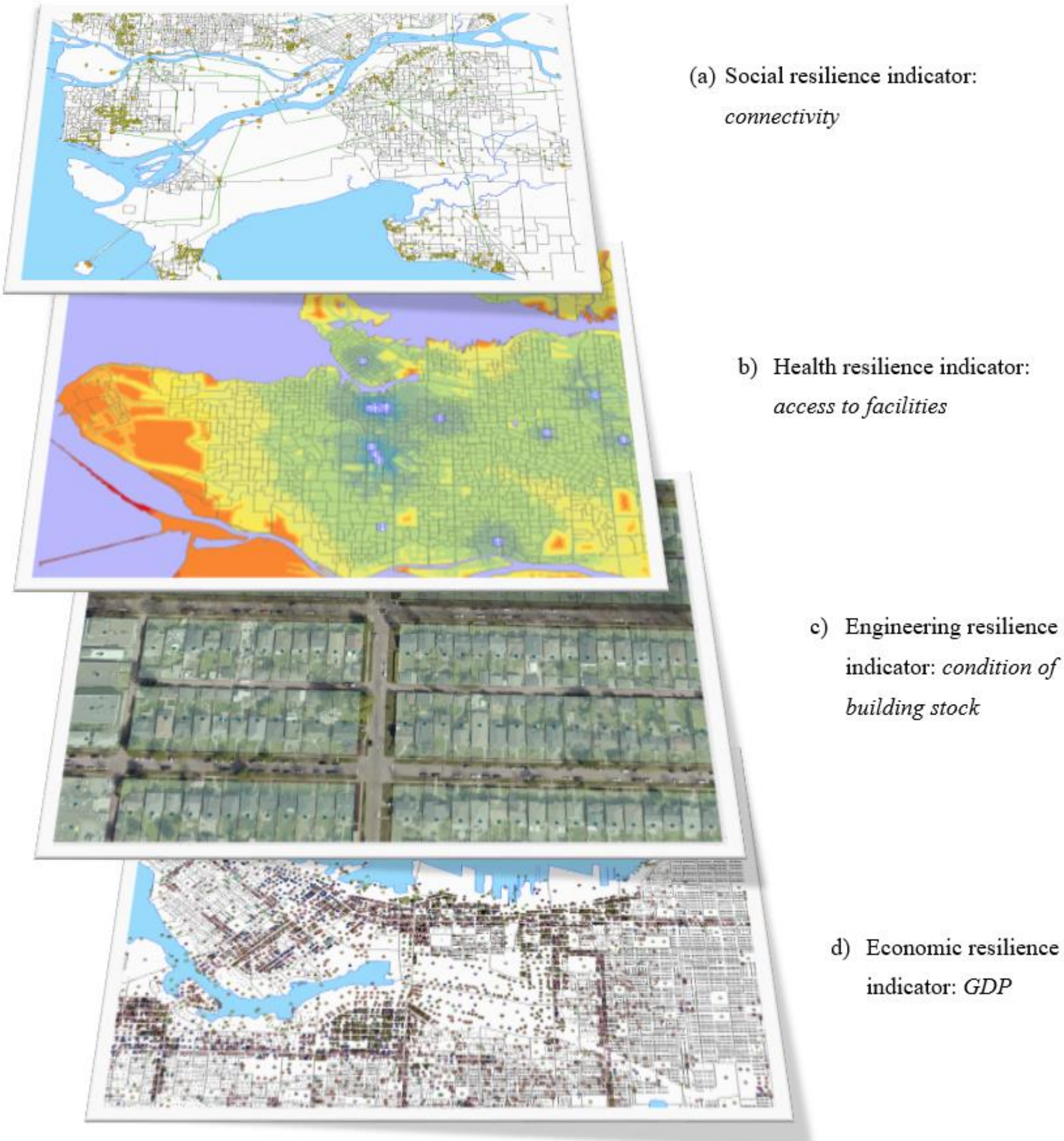


Figure 33: A selection of spatial inputs collected for use in disaster resilience quantification as part of the DRST

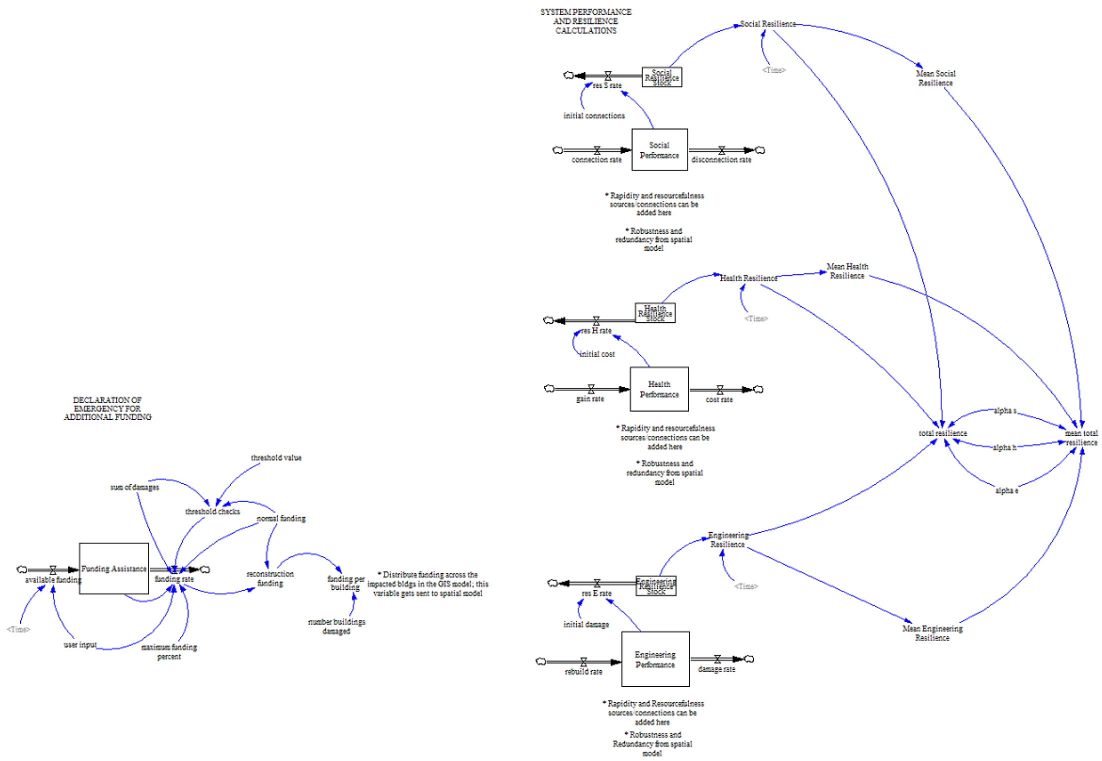


Figure 34: Dynamic disaster resilience quantification Vensim model

The following equations describe the emergency funding component of the model, which represents the amount of additional disaster assistance funding available during a disaster, above and beyond local resources (Figure 35).

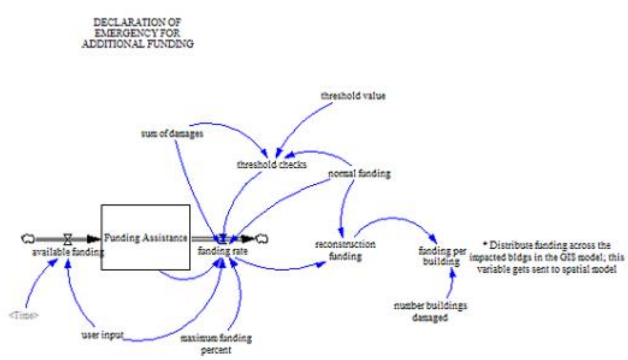


Figure 35: Emergency funding component of the DRST Vensim model

The *funding assistance* stock represents the total available funding above and beyond local available resources to assist in disaster recovery efforts:

$$Funding\ Assistance\ (\$) = available\ funding(\$/wk) - funding\ rate(\$/wk) \tag{5.1}$$

This stock is modified by the following rates:

$$available\ funding\left(\frac{\$}{wk}\right) = user\ input(\$) \tag{5.2}$$

And,

$$funding\ rate\left(\frac{\$}{wk}\right) = IF\ THEN\ ELSE\ (threshold\ checks = 1 :AND: Funding\ Assistance > 0, MIN(maximum\ funding\ percent * user\ input, sum\ of\ damages - normal\ funding, 0) \tag{5.3}$$

Further, the *user input* variable is specified as a constant value, but it is also a GAME variable; in other words, this variable can be modified during the course of the simulation. In this particular case, the *user input* variable can be modified by the user when the DRST Python program is run, the user is prompted to enter a value for this variable via the GUI. Modifying this variable can influence system behaviour by changing the amount of available funding for recovery efforts.

$$\text{user input } (\$) = GAME[2{,}000{,}000{,}000] \tag{5.4}$$

The *Available Funding* only becomes accessible once a threshold value is crossed. The threshold value is intended to represent the point at which the disaster has become unmanageable with only local resources. This threshold can be considered representative of a city's official declaration of an emergency, when national and even international funding may become available. The actual threshold used to determine the point an emergency declaration is difficult to determine and may vary with each municipality or even with each individual decision maker. The threshold value in this model can therefore be modified by the user to best represent local decision maker profiles. The *threshold value* is a threshold variable used to trigger access to the emergency funding assistance. This variable is initialized as a constant, but can be modified by the user at the start of the simulation via the DRST GUI:

$$threshold\ value = GAME[100{,}000{,}000] \tag{5.5}$$

The *sum of damages* variable represents the current states of damages in the engineering sector. It's initialized as zero and assumes the value of building damages at each subsequent time step.

$$sum\ of\ damages = GAME[0] \tag{5.6}$$

The *normal funding* variable is used to represent resources available at the local level, independent of additional (external) funding support. This variable is a constant in the model and unlike many of the other variables in this sector of the model, is not a gaming variable.

$$normal\ funding = 10{,}000{,}000 \tag{5.7}$$

The above variables are then used as part of a threshold check to determine whether an emergency has been declared which is subsequently used to release the emergency funds. The *threshold checks* variable uses a conditional check with two criteria to be satisfied to pass the check. One criterion is that the *sum of damages* in the engineering domain is greater than the *threshold value* (representative of a declaration of emergency) and the second criteria is that the *sum of damages* is greater than *normal funding* (actually exceeds the local resource capacity). This prevents an emergency declaration to be declared without necessity. If the checks are passed, a value of 1 (or TRUE) is sent to the *funding rate* variable to release the additional funding assistance. If the checks are not passed, a value of 0 (or FALSE) is passed to the *funding rate* variable.

$$\begin{gathered} threshold\ checks = IF\ THEN\ ELSE(sum\ of\ damages > threshold\ value \\ :AND: sum\ of\ damages > normal\ funding, 1, 0) \end{gathered} \tag{5.8}$$

The *reconstruction funding* variable is representative of the amount of resources that is sent to recovery efforts in the disaster resilience quantification sector of the Vensim model. When emergency funds are released, they are added to the pool of regular funding:

$$reconstruction\ funding = funding\ rate + normal\ funding \tag{5.9}$$

The *reconstruction funding* is then distributed across the engineering and economic sectors through the variable *funding per building*. This variable uses a conditional check to distribute resources (equally) amongst the damaged buildings:

$$\begin{aligned} funding\ per\ building = IF\ THEN\ ELSE(&number\ of\ buildings \\ &= 0, 0, reconstruction\ funding \\ &/number\ buildings\ damaged) \end{aligned} \tag{5.10}$$

where,

$$number\ buildings\ damaged = GAME[0] \tag{5.11}$$

The *number buildings damaged* is a GAME variable that is initialized to zero, but is modified during the DRST simulation as this variable is retrieved from the DRST spatial model. Subsequently, the *funding per building* variable then gets sent back to the GIS spatial model at the end of the simulation time step.

Figure 36 illustrates the equations that describe the integrated disaster resilience calculations component of the model.

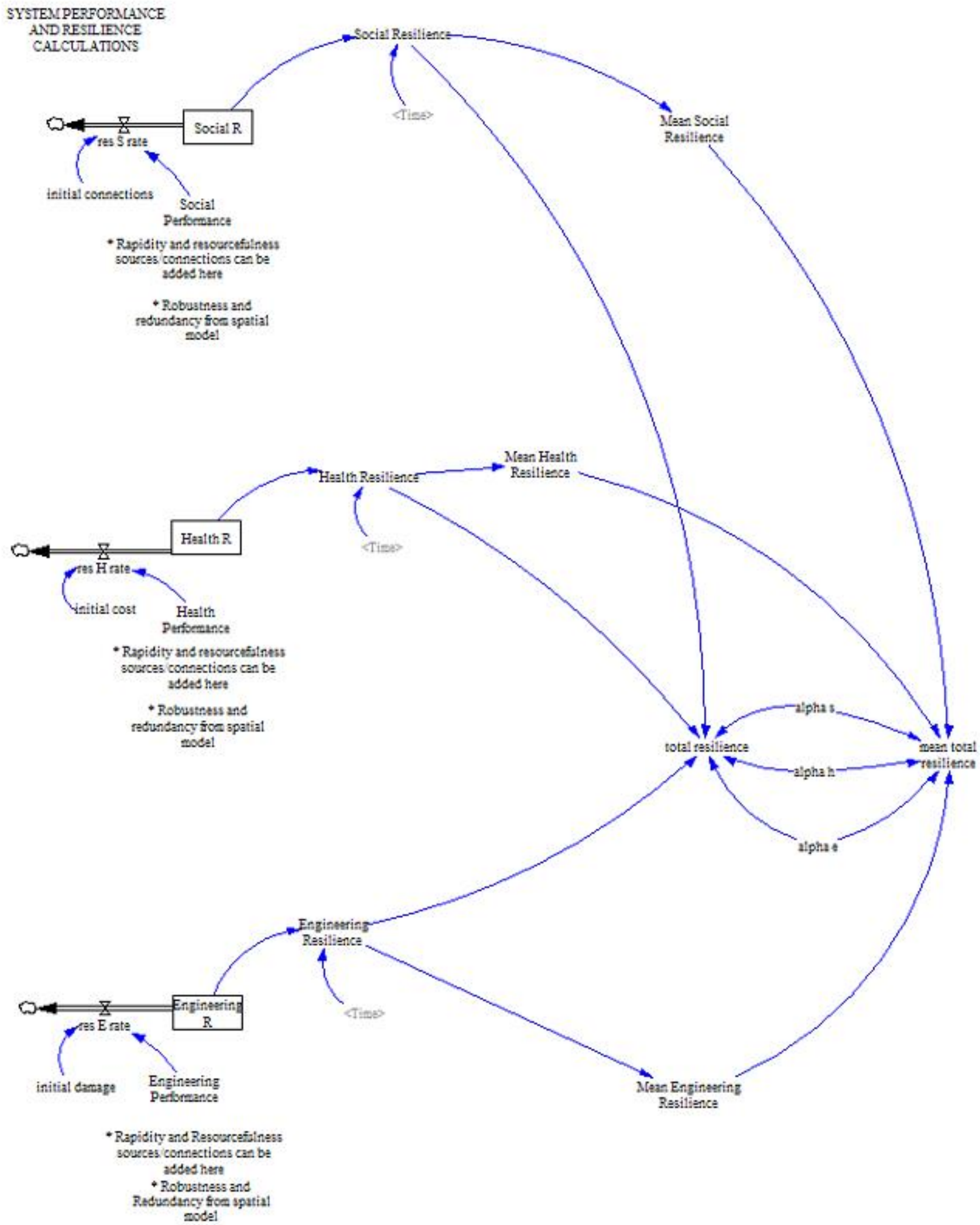


Figure 36: Disaster resilience calculation component of the DRST Vensim model

Resilience calculations for three of the four resilience domains are modelled in Vensim. The primary relationships between model variables and model feedbacks are spatial and are therefore represented in the ArcPy / GIS component of the DRST. The Vensim modelling of resilience domains is used primarily to facilitate the resilience calculations. Each of the domains (social, health, and engineering) has the same model structure, and similar calculation for resilience quantification:

$$Social\ R[DAUID] = -resSrate[DAUID] \tag{5.12}$$

$$Health\ R[DAUID] = -resHrate[DAUID] \tag{5.13}$$

$$Engineering\ R[DAUID] = -resErate[DAUID] \tag{5.14}$$

The $[DAUID]$ field stands for “Dissemination Area Unique ID”; it demarcates a subscript in the model. The subscript allows the model to create as many structures as there are subscript elements. This allows model variables to assume various values without having to make multiple copies of the model structure. It simplifies the visual representation of the system whilst also avoiding replication. In this particular application for Metro Vancouver, the $[DAUID]$ subscript is an array of over 3000 elements which represent unique identifiers of each dissemination area in the model. This allows resilience calculation for each domain to be performed at the DA level, across all the DAs in Metro Vancouver. Although it may appear strange that there is no inflow into the stock, it is the result of an implementation detail. Since the flow depends on variables sent from GIS, to ease implementation just a single flow is represented, however the variable sent can assume either a positive (+) or negative (-) value. The positive values deplete the resilience stock and the negative values actually fill the stock since the expression of outflow is a negative rate, creating a double negative which produces a positive flow. The equations for the performance metric variables are as follows:

$$Social\ Performance[DAUID] = GAME[0] \tag{5.15}$$

$$Health\ Performance[DAUID] = GAME[0] \tag{5.16}$$

$$Engineering\ Performance[DAUID] = GAME[0] \tag{5.17}$$

The performance variables are all initialized as zero, however this value is not important to the calculation because these variables are designated as gaming variables which means the value of the performance metric is retrieved from GIS at each time step. These variables are also subscripted with $[DAUID]$ which means the variable is calculated (retrieved) for each dissemination area. The initialization of the Performance metric to a value of zero in equation (5.17) is not significant to the simulation since there is a game variable in the model which initializes each of the Performance metric using GIS data. Similarly, the initialization variables are also GAME variables with initial values of zero:

$$Initial\ connections\ [DAUID] = GAME[0] \tag{5.18}$$

$$Initial\ damage\ [DAUID] = GAME[0] \tag{5.19}$$

$$Initial\ cost\ [DAUID] = GAME[0] \tag{5.20}$$

These initialization variables are set at the beginning of the simulation using performance metric data drawn from GIS. These values are held for the remainder of the simulation to normalize the performance metrics for the resilience calculation. A conditional statement was used to define domain resilience, primarily for computational reasons in the system dynamics simulation model:

$$Social\ Resilience = IF\ THEN\ ELSE\ (Time = 0, SocialR[DAUID], SocialR[DAUID]/Time) \tag{5.21}$$

$$Health\ Resilience = IF\ THEN\ ELSE\ (Time = 0, HealthR[DAUID], HealthR[DAUID]/Time) \tag{5.22}$$

$$Engineering\ Resilience = IF\ THEN\ ELSE\ (Time = 0, EngineeringR[DAUID], EngineeringR[DAUID]/Time) \tag{5.23}$$

This condition prevents an indeterminate error from being thrown at $time = 0$. These resilience values are then spatially aggregated across DAs to reflect a city-wide resilience metric over time:

$$Mean\ Social\ Resilience = SUM(Social\ Resilience[DAUID!])/ELMCOUNT(DAUID) \tag{5.24}$$

$$Mean\ Health\ Resilience = SUM(Health\ Resilience[DAUID!])/ELMCOUNT(DAUID) \tag{5.25}$$

$$Mean\ Engineering\ Resilience = SUM(Engineering\ Resilience[DAUID!])/ELMCOUNT(DAUID) \tag{5.26}$$

These average values are then combined in the $Total\ Resilience[DAUID]$ variable using weights, α as follows:

$$Total\ Resilience[DAUID] = alphaS * mean\ social\ resilience[DAUID] + alphaE * mean\ engineering\ resilinece[DAUID] + alphaH * mean\ health\ resilience[DAUID] \tag{5.27}$$

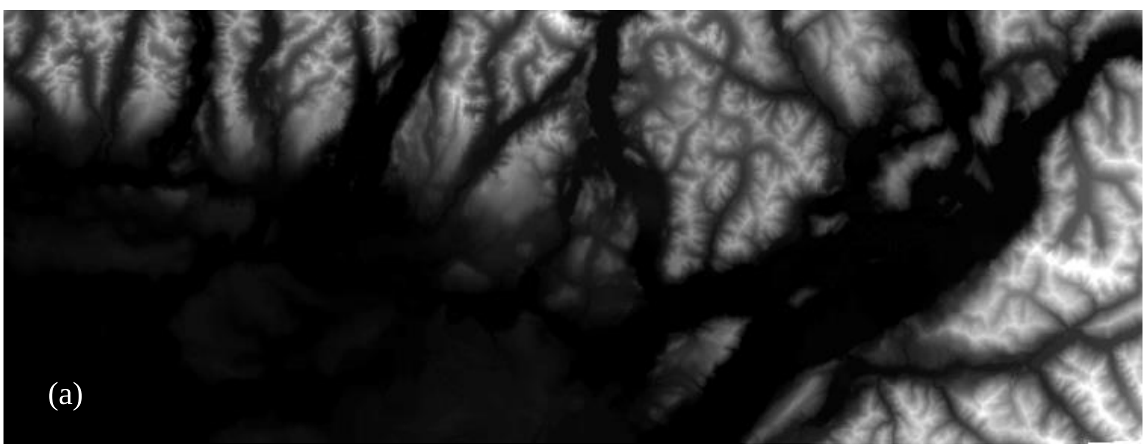
The alpha, α, weights [0,1] are intended to capture decision maker priorities. This provides an opportunity for decision makers to directly influence the resilience calculation. Weights for this particular application were not established with stakeholders and were therefore set to a value of 1 in the model, however determining appropriate weights could be an area of future work. The system dynamics model was then run considering continuous flood hazard simulations to test the impact that various adaptation options have on resilience.

5.3.2 Implementation: Climate Change Influenced Hazard Definition

As a coastal and mountainous province, British Columbia (BC) has unique climate and topography and is no stranger to riverine and coastal flooding. As such, a history of hydraulic modelling and floodplain mapping has developed in BC. There is an extensive levee network along the Fraser River and its tributaries which contributes to the hydraulic characteristics of the basin. The remainder of this sub-section will describe the modelling and simulation procedure used to generate a set of dynamic inundation maps for the Fraser River under climate change. This sub-section concludes with the results for generating inundation maps considering climate change. These maps are used for hazard characterization and serves as one of the primary inputs into the DRST.

5.3.2.1 British Columbia climate and topography

BC has high spatial climate variability due to its unique topography and proximity to both coastal and inland waters. BC is also characterized by wide variations in land elevation including the highly mountainous Rockies region inland and very low coastal delta regions near the ocean (Figure 37). The topography of the landscape is shaped, in part, by hydrological processes. In turn, the topography is fundamental to defining regional flow characteristics. This concept is fundamental to understanding hydrologic and hydraulic dynamics within a catchment.



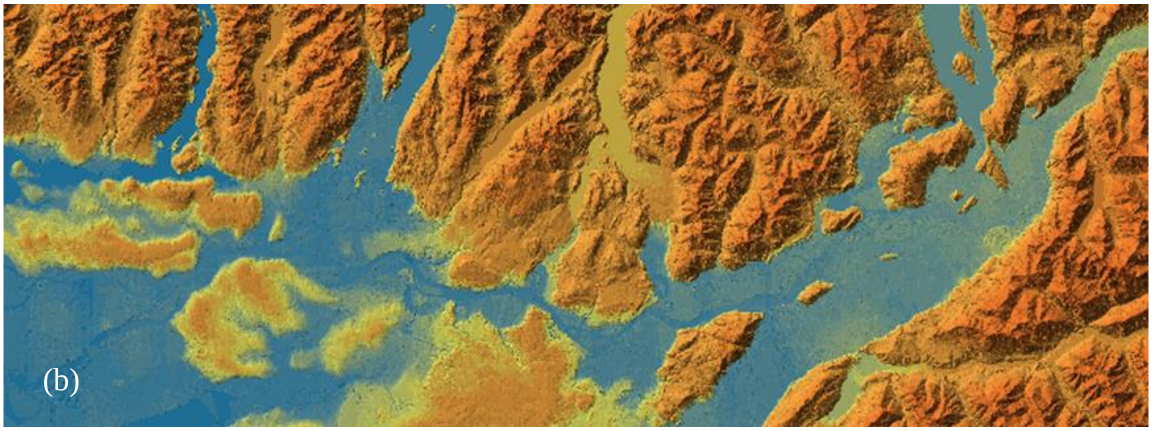


Figure 37: Metro Vancouver, the Fraser River, and its tributaries as: (a) a DEM of low elevations (black shade) and high elevations (white shade); and (b) a TIN of low elevations (blue colour) and high elevations (red colour)

The Fraser River flows from the headwaters in the Rocky Mountains into the Straight of Georgia just south of the city of Vancouver. The area along the river experiences high levels of development and human activity. In order to protect densely populated urban communities and infrastructure from effects of flooding and erosion, Metro Vancouver's waterways are characterized by an extensive network of dikes, concentrated mostly along the Fraser River and the Pacific coast. The construction of the dike network was initiated after extensive overland flooding during the flood-of-record in 1894. Many of these initial dikes fell into disrepair and in 1948 another high flow event caused dike failures along the river which again caused significant flooding. Since then, the dike network has been updated and over 300 km of river and sea dikes now protect river-side communities. However, a qualitative dike elevation assessment suggests that most of the network doesn't meet the design water levels plus 0.6 m freeboard requirements, and that some of the current dike crests even fall below current design water levels (MFLNRO, 2014). In the past decade, many communities in Metro Vancouver have experienced high population growth and infrastructure development which means there would likely be significant consequences that large-scale flooding may have on these communities.

The scope of this research includes assessing and examining the impacts of climate change on precipitation and runoff events for BC's Fraser River and coast along the Pacific Ocean.

The purpose in performing this analysis is to generate climate change influenced inundation maps which form the basis for resilience assessment using the DRST.

5.3.2.2 Brief history of hydraulic modelling and floodplain mapping in British Columbia

Inundation maps are primarily used to identify areas susceptible to flooding; typically near water-bodies such as oceans, rivers, lakes and marshes. The identification of these areas is especially important for infrastructure design, maintenance and protection. In addition, inundation maps are frequently used to form the technical basis for land use planning, community development bylaws, emergency planning, and flood hazard management (Kerr Wood Leidal Associates Ltd., 2011). These maps are the basis for DRST hazard assessment. They incorporate the effects of climate change in the basin and are the direct input into the DRST.

A floodplain mapping agreement officially known as, “An Agreement Respecting Floodplain Mapping in the Province of British Columbia” was signed in 1987 and amended in 1994 between Canada and the province of British Columbia which addressed, among other items:

- Restricted development by both governments in flood vulnerable areas;
- Required flood protection measures be incorporated into new development areas in floodplains;
- Recognized the need for updated flood mapping programs and integrated water resources management.

In 2004, the Province of BC transferred the all aspects of floodplain mapping and related decision-making responsibilities to local governments (Kerr Wood Leidal Associates Ltd., 2011). The province no longer financially supported the development or maintenance of floodplain maps.

In 2011, Kerr Wood Leidal released a report for the MFLNRO on Coastal Floodplain Mapping Guidelines and Specifications which provides suggestions for design flood construction levels (FCLs), introduces new standards for provincial topographic mapping, and encourages local governments to develop coastal floodplain maps based on best practices (Kerr Wood Leidal Associates Ltd., 2011). In partial fulfillment of the recommendations, the Fraser Basin Council (FBC) updated the design flood profile for the Fraser River and in 2005 Northwest Hydraulic Consultants (NHC) was retained to develop a 1-D MIKE 11 hydraulic model for the Fraser River from Sumas Mountains to Georgia Strait (NHC, 2008). This model was then taken over by the BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) and updated in 2014 using new data from 2007, 2011, and 2012 for re-calibration. The most recent publicly available report (June 2014 at the time of this thesis) contained output from hydraulic analyses in the form of water levels at various locations along the river under two climate scenarios. There is extensive hydraulic analysis and discussion in the 2014 report. However, the model was run under an assumption which makes it inappropriate for the DRST, specifically:

"At the locations where "levees" are specified in the model x-sections, the model assumes glass walls in case the water level goes higher than the levee top (or dike crest) and does not allow any spillage. In the case a dike is breached or overtopped, the actual water levels would be different from the model water levels."

Flood Safety Section, Ministry of Forests, Lands, and Natural Resource Operations 2014, pg. 23

This assumption restricts the model and prevents simulation of any over bank flooding. Not only is this assumption rather optimistic and improbable, it could also be construed as misleading by indirectly suggesting that communities along the Fraser River do not need to anticipate or prepare for flood events. Thus, the results from this report could not be used and therefore it was necessary to devise a means to generate inundation maps considering both riverine flooding and SLR under climate change to be used as input into the DRST. As such, the hydraulic model had to satisfy the following criteria:

- Simplified model development;
- Rapid simulation;

- Use of widely accepted methods in the hydrologic and engineering communities;
- Be calibrated to observed historical events;
- Be able to incorporate climate change;
- To the best of its ability, be able to simulate realistic water surface profiles;
- Allow easy incorporation of new floodplain data, should it become available in the future.

Based on the criteria above, hydraulic modelling was performed using the US Army Corps of Engineers HEC-RAS hydraulic modelling software combined with the HEC-GeoRAS extension. HEC-RAS was used for hydraulic modelling calculations and HEC-GeoRAS is an extension compatible with ArcMap software, used to prepare geospatial inputs and process geospatial outputs of the HEC-RAS simulation. This follows the same generic procedure as outlined in the description of the physical hazard model domain.

5.3.2.3 Climate change scenarios

Climate change scenarios were required to obtain spatial and temporal estimates for future regional climate variables, including precipitation. The climate change scenarios used in developing inundation maps in this study were provided by Pacific Climate Impacts Consortium (PCIC) in 2014; the bias-corrected models and streamflow projection datasets have since been made publicly available online through PCIC's website. PCIC used a set of scenarios to generate estimates of precipitation which were subsequently used in hydrologic modelling to generate estimates of future streamflow. PCIC employed the use of three climate change emissions scenarios (A1B, A2, and B1) and eight GCMs initially proposed in the IPCC's AR4. GCM outputs were then downscaled using the Bias Corrected Spatial Disaggregation (BCSD) method (Werner, 2011). Additional information on the basis of climate change scenarios selection can be found in (Shrestha et al., 2012). These climate change scenarios were used to generate climate change influenced inundation mapping for Metro Vancouver.

5.3.2.4 Climate change influenced hazard modelling: Hydrology

Shrestha et al. (2012) discovered that, generally, peak streamflows in the Fraser River basin are likely to decrease in the future. However, an increase in overall streamflow volumes is likely to be observed. As input into the DRST, peak streamflows are of primary interest in order to simulate large-scale, widespread flood events, and are therefore used to describe the hydrological events of interest. Hydrologic modelling was then implemented to obtain streamflows for the Fraser River and its tributaries under the conditions of various climate scenarios.

The spatially distributed hydrologic modelling and simulation for the region was conducted by Pacific Climate Impacts Consortium (PCIC) at the University of Victoria using the Variable Infiltration Capacity (VIC) hydrologic model (Shrestha et al., 2012). Using observed regional historical precipitation data, GCMs, and IPCC's SRES A1B, A2, and B1 emissions scenarios, PCIC generated streamflows using the VIC hydrologic model. The hydrologic simulation was conducted and streamflows generated for four locations corresponding to the following Water Survey of Canada gauge locations (Figure 38):

1. Fraser River at Mission (08MH024) – FRSMI
2. Fraser River at Hope (08MF005) – FRSHP
3. Chilliwack River at Vedder Crossing (08MH001) – CHILL
4. Harrison River near Harrison Hot Springs (08MG013) – HARRI

PCIC generated streamflows for 24 scenarios: 1 base case and 23 simulations based on climate projections (Table 4); the GCMs (based on the World Climate Research Program's Coupled Model Inter-Comparison Phase 3 Project) and SRES emissions scenarios A1B, A2, and B1 from IPCC AR4. PCIC provided the streamflow data at both daily and monthly time scales, with flows for multiple GCMs under all three emissions scenarios, for each of the four WSC gauge sites (Figure 38). The projected streamflows are from 2050 – 2098 (48 years) and the base run covers 1950 – 2006 (56 years). As input into hydraulic modelling for Metro Vancouver, a subset of the projected streamflows (CGCM3-AlB and CGCM3-B2) plus the base case were selected.

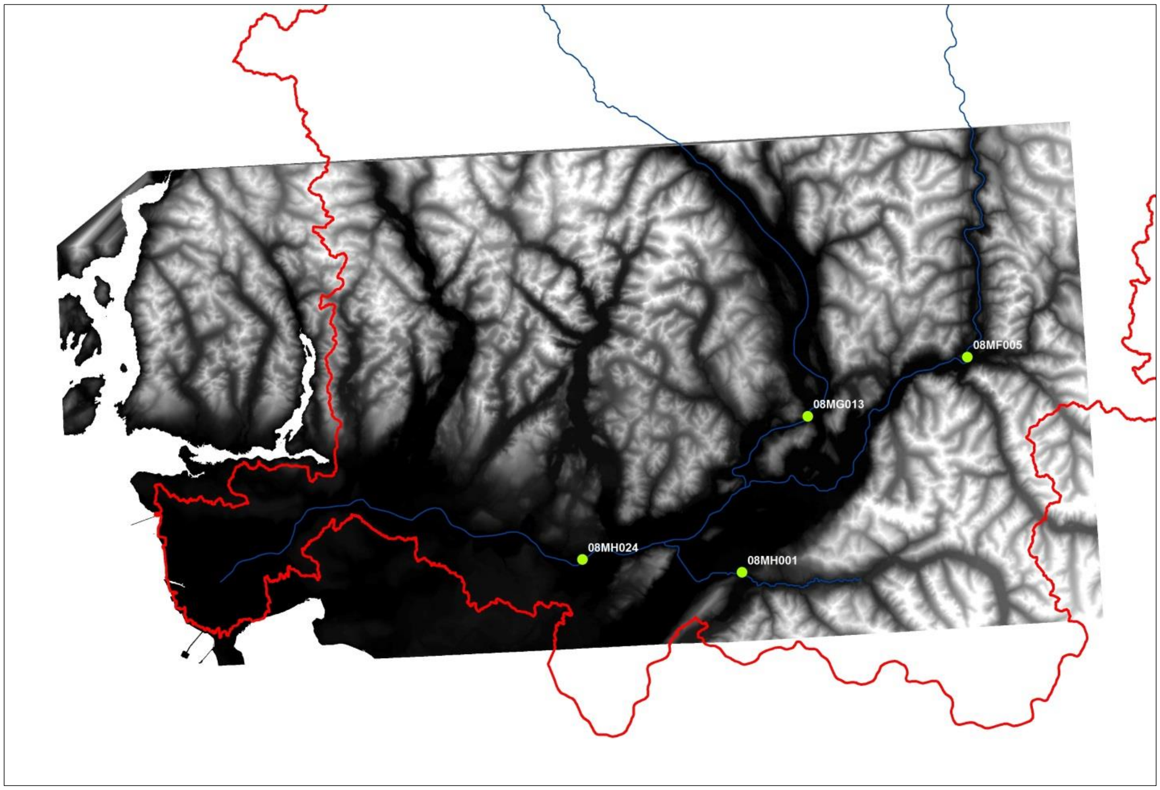


Figure 38: The four Water Survey of Canada gauge sites (08MH024; 08MF005; 08MH001; 08MG013) in British Columbia along the Fraser River and its tributaries (provided by Markus Shnorbus, PCIC 2014)

Table 4: Streamflow projection availability through PCIC Portal for selected GCM and emissions scenarios

	Scenario		
GCM	A1B	A2	B1
HadCM	Y	Y	Y
GFDL2.1	Y	Y	Y

CSIRO35	Y	Y	Y
CCSM3	Y	Y	Y
HadGEM1	Y	Y	N
MIROC3.2	Y	Y	Y
CGCM3	Y	Y	Y
ECHAM5	Y	Y	Y
Historical	-	-	-

Annual streamflow maxima were fit to various continuous probability distribution functions using an R statistical modelling package to determine which distribution provided the best fit. Based on shape, scale, and location parameter estimations using L moment of methods, it was determined that most of the streamflow extremes were best described using a 3-parameter Weibull distribution:

$$f(x;k,\lambda,\theta) = \frac{k}{\lambda}\left(\frac{x-\theta}{\lambda}\right)^{k-1} e^{-\left(\frac{x-\theta}{\lambda}\right)^{k}} \tag{5.28}$$

where, k is the shape parameter, λ is the scale parameter, and θ is the location parameter.

Significant differences can be observed in the annual peak maximums between the baseline and climate change scenarios for each of the 100-, 200-, and 500-year peak streamflows (Table 5). However, only minor differences are observed between each of the two selected climate change scenarios (A1B and B1). Lowest flows were observed in the baseline scenario and the highest flows were observed in the simulated A1B emissions scenario. The 500-year baseline, B1, and A1B streamflow scenarios were selected to generate water surface profiles for the subsequent hydraulic analysis to capture extreme flooding conditions.

Table 5: Statistical 100-, 200-, and 500-year streamflow values for three climate scenarios and four stream gauge locations along the Fraser River and its tributaries

Climate Scenario			Branch/Tributary: Chilliwack at Vedder (08MH001)	Fraser at Hope (08MF005)	Harrison River (08MG013)	Fraser at Mission (08MH024)
Baseline	Parameters	Location	247	7850	1335	9346
		Scale	78	1488	203	1699
		Shape	0.16	-0.41	-0.18	-0.38
	Streamflows (m^3/s)	100-yr	779	10934	1973	13028
		200-yr	900	11071	2031	13207
		500-yr	**1081**	**11202**	**2098**	**13382**
Climate Scenario A1B	Parameters	Location	354	8063	1358	9512
		Scale	179	1651	260	1912
		Shape	0.2	-0.13	-0.12	-0.15
	Streamflows (m^3/s)	100-yr	1692	13768	2281	15859
		200-yr	2022	14369	2382	16490
		500-yr	**2533**	**15083**	**2503**	**17228**
Climate Scenario B1	Parameters	Location	322	7901	1289	9334
		Scale	115	1447	199	1616
		Shape	0.24	-0.15	-0.09	-0.16
	Streamflows	100-yr	1300	12719	2041	14544

	(m^3/s)	200-yr	1568	13200	2131	15041
		500-yr	**1999**	**13764**	**2240**	**15615**

Inflow hydrographs were generated for the 500-year streamflow on the Fraser River at Hope (WSC gauge 08MF005) and the two tributaries Chilliwack at Vedder (gauge 08MH001) and Harrison River (gauge 08MG013). This is equivalent to simulating the 1 in 500-year events for each tributary, which does not necessarily produce a 500-year event at downstream gauges, but it does provide a “worst case scenario” to simulate the situation in which all reaches simultaneously experience a 1 in 500-year event.

The files used in the current analysis were provided directly by PCIC, however since January 2014 and September 2014, PCIC have made streamflows and gridded hydrologic model outputs and statistically downscaled climate scenarios projections publicly available through their data portal page (Pacific Climate Impact Consortium, 2014).

5.3.2.5 Climate change influenced hazard modelling: Hydraulics

Hydraulic modelling was then completed to generate water surface profile (i.e. water levels) and inundation maps for the Fraser River under various climate change scenarios. The water surface elevations were converted into inundation maps using spatial analyst tools in ArcGIS.

HEC-RAS software was used for hydraulic analysis. This software was developed and used by the United States by the US Army Corps of Engineers for hydraulic analysis. The MFLNRO uses the proprietary 1-D modelling software called MIKE11 (DHI) for their hydraulic analyses and flood forecasting model. The following procedure is somewhat unique to the preparation, modelling, and simulation using HEC-RAS software, but the procedure shared many similarities to the way MIKE11 data, modelling, and simulation would be prepared and performed. The procedure would be similar to derive the input for the MIKE11 model as described in NHC (2008). An overview of the processes is provided in the following section.

Multiple DEMs covering the Metro Vancouver and Fraser River reaches were obtained in 2014 from the government of Canada's federal online open data portal (Government of Canada, n.d.). The digital elevation data is approximately 25m x 25m resolution and its horizontal reference datum is North American Datum of 1983 (NAD83). The ground elevations provide estimated values of elevation points measured relative to mean sea level (MSL) and are expressed as integers. Manning's roughness values (*n*) used in the current analysis is based off the Manning coefficients provided in the 2014 Updated Fraser River Flood report (Table 6). Where more than one Manning coefficient was provided for a particular reach, an average value was used. The water flow paths, stream centerline, channel banks, and cross-section locations were digitized in ArcGIS using the HEC-GeoRAS extension (Figure 39). These data were digitized visually, based on a georeferenced channel network diagram used by MFLNRO to develop their MIKE11 hydraulic model. The program then extracts data from the DEM surface to generate model cross sections. However, because LiDAR is a remote sensing technique that uses a pulsed light source for measurements, it is not able to penetrate the water surface and instead reflects off the water surface. Therefore, the elevation data (and terrain file) only consist of top of water elevations and do not include bathymetry. Since bathymetry is required to appropriately model river hydraulics, assumptions were made by the author to estimate the depth of the river bed for purposes of hydraulic modelling (Figure 40). Additional hydraulic modelling assumptions can be found in Appendix G.

Table 6: Manning roughness coefficients for Fraser River and its tributaries

Main River/Tributary Name	Manning Roughness Coefficient in Channel (Absolute Value) *Dimensionless*	Manning Roughness Coefficient Over Banks (Relative to Channel) *Dimensionless*
Fraser River	0.031	1.13
Harrison River	0.033	1.5

Vedder River	0.032	1.5

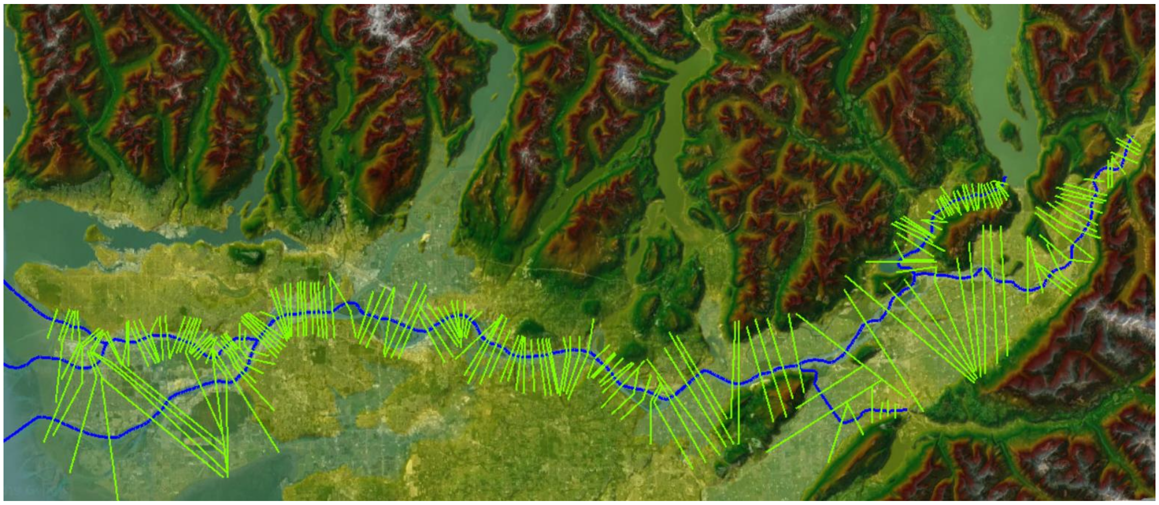


Figure 39: HEC-RAS model geometry (river centerline and cross sections)

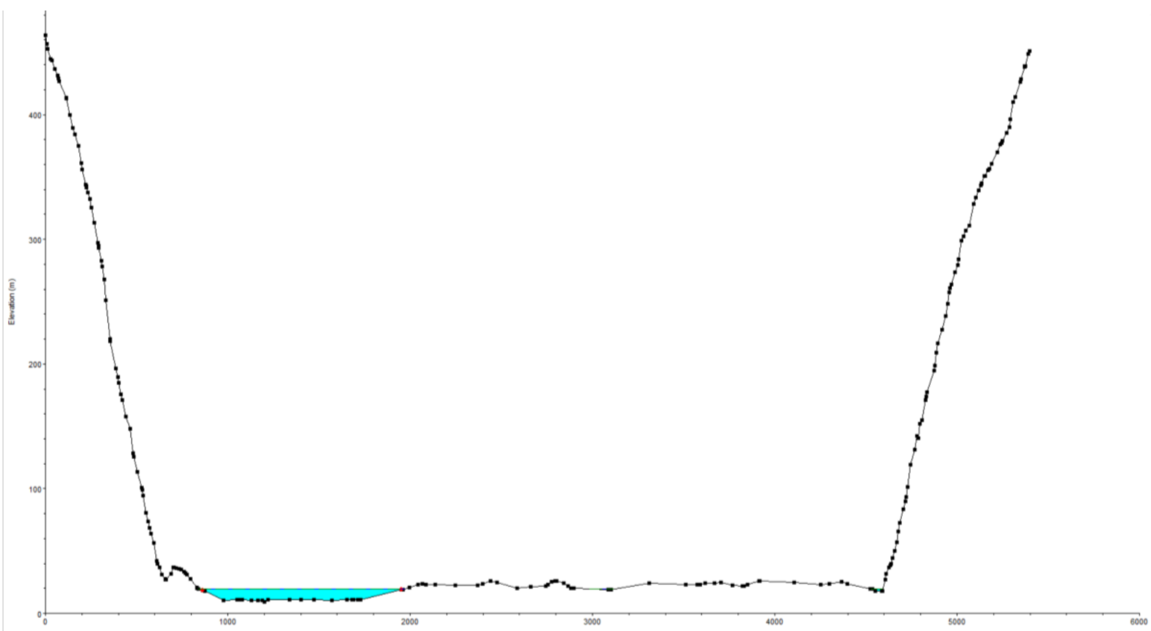


Figure 40: Example of one of the cross sections from the HEC-RAS model

5.3.2.6 Climate change influenced hazard modeling as model boundary conditions

In order to assess the impacts of climate change on coastal cities more completely, projections of sea level rise (SLR) were required. The DRST uses these SLR projections to determine effects on coastal and riverine water levels and possible long-term climate change impacts to coastal regions. The IPCC AR4 and AR5 identify SLR as a significant hazard to coastal cities. AR5 introduced four new emissions scenarios called Representative Concentration Pathways (RCPs). These RCPs are all based on different degrees of radiative forcing, under scenario-specific assumptions, and were developed by different organizations. Therefore, there is no direct correlation between them. They are used to capture the effects of changes in GHG concentrations on climate variables; they are the climate change component of SLR analysis.

The SLR modelling and projections were completed by Agam (2014). The projections of sea level rise and global mean temperature presented in AR5 are not temporally or spatially uniform and therefore a regional-scale model was developed by Agam (2014). The global SLR projections were then analyzed in the context of two significant regional hydrodynamic considerations for the Metro Vancouver Area: ocean tides and vertical land movements. Sea level rise projections for the region of Metro Vancouver, including influences of the local tides near the Fraser River, are in Agam (2014).

These SLR projections - in addition to the aforementioned climate change influenced hydrologic model outputs - were then used in hydraulic modelling and simulation. The mean water surface elevations serve as boundary conditions in the hydraulic model at the four outlets of the Fraser River into the Pacific Ocean. In an effort to minimize the amount of data, simulation and post-processing required, only two of the RCP scenarios (RCP2.6 and RCP8.5) were selected in the process of generating inundation maps. RCP2.6 and RCP8.5 provide the lower and upper boundaries, respectively, of the RCP scenarios. This reduces the uncertainty associated with selecting a single climate model or RCP scenario and was able to capture a broad range of possible climate change impacts. Therefore, three hydraulic model boundary conditions were considered in this study: RCP2.6 (2100); RCP8.5 (2100) and base case (no SLR).

5.3.2.7 Hydraulic Modelling Results

There is no basis for assuming that trends in historic data will continue into the future. Therefore, the modified streamflow datasets were used in hydraulic modelling. The use of continuous hydraulic simulation was applied to investigate the inundation extent and depths of sea level rise and climate change influenced riverine flooding. The methodology applied in continuous hydraulic simulation was ultimately the application of a novel dataset in conjunction with traditional modelling techniques. Continuous simulation provided an improved understanding of the riverine response to sea level rise, which may ultimately inform the future evaluation of coastal and interior climate change adaptation decisions. The inundation maps generated for other scenarios are included in Appendix F.

Additional work is recommended to establish a definitive linkage between observed trends and climate change for the Fraser River Basin. The approach adopted in this application is subject to unquantifiable uncertainty but recognizes the non-stationarity of historic peak flows for the purposes of hydraulic modelling and simulation and ultimately, for hazard definition as part of demonstrating the disaster resilience quantification framework for use in the DRST.

5.3.3 Implementation: Generating Adaptation Options

A simulation scenario represents specific courses of action that modifies system input. These scenarios are designed to test system response to a set of input conditions (Simonovic S. P., 2009) and may be used to represent a policy. The purpose of simulating various adaptation scenarios is to observe changes in resilience as model output; this way the resilience may be used as the decision making criteria in selecting adaptation scenarios which offer the highest increase in system resilience. The same model can be tested under various simulation scenarios to compare behavior under different sets of input conditions. Real policy systems are highly nonlinear in behaviour and often conflict or reinforce each other. Therefore, in some cases, the impact of policy decisions in a combination of particular resilience components may be of more interest than the sum of their impacts. The manner in which a municipality formulates policy decisions is not explicitly represented in the DRST but is incorporated as a set of adaptation scenarios. For example, the decision to increase number of emergency responders and safety personnel, or to coordinate allocation of resources for before, during, and after a disaster event. To examine the potential effectiveness of these types of options, three hypothetical adaptation scenarios were simulated using the DRST. The process for developing and implementing adaptation scenarios is discussed further in this section.

The three adaptation scenario options being tested with the DRST represent potential non-structural measures in the categories of: mobile health services, managed retreat, and funding.

1. The first adaptation option is non-structural; to provide access to additional emergency health services during a disaster via a mobile hospital. For many individuals, access to a hospital during a disaster event can become quite challenging and so this option simulates a mobile station that becomes active part-way through the simulation (at time step 6).

2. The second adaptation option is non-structural; managed retreat from the Pitt Meadows community in Burnaby, BC. This option assumes that the properties in the Pitt Meadows community are purchased by the government and the population is relocated elsewhere, outside of the floodplain. The land therefore no longer supports commercial or residential activities.

3. The third adaptation option is non-structural; access to additional sources of funding. This option uses a threshold value which is intended to represent the time at which an emergency declaration is made. Declaring an emergency provides access to additional funding sources which may include federal or international aid. This option specifies aid in terms of dollars, however those dollars could actually reflect various types of resource supplies. The money could be used to purchase mobile health units, mobile cellular towers, or used to hire additional contractors to help rebuild damaged homes. The additional funding is only accessed once the threshold is crossed, otherwise systems function under “normal” conditions rather than “emergency” conditions.

Systems do not have access to any additional funding until emergency conditions are satisfied.

This list of scenarios is not exhaustive, and there are an unlimited number of potential adaptation options that could be tested using the DRST; these three just provide an illustrative selection of possible non-structural options. These three options were identified as a few of the more robust, plausible, and possible options likely to be considered in the socio-political context of Metro Vancouver and were selected in consultation with local stakeholders. These options could be expanded to include potential structural adaptation options.

Various combinations of hydraulic modelling scenarios, SLR scenarios, and adaptation options were tested using the DRST (Table 7). Together, these combinations represent a very small selection of alternatives that could be tested using the DRST. Any combination of riverine climate scenario, sea level rise scenario, and hydraulic event could be simulated in the DRST. However, a subset of these scenario combinations was selected for illustrative purposes. Two SRES-based hydraulic climate scenarios plus baseline were modeled to represent a lower and upper range of potential riverine impacts. Since the A1B scenario generates more significant flooding extent and depths than the baseline scenario, it would likely result in greater impacts and was therefore carried forward to be modeled in combination with the various adaptation options. Only the 500-Year riverine flooding event was simulated since the Fraser River diking network is designed to provide levels of protection above the (current) 200-Year event. Even modeling a 200-Year climate change influenced riverine flooding event does not yield significant flooding in Metro Vancouver and it was therefore deemed an inadequate proof-of-concept example. The 500-Year climate change influenced riverine flood event results in fairly significant flood extent and depths across Metro Vancouver and thus, the 500-Year event was carried forward and used in all of the proof-of-concept simulation scenarios. The lower bound sea level rise scenario (RCP 2.6) was selected for most of the simulation scenarios because RCP 8.5 provided significant downstream flooding at the beginning of the simulation. Since SLR occurs slowly over many years (as compared to a daily or weekly duration riverine flooding event), the flooding generated under RCP 8.5 was too significant to make an effective proof-of-concept example. These simulation scenarios represent only a small subset of possible simulation scenarios that could be tested in the DRST. However, the combination of various scenario options was selected to best demonstrate the proposed resilience quantification method and implementation framework. The results of these simulations can be compared to each other to provide an indication of which of these option(s) may contribute most significantly to climate change adaptation. These options could be presented to decision makers for consideration in additional studies as possible adaptation options.

Table 7: Summary of hydraulic, SLR, and adaptation options tested using the DRST

Simulation Scenario	Hydraulic Climate Scenario	Hydraulic Event	SLR Scenario	Adaptation Option
1	Baseline	500-Yr	None	None
2	A1B	500-Yr	RCP 2.6	None
3	B1	500-Yr	RCP 2.6	None
4	A1B	500-Yr	RCP 2.6	Mobile Hospital (1)
5	A1B	500-Yr	RCP 2.6	Managed Retreat (2)
6	A1B	500-Yr	RCP 2.6	Emerg. Funding (3)

5.3.4 Implementation: Identifying Thresholds

Only two parts of the model are currently driven by threshold behaviour: (i) cell phone tower capacity in the spatial model of the social domain; and (ii) the emergency funding component of the system dynamics model. In case (i) each cell phone service tower has a maximum threshold of users. Once this threshold is reached, the cell tower can no longer service additional customers. Therefore, the remaining unserved customers are assigned to a nearby alternative tower until it also reaches its threshold (capacity). This process iterates until either all the customers have been serviced or all of the towers have run out of capacity. In case (ii), once the user-specified threshold value is crossed, the simulation model releases additional emergency funds to assist in recovery efforts. In effect, this threshold is simulating the "Resourcefulness" component of adaptive capacity. The default selection of threshold values and threshold behaviours was based on scientific research and expert opinions, though a more thorough re-examination of this threshold value, and identifying other key thresholds in disaster resilience is recommended as part of future work. For now, the user is free to specify this threshold value for every simulation.

5.4 Running the DRST

The DRST can be run for each of the simulation scenarios previously identified in Table 7 by executing the Python program. The Python program executes the spatio-temporal model and saves resilience outputs in the form of maps and tables. A graphical user interface (GUI) was created for the tool to facilitate running various combinations of flood maps and adaptation options. Additional information on using the GUI to set up and run simulation scenarios is provided in Appendix H.

5.5 Results

Using the resilience quantification framework, spatial and temporal data, climate change influenced inundation maps for the Fraser River, the resilience calculations presented in Chapter 3, and the simulation methodology presented in Chapter 4, it was possible to estimate dynamic spatio-temporal resilience for the simulation/adaptation scenarios presented in Table 7 for Metro Vancouver. The DRST generates tables and maps for every time step, for each resilience domain (except economic), plus total resilience for each time step, for each of the 7 scenarios. The results of the above simulations therefore amount to over 300 output maps. In addition, there are a number of intermediate map files that are generated by the program, including cost distance rasters which are used in the calculation of health resilience (Figure 41). Other intermediate maps are generated and then saved over in subsequent timesteps, but the result is that over 400 maps are created for the scenarios listed in Table 7. Therefore, the maps presented in this section reflect only a portion of the total number of maps produced by the DRST. The maps were chosen to demonstrate DRST outputs and support key findings. For the full set of maps the reader is referred to the supplemental electronic submission files (Appendix F).

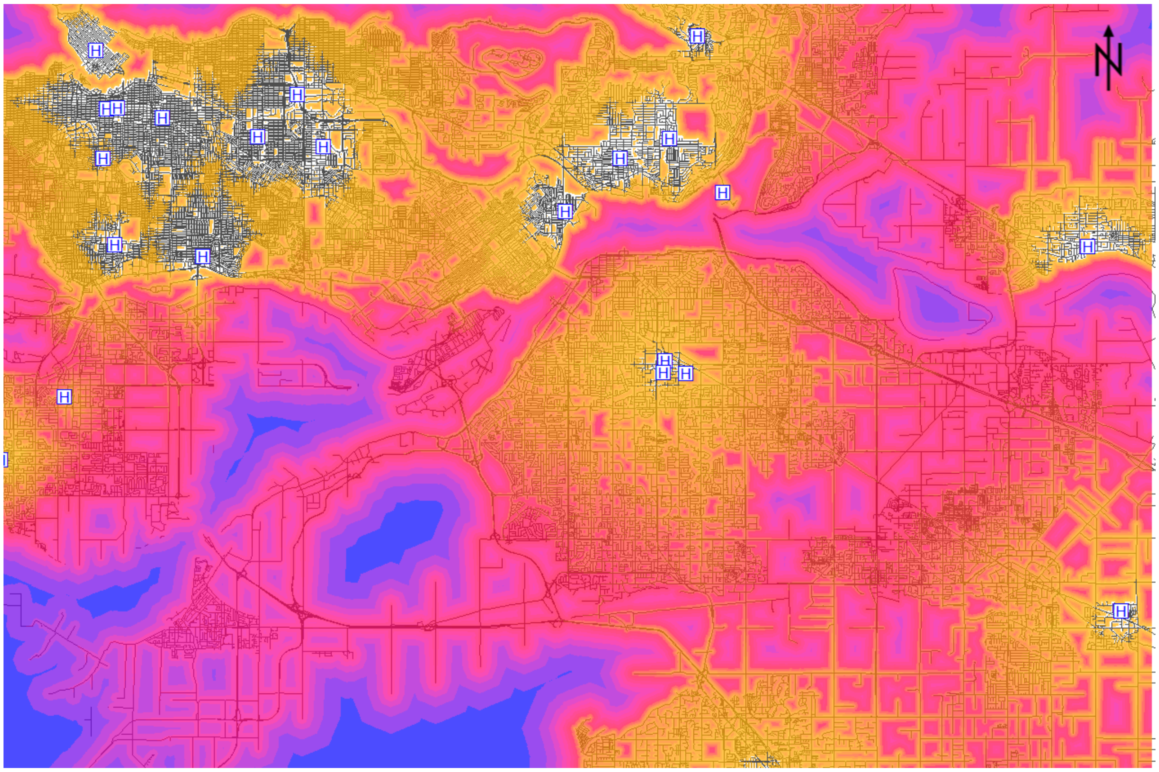
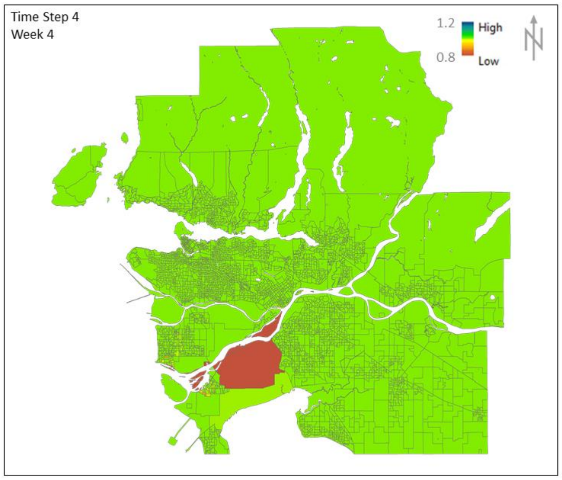


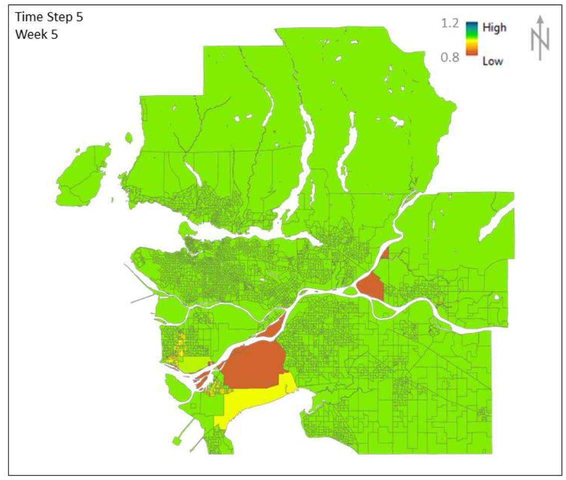
Figure 41: A sample map of the cost-distance algorithm output used by the DRST in the calculation of health resilience for one scenario (Baseline), for one time step (*t=0*); the 'H' symbols represent hospitals; yellow is low cost-distance, purple is high cost-distance

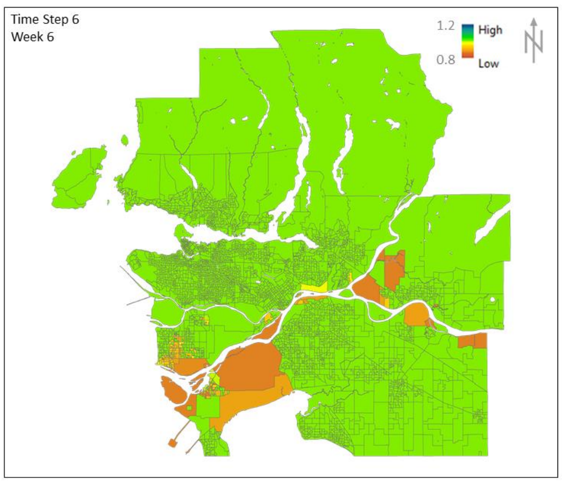
5.5.1 Spatial Representation of Resilience

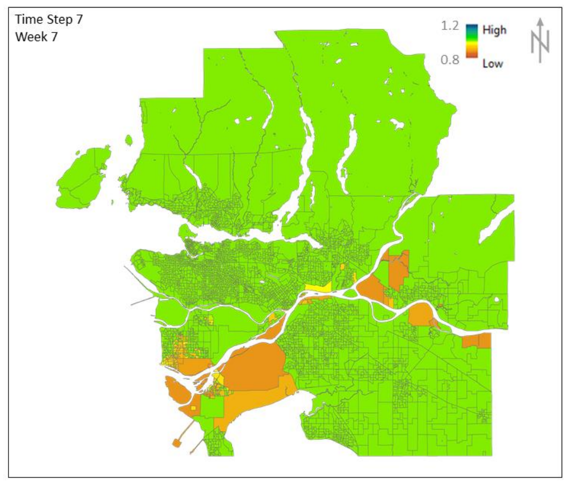
The maps in Figure 42 provide an opportunity to assess engineering resilience in space and time at the DA level. With the maps of the entire Metro Vancouver region over the simulation period, it is possible to target areas that experience the greatest change for further investigation as to why the resilience in a particular area may be higher (or lower) than anticipated. These may also be target locations to implement adaptation options such as improved building codes, flood protection, or targeted disaster recovery operations.

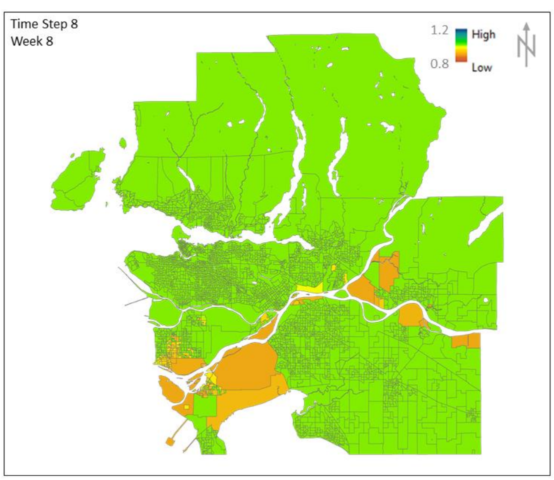
For example, the maps in Figure 42 indicate that the DAs in the vicinity of the river and mouth of the river at the ocean have lower engineering resilience than DAs in interior Metro Vancouver. Focusing in on a few of these areas, it can be seen that engineering resilience does in fact change between simulation scenarios. For DAs 59151572, 59151913, 59153003, and 59153027, resilience in Scenario 2 is less than in Scenario 1 (Figure 44). This is due to more significant flooding extent and depths in Scenario 2. This is reflected in the system performance curve, as damage accumulates over time through the use of the stage-damage curves. Figure 43 also demonstrates the change in resilience for the DA in Pitt Meadows under Scenario 5. Scenario 5 represents managed retreat option in which structures are no longer located in the flood susceptible area. So even though the DA is subjected to the same flooding extent and depth as Scenario 2, there are no structures exposed to flooding and therefore engineering system performance is maintained at pre-disturbance levels and resilience value is 1.

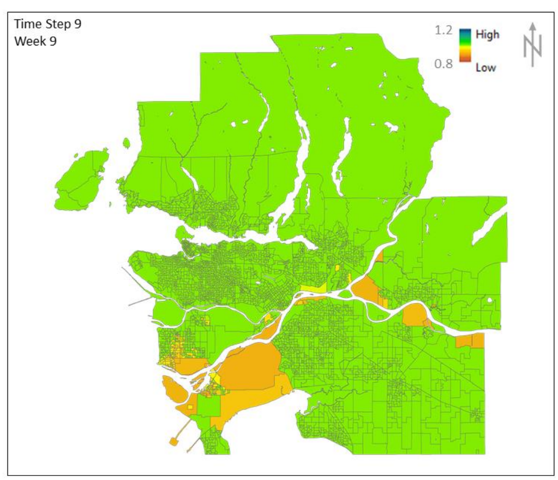

Time Step 4
Week 4
1.2
High
0.8
Low
N


Time Step 5
Week 5
1.2
High
0.8
Low
N


Time Step 6
Week 6
1.2
High
0.8
Low
N


Time Step 7
Week 7
1.2
High
0.8
Low
N


Time Step 8
Week 8
1.2
High
0.8
Low
N


Time Step 9
Week 9
1.2
High
0.8
Low
N

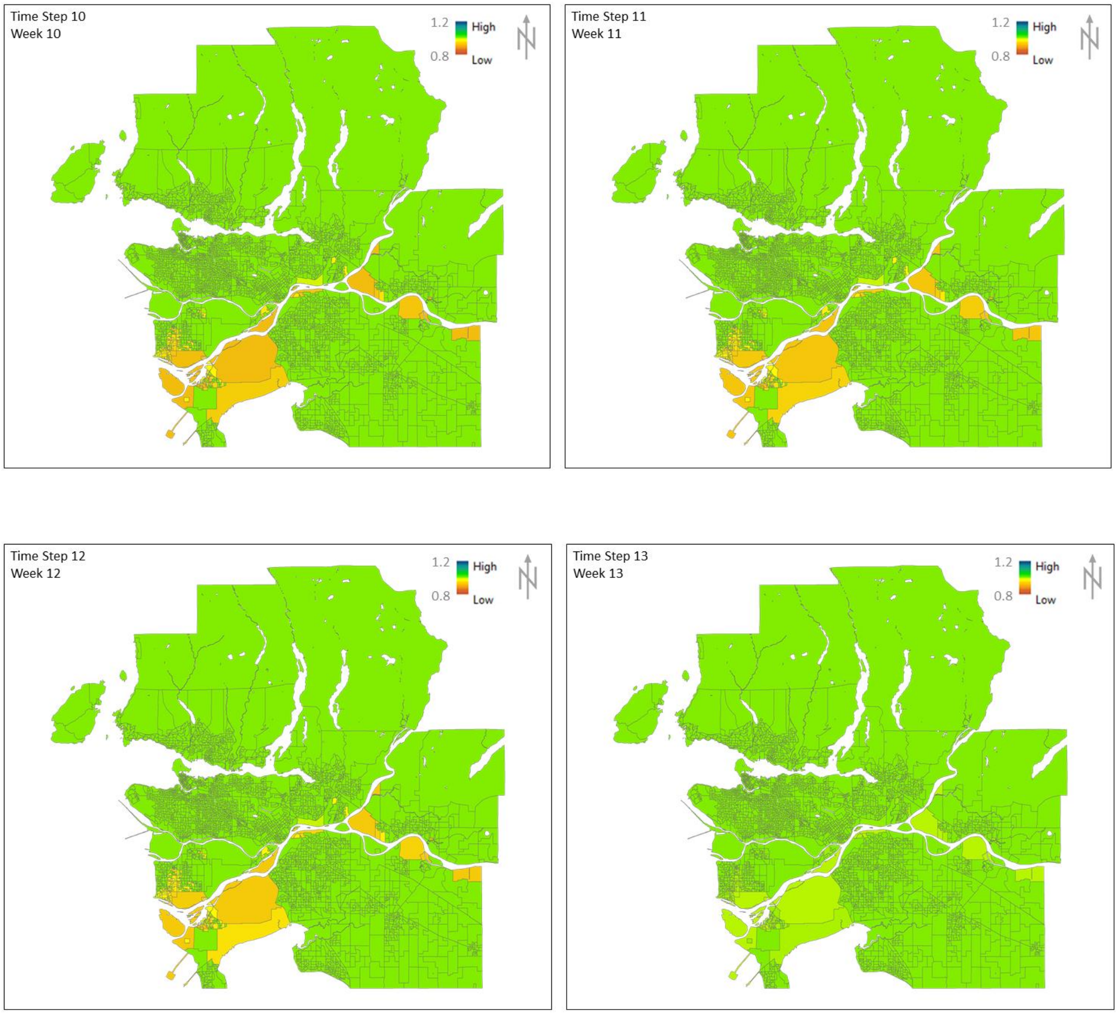


Figure 42: Spatial engineering resilience for Scenario 2 across dissemination areas for Metro Vancouver (14 total time steps); maps in NAD 83 CRCS

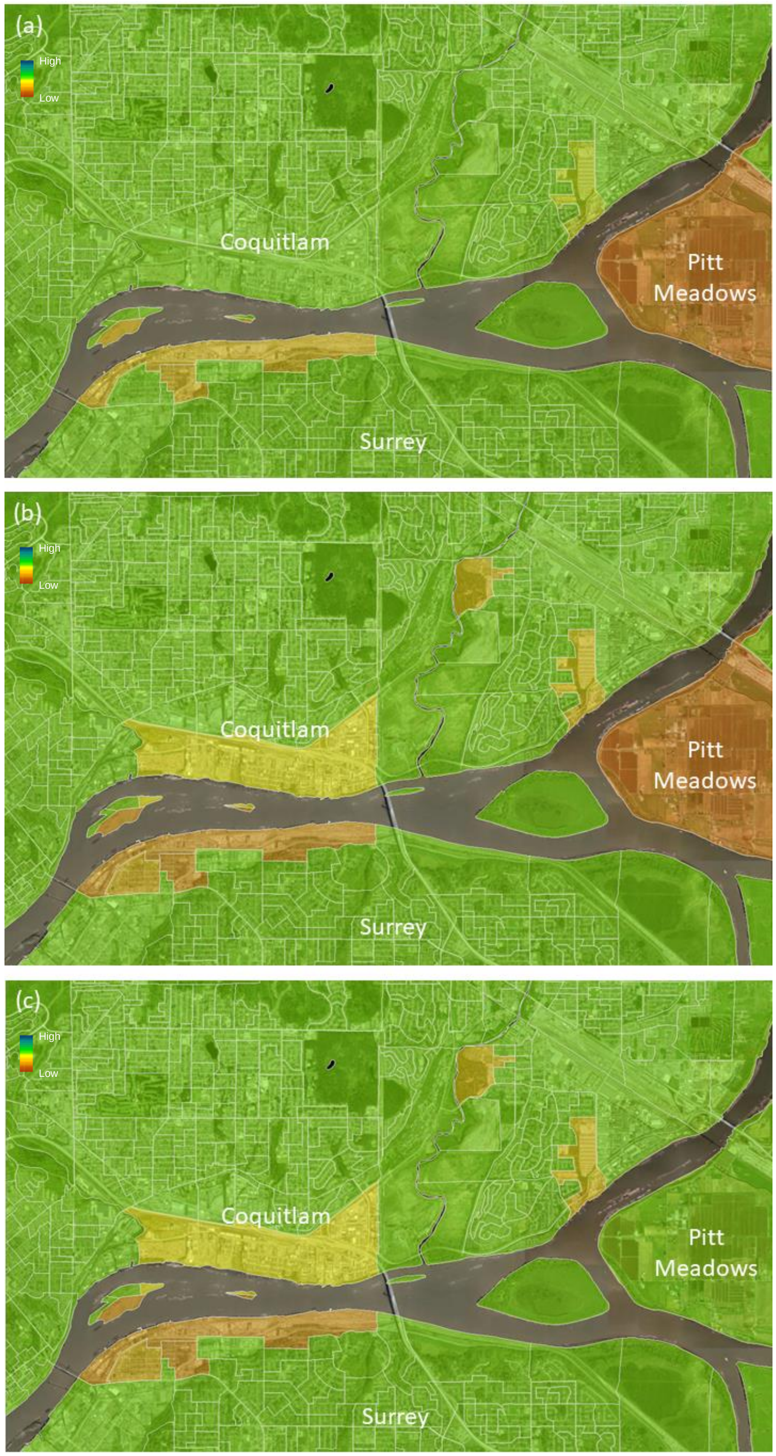
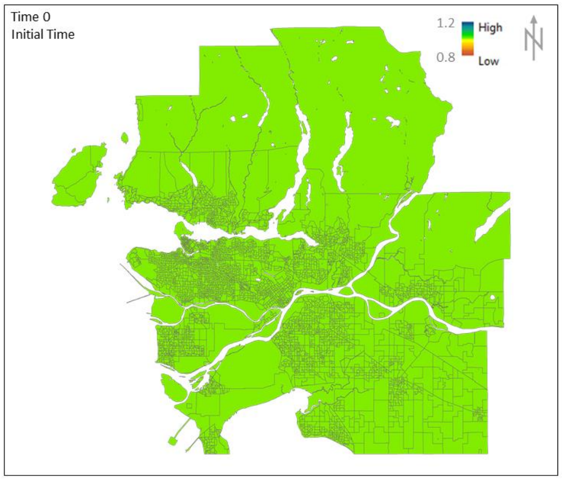
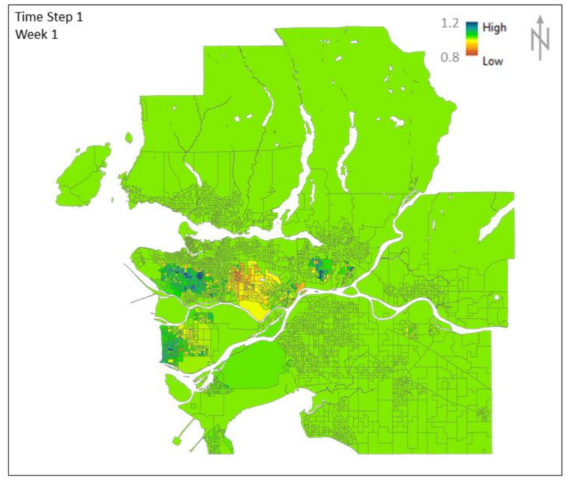
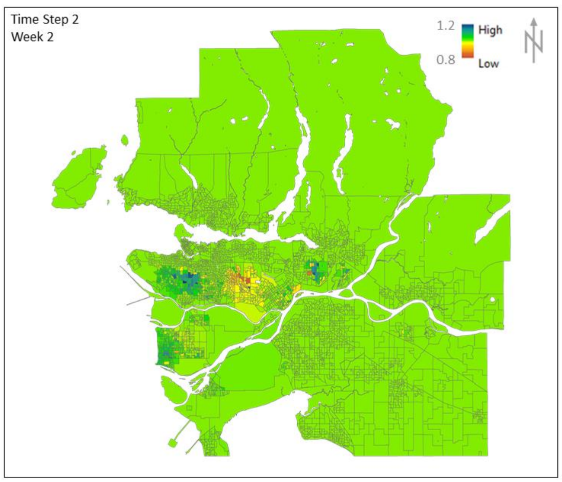


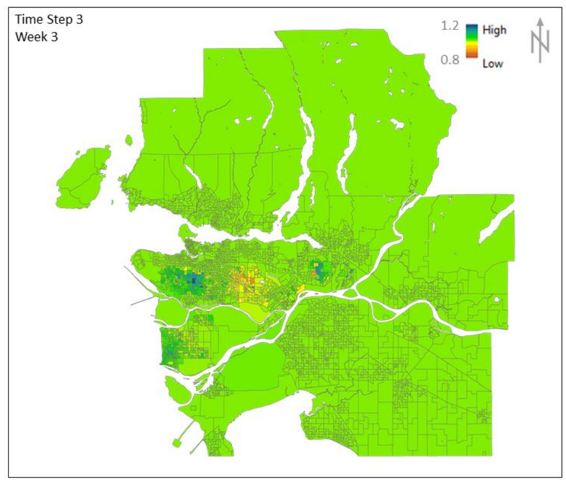
Figure 43: Engineering resilience at one time step (t = 7) for (a) Scenario 1; (b) Scenario 2; and (c) Scenario 5 near the Fraser River in the member municipalities of Coquitlam, Surrey, and Pitt Meadows

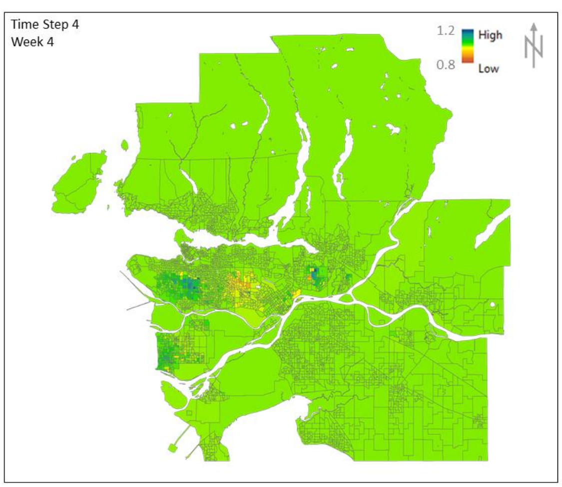
The maps in Figure 44 provide an opportunity to see at the Regional level what is happening to health resilience in space and time. These may be target locations to implement adaptation options such as mobile health care (hospitals), raising roads, or to target disaster emergency response and recovery operations. Taking a closer look at a few of these areas, it can be seen that health resilience changes between simulation scenarios for certain DAs. For many DAs in the City of Delta, health resilience in Scenarios 1, 2, and 3 is low due to the inundation of local roads, restricting access to hospitals. The closest (non-auxiliary) hospitals are in neighbouring cities of Richmond, Surrey, and White Rock (Figure 45). As roadways become inundated, the "cost" to get to hospitals increases and system performance decreases. However, Scenario 4 represents the mobile hospital adaptation option in which a mobile hospital is set up in the City of Delta to service the area during a flood. So even though the DAs in Delta are subject to the same flooding extent and depth as Scenario 2, the addition of a mobile health unit improves system performance and resilience exceeds pre-shock levels (Figure 46).

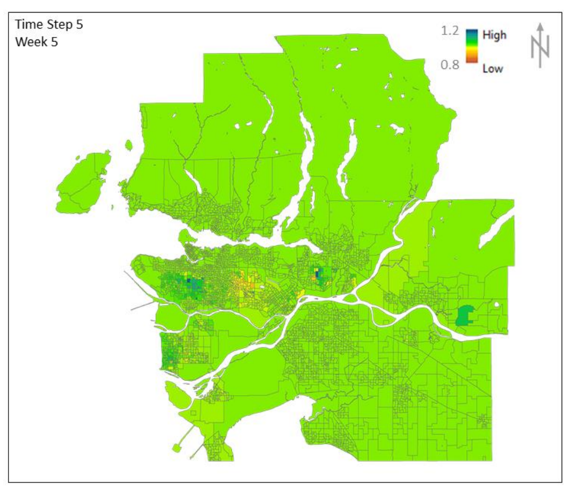

Time 0
Initial Time
1.2
High
0.8
Low
N

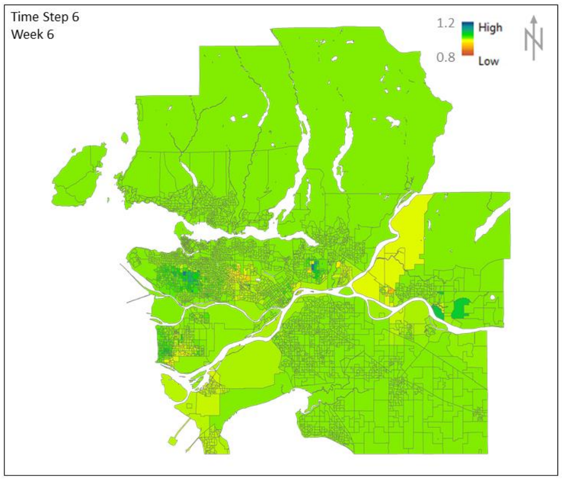

Time Step 1
Week 1
1.2
High
0.8
Low
N

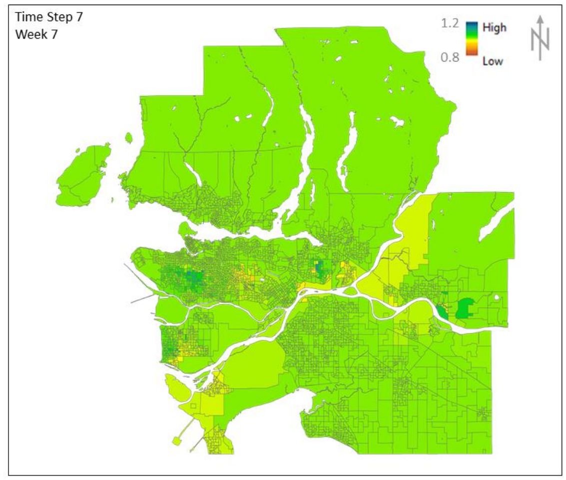

Time Step 2
Week 2
1.2
High
0.8
Low
N

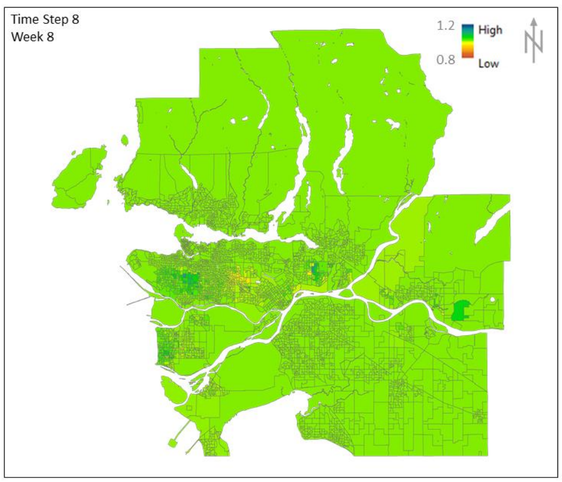

Time Step 3
Week 3
1.2
High
0.8
Low
N

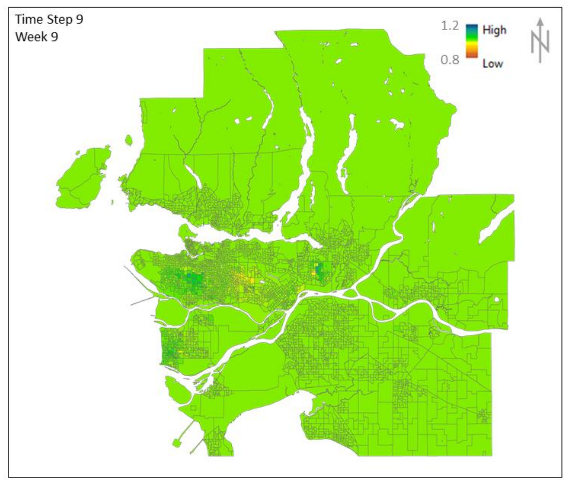

Time Step 4
Week 4
1.2
High
0.8
Low
N

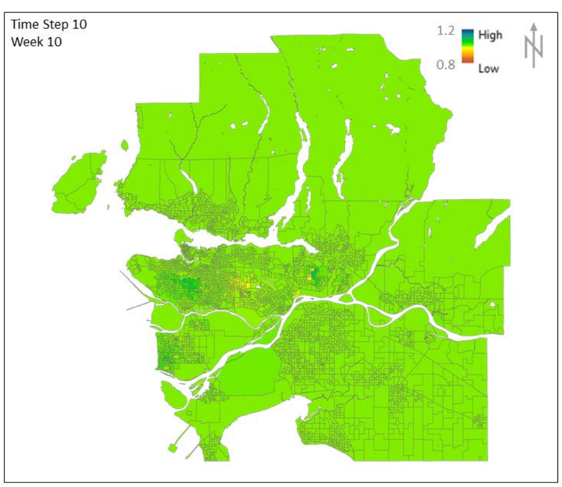

Time Step 5
Week 5
1.2
High
0.8
Low
N

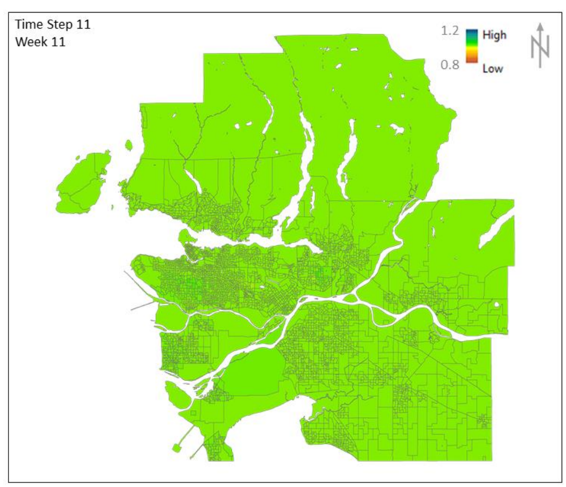

Time Step 6
Week 6
1.2
High
0.8
Low
N


Time Step 7
Week 7
1.2
High
0.8
Low
N


Time Step 8
Week 8
1.2
High
0.8
Low
N


Time Step 9
Week 9
1.2
High
0.8
Low
N


Time Step 10
Week 10
1.2
High
0.8
Low
N


Time Step 11
Week 11
1.2
High
0.8
Low
N

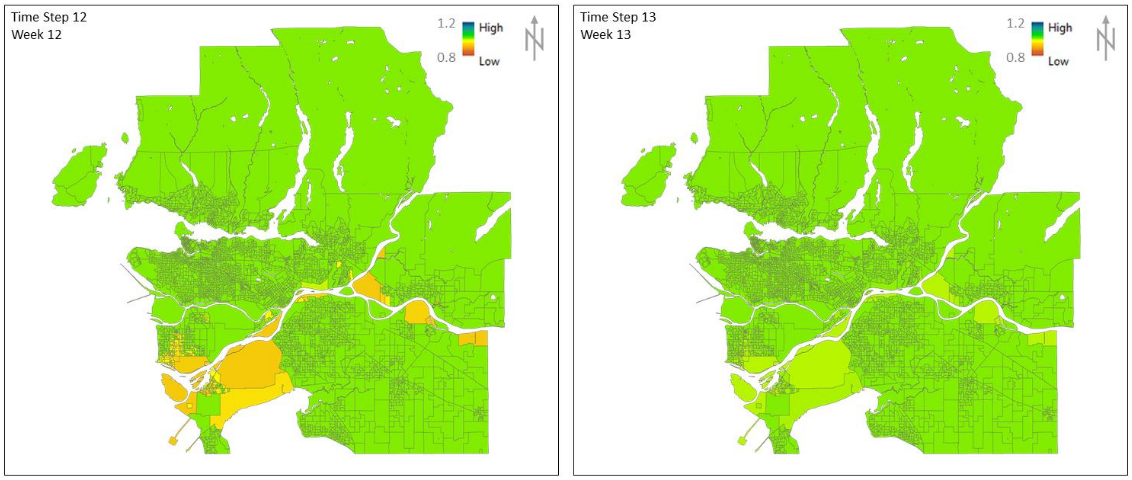


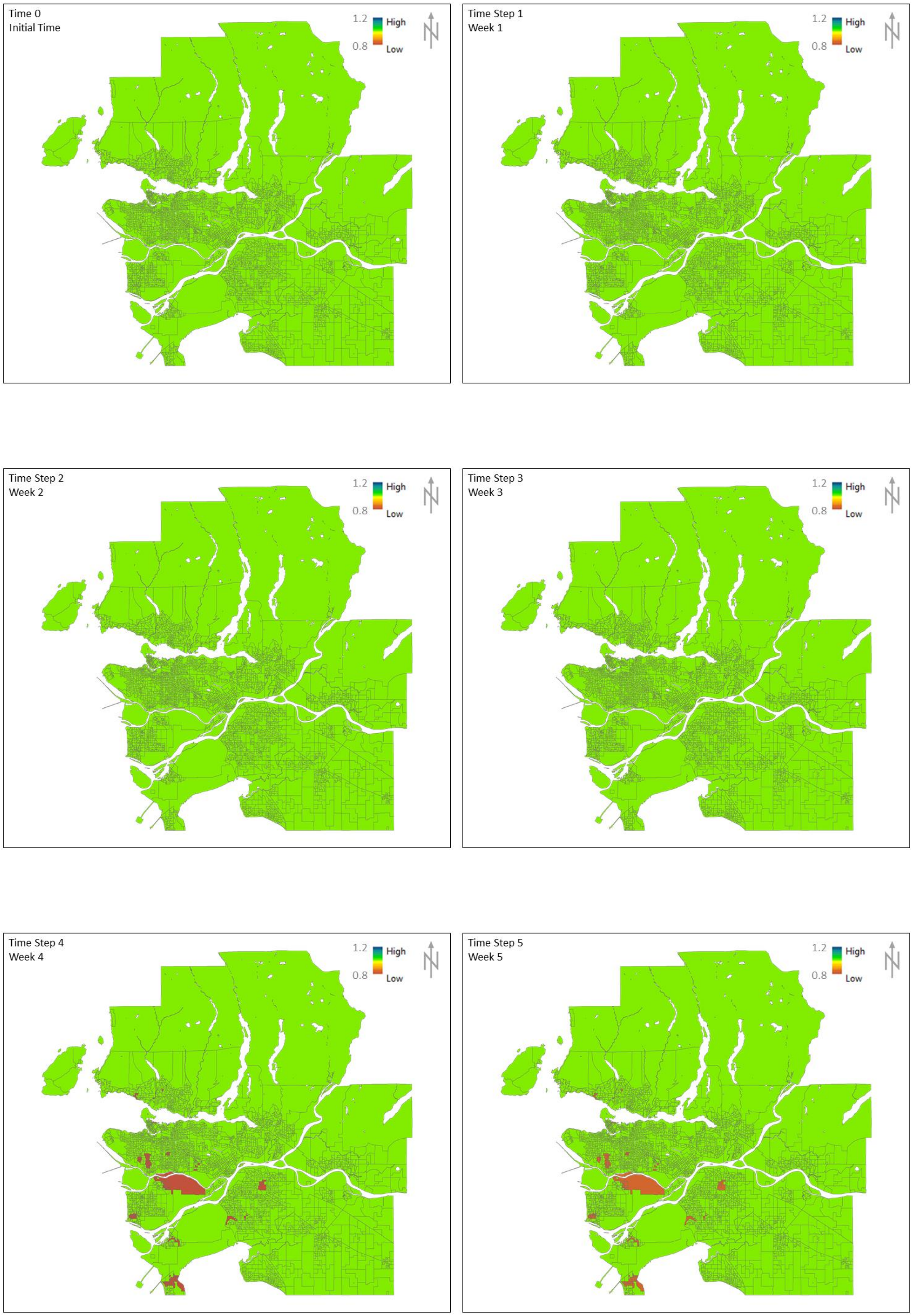
Figure 44: Spatial health resilience for Scenario 2 across dissemination areas in Metro Vancouver (14 total time steps); maps in NAD 83 CRCS

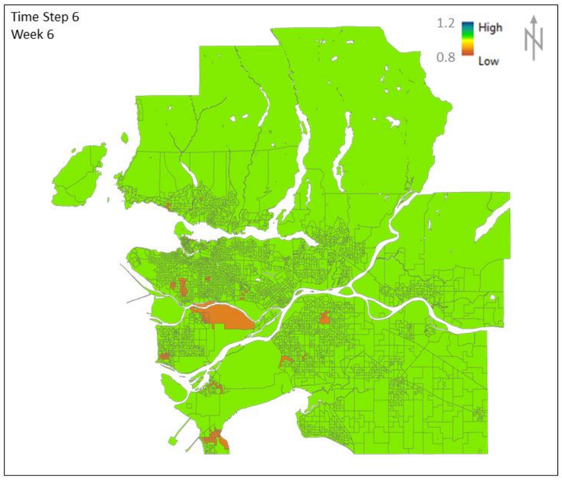
Figure 45: Hospitals (non-auxiliary) near the City of Delta

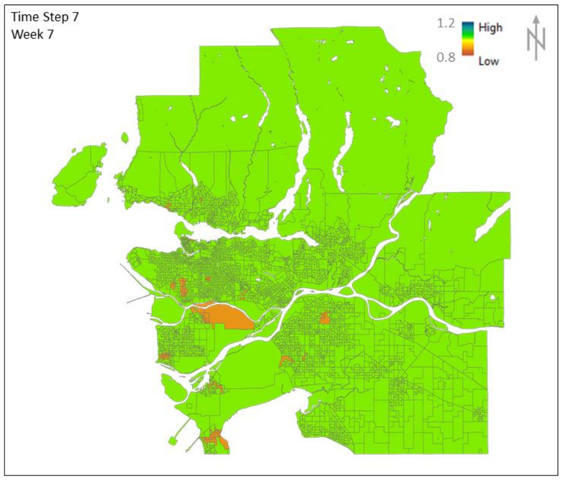
Figure 46: Health resilience at one time step (t = 7) for (a) Scenario 1; (b) Scenario 2; and (c) Scenario 4 for the cities of Richmond, Delta, Surrey, and White Rock

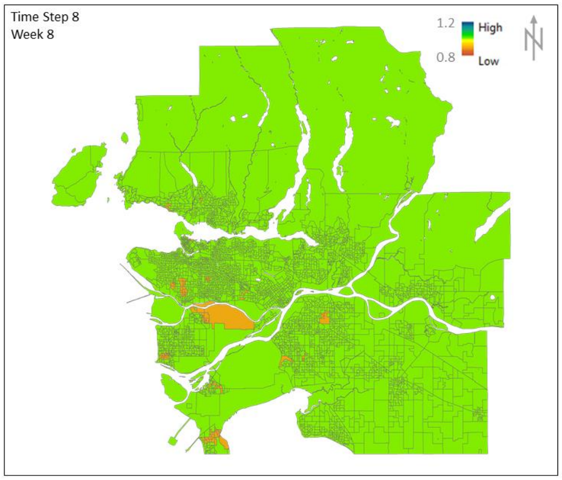
The maps in Figure 47 provide an opportunity to see at the Regional level what is happening to social resilience in space and time. These may be target locations to implement adaptation options such as backup emergency generators, mobile cell phone stations, or something more drastic such as switching to alternative energy sources. The social system yields particularly interesting results since its performance is network-based. Spatially, this means that even service areas which are not directly inundated can be impacted by the flood event. The spatial distribution in resilience values shown in the maps in Figure 47 are driven by the algorithm currently implemented in the DRST, specifically the iterative process of assigning cell phone users to operational (available) cell phone towers. Taking a closer look at some of these areas, it can be seen that social resilience changes over time and space for certain DAs. As flooded substations lose power, nearby cell towers are impacted and also lose power. Subsequently, the remaining (powered) cell towers iteratively pick up the unserved customers from the impacted DAs. The capacity of each cell tower limits how many additional customers can be picked up from the impacted area. As Figure 48 demonstrates, not all of the impacted areas are able to be serviced by the remaining towers. This has an impact on social system performance, and subsequently system resilience, since the social resilience indicator was defined as *connectivity* and its metric of system performance is represented as people serviced.

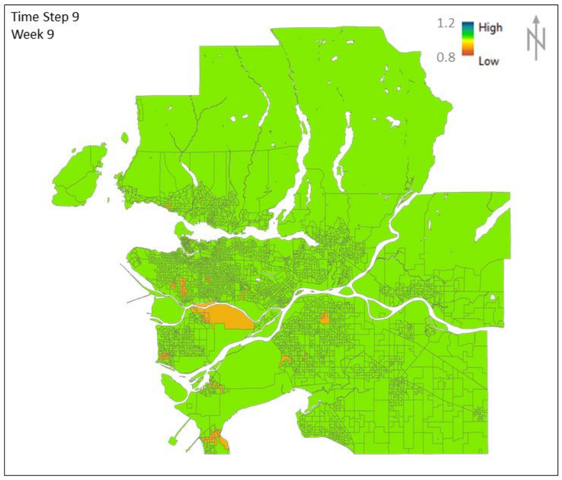
What’s also interesting to note is that although the Regional scale was selected as the focal scale for this application, it’s possible that if power were to be supplied from sources outside of the Region, impacts may still be present at the Regional-level. Oftentimes system impacts are not constrained within jurisdictional boundaries, which emphasizes the importance of capturing cross-scale resilience; influences from above, and below, the focal scale.

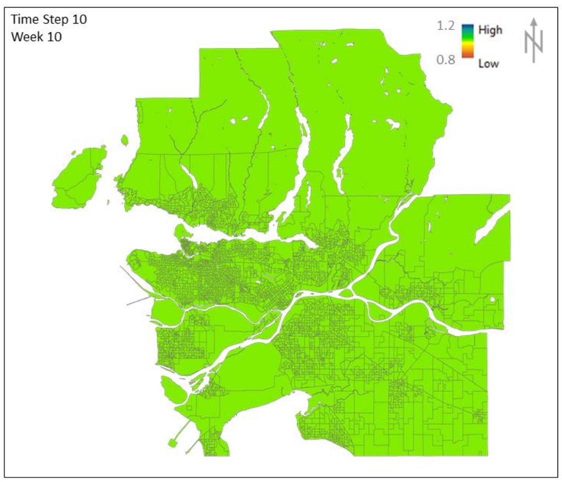

Time 0
Initial Time
1.2
High
0.8
Low
Time Step 1
Week 1
1.2
High
0.8
Low
Time Step 2
Week 2
1.2
High
0.8
Low
Time Step 3
Week 3
1.2
High
0.8
Low
Time Step 4
Week 4
1.2
High
0.8
Low
Time Step 5
Week 5
1.2
High
0.8
Low

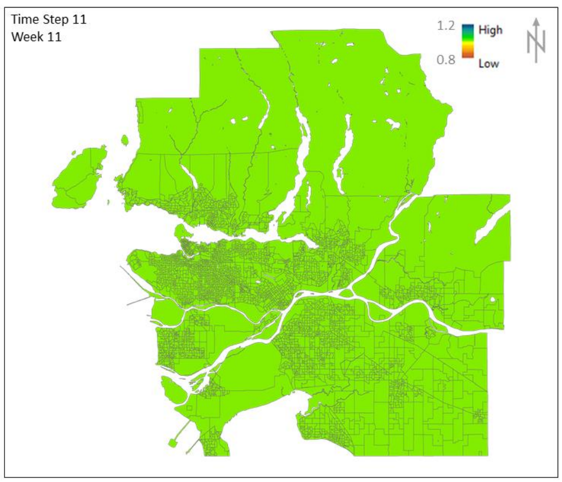

Time Step 6
Week 6
1.2
High
0.8
Low


Time Step 7
Week 7
1.2
High
0.8
Low


Time Step 8
Week 8
1.2
High
0.8
Low


Time Step 9
Week 9
1.2
High
0.8
Low


Time Step 10
Week 10
1.2
High
0.8
Low


Time Step 11
Week 11
1.2
High
0.8
Low

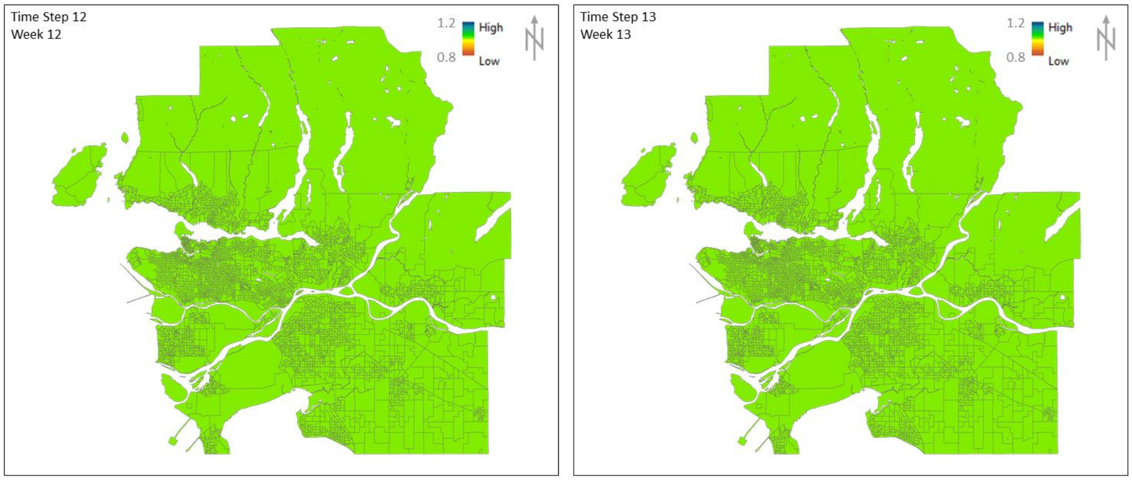


Figure 47: Spatial social resilience for Scenario 2 across dissemination areas in Metro Vancouver (14 total time steps); maps in NAD 83 CRCS

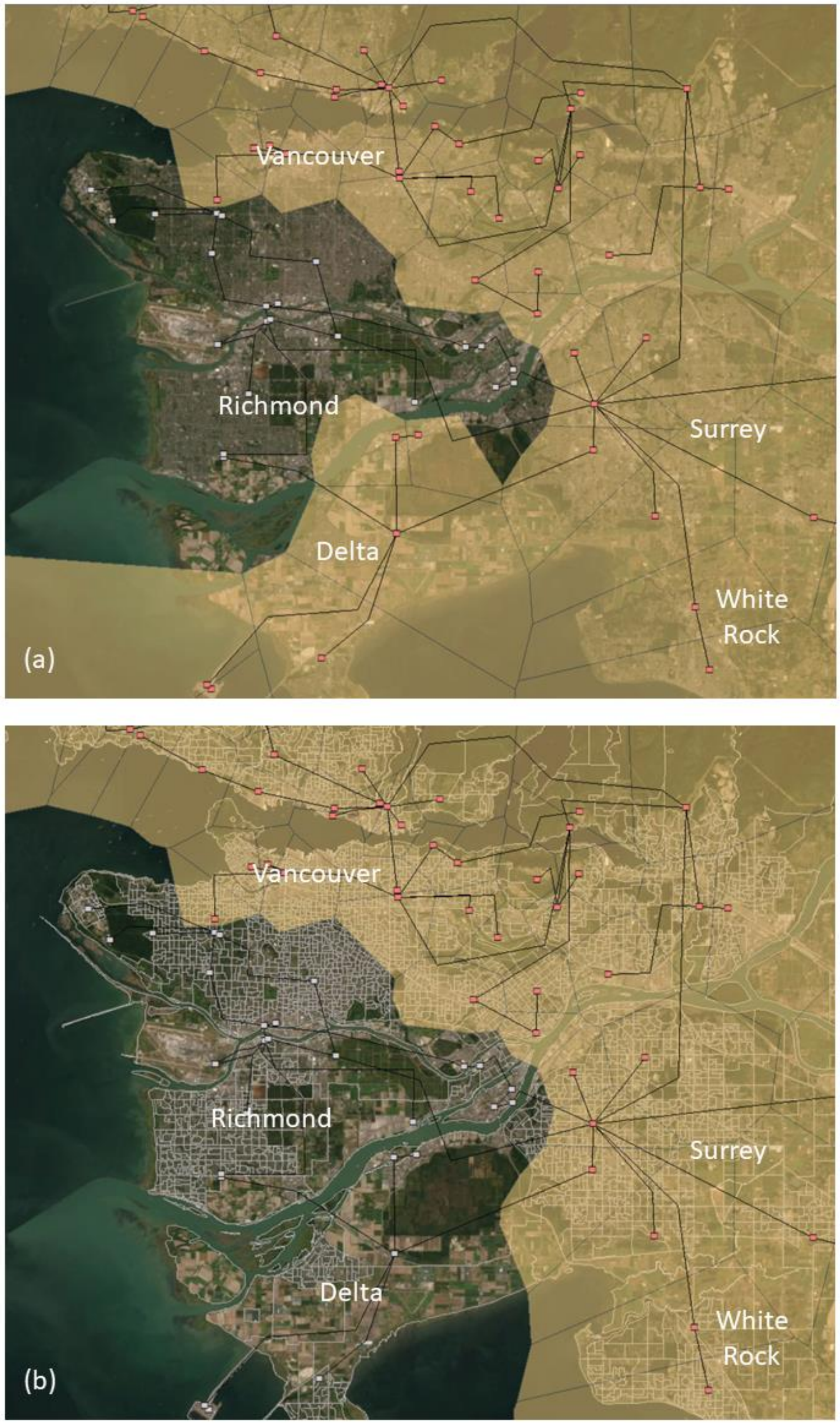


Figure 48: Difference in social system impacts for one time step (t = 4) for (a) Scenario 1; and (b) Scenario 2

5.5.2 Temporal Representation of Resilience

Maps are useful tools in the spatial representation of disaster resilience and the map set (time series of maps) can provide insight into these spatial changes over time. However, when considering the focal (Regional) scale of resilience assessment, it’s useful to look at the simulation output graphs. These can provide insight into temporal dynamics of disaster resilience and provide a convenient mechanism for scenario comparison.

Figure 49 shows temporal engineering resilience results for three (3) climate scenarios and one (1) adaptation scenario. Everything else being equal, climate change has an impact on Regional engineering resilience. As expected, resilience is lowest in Scenario 2, Scenario 1 is the highest, and Scenario 3 slightly outperforms Scenario 2. When considering the emergency funding adaptation option (Scenario 6), it can be seen that declaring a state of emergency and getting access to additional resources, results in higher resilience; system performance is equally impacted by flooding (the disturbance), but the additional funding allows the system to recover faster. This funding availability is driven by threshold behaviour. This threshold is a gaming variable in the simulation and can be modified at the beginning of a simulation to determine the impacts that the funding threshold has on resilience.

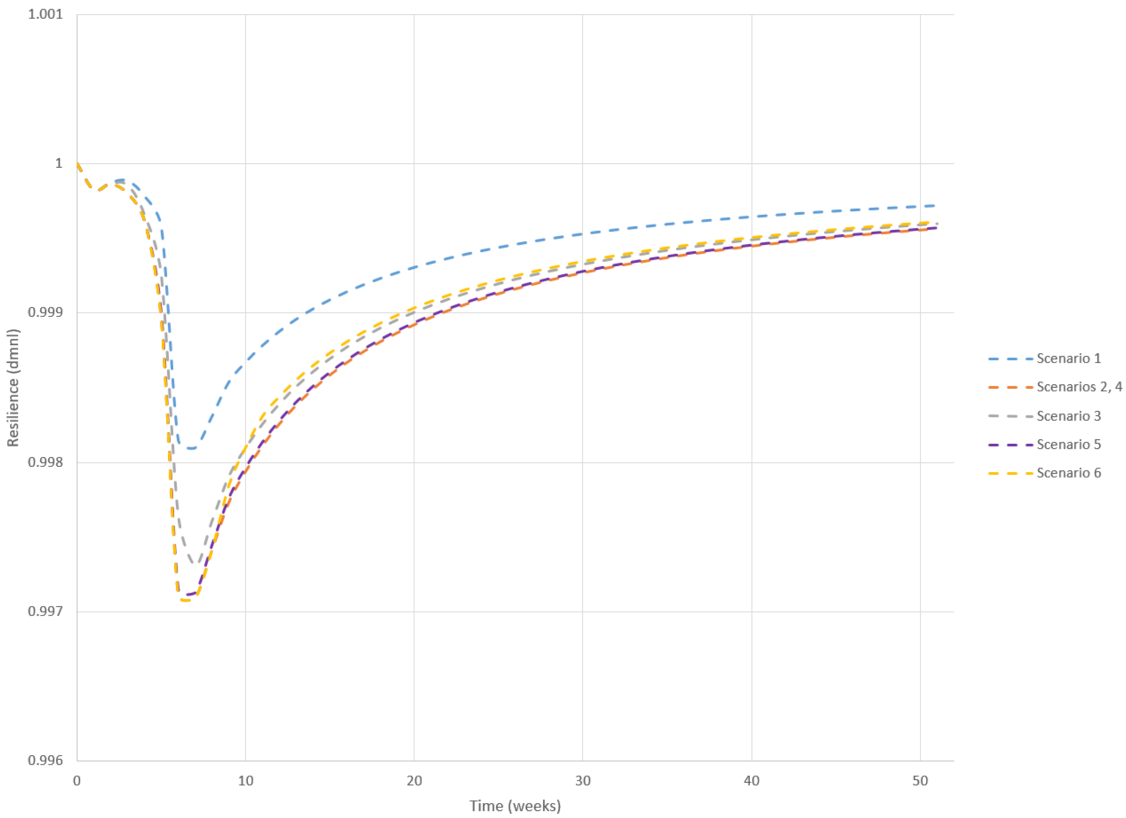


Figure 49: Engineering resilience (Metro Vancouver)

Figure 50 shows temporal social resilience results for three (3) climate scenarios. It can be seen that everything else being equal, climate change has an impact on Regional social resilience. As expected, resilience is lowest in Scenario 2, Scenario 1 is the highest, and Scenario 3 slightly outperforms Scenario 2. All scenarios return to pre-disturbance performance levels by the end of the simulation period. Social resilience recovers more quickly than the engineering sector.

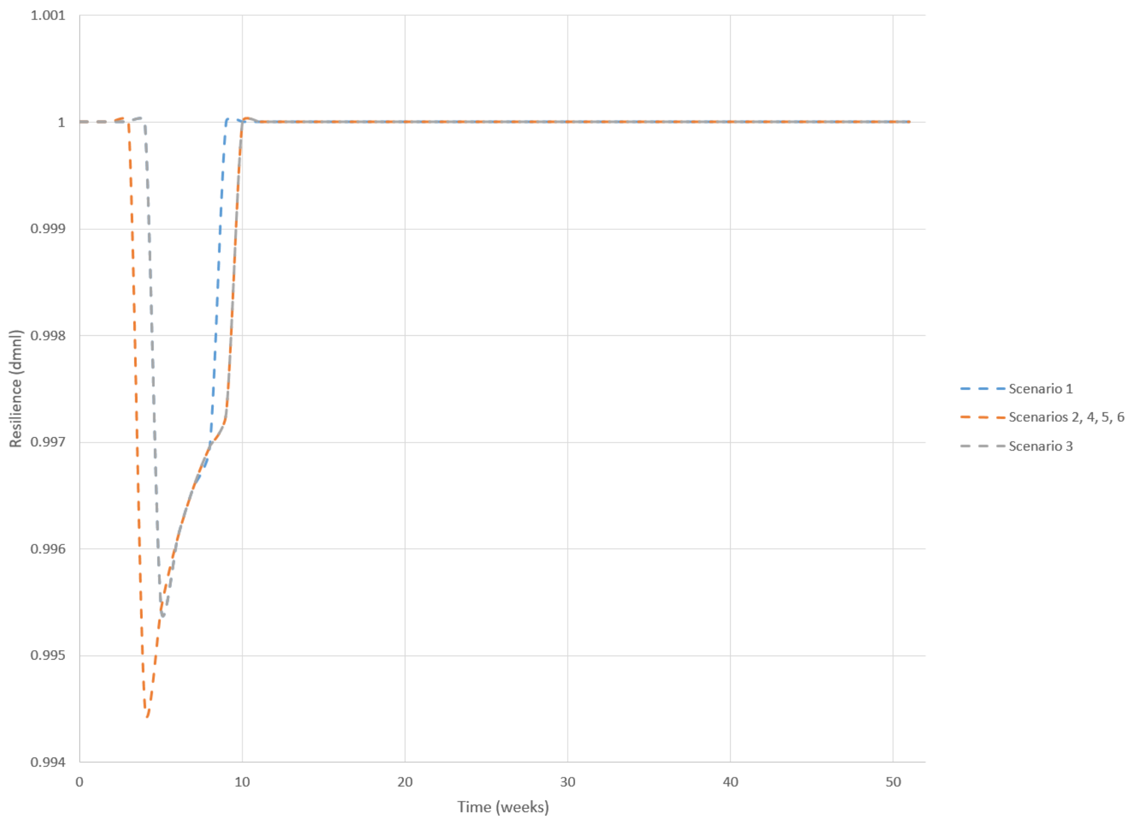


Figure 50: Social resilience (Metro Vancouver)

Figure 51 shows temporal health resilience results for three (3) climate scenarios and one (1) adaptation option. It can be seen that everything else being equal, climate change has an impact on Regional health resilience. As expected, resilience is lowest in Scenario 2, Scenario 1 is the highest, and Scenario 3 slightly outperforms Scenario 2. When considering the mobile hospital adaptation option (Scenario 4), it can be seen that the addition of a mobile hospital station results in higher overall resilience; system performance (and subsequently resilience) jumps higher since the addition of a temporary hospital service occurs before the peak of the flood. The time and location of the mobile hospital service was pre-determined and is unchangeable during the simulation, however with slight modification to the DRST, the timing, location, and number of mobile stations could all be adjusted to reflect any number of additional options.

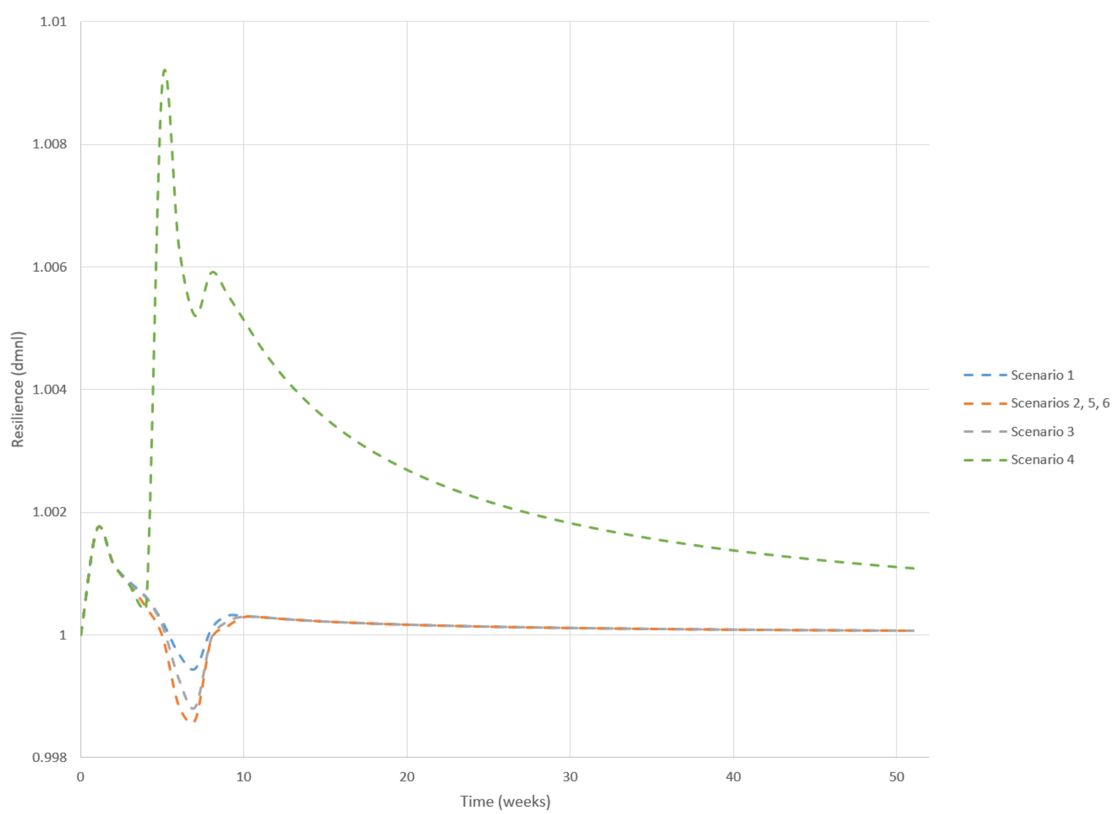


Figure 51: Health resilience (Metro Vancouver)

Figure 52 shows temporal economic resilience results for three (3) climate scenarios and three (3) adaptation options. It can be seen that everything else being equal, climate change has an impact on Regional economic resilience. As expected, resilience is lowest in the Scenario 2, Scenario 1 is the highest, and Scenario 3 slightly outperforms Scenario 2. When considering any of the three (3) adaptation options, it can be seen that they do not significantly impact economic resilience. Over the course of the one (1) year simulation period, the economic resilience remains below a value of 1.0, indicating resilience has not returned to pre-shock state. At the end of the simulation, they do not show any signs of recovery, however this interpretation of these results could be a little misleading; provided a longer simulation period, the resilience values actually begin increasing, approaching, and even surpassing a value of 1.0 (Figure 53). The reasons for this behaviour is in part due to the implementation of the economics domain in the DRST, operating as an optimization model.

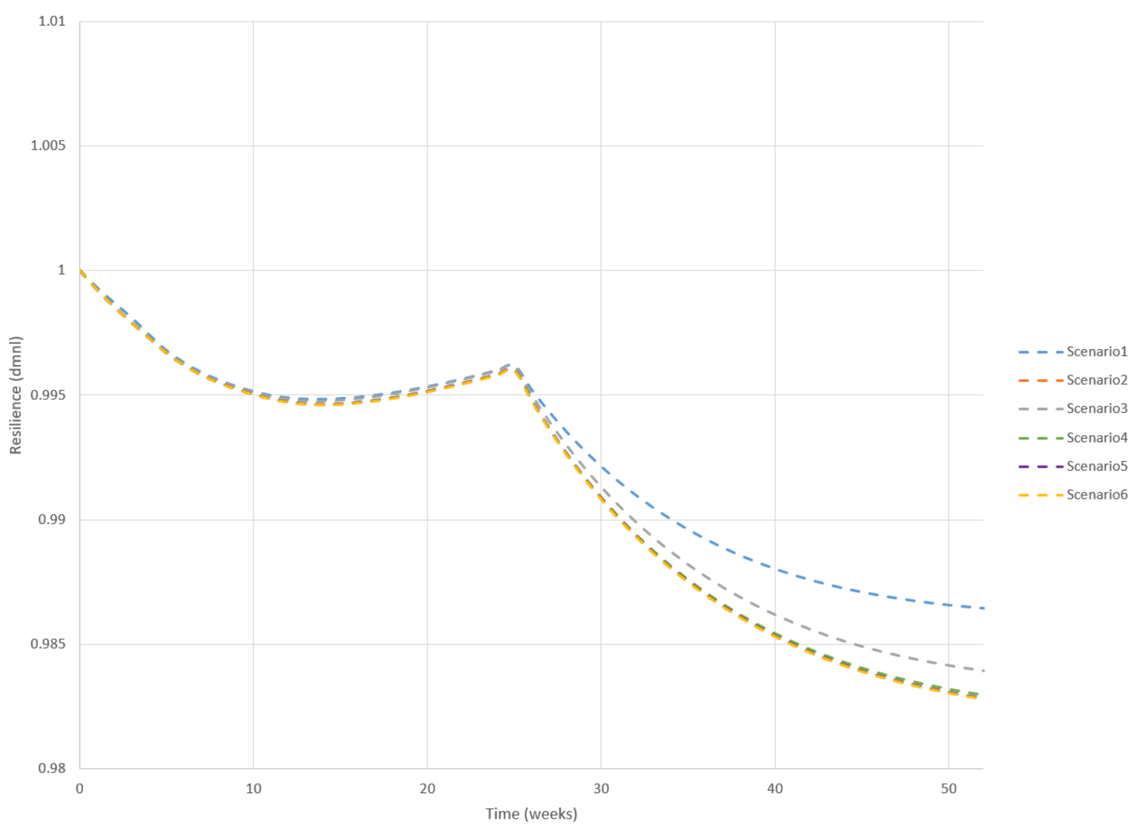


Figure 52: Economic resilience (Metro Vancouver)

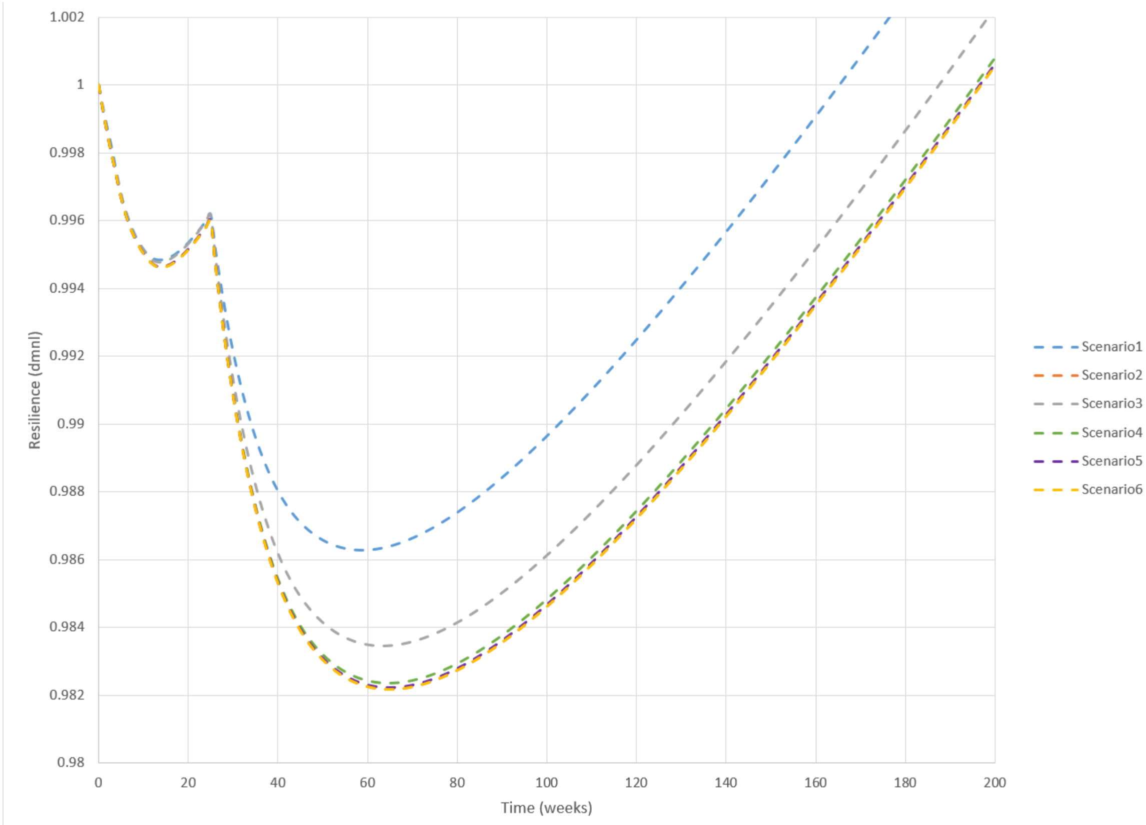


Figure 53: Economic resilience modelled over a longer (nearly 4 year) time period

Figure 54 shows temporal total resilience results for three (3) climate scenarios and three (3) adaptation options. It can be seen that everything else being equal, climate change has an impact on Regional total resilience. When comparing the three (3) climate change scenarios (Scenario 1, Scenario 2, and Scenario 3) as expected, resilience is highest in Scenario 1; lowest in Scenario 2; and Scenario 3 slightly outperforms Scenario 2. This is because the climate-change influenced hydrometeorological hazards are influencing system performance across all of the resilience domains.

When considering the three (3) adaptation options, (retreat, mobile hospital, and funding), it can be seen that all of the adaptation options contribute to higher levels of overall resilience, however Scenario 4 (mobile hospital) outperforms the other adaptation options. Scenario 5 (managed retreat) does not significantly impact the overall resilience calculation, as its total resilience is only marginally higher than Scenario 2.

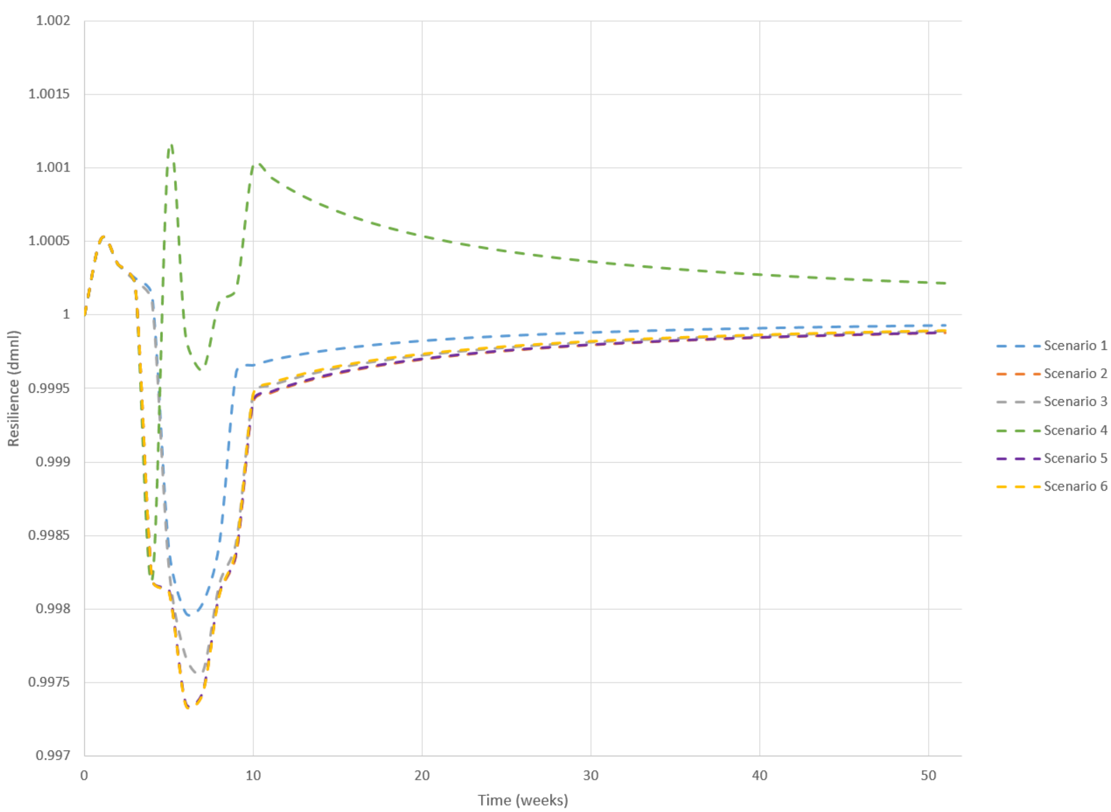


Figure 54: Total resilience (Metro Vancouver)

Overall, the simulated change in resilience values is relatively low; the entire range of resilience values fluctuates only within the range of 0.994 and 1.01. This is because resilience, as per equation (3.3), is a function of the initial system performance. Since the focal scale for resilience was established as the Metro Vancouver (regional) level, the initial system performance is a function of the entire regional system. Therefore, engineering performance at the regional level is described by the impacts to the entire regional-scale building stock. Similarly, social resilience is a function of the impacts and capacity of the entire regional population, health resilience is a function of the impacts and capacity of region-wide access to healthcare facilities, and economic resilience is a function of the regional economy. The impact of flooding on individual DAs can be significant as observed in the maps presented in Figure 42, Figure 44, and Figure 47. However, this resolution is lost when only evaluating resilience at the Regional level. As the spatio-temporal maps in this chapter illustrate, resilience changes rather significantly at the DA level. This stresses the importance of selecting a meaningful focal scale for resilience assessment. The focal scale will drive the resolution of the resilience assessment and conclusions.

Ultimately, the results suggest that overall Metro Vancouver is relatively resilient to particular climate change influenced hydrometeorological disasters. However, particular care should be exercised in the interpretation of these results since resilience is not evenly distributed across the Region. Dissemination areas in the City of Richmond and Delta are generally less resilient than the rest of the Region.

5.6 Chapter Summary

An application of the resilience quantification framework and calculation methodology was applied to the region of Metro Vancouver, BC, Canada. First, the resilience landscape was set and disaster resilience was characterized. Data was collected and a simulation model was built to reflect four (4) important resilience domains. A single metric was selected to represent system performance for each of the four (4) domains (engineering, social, health, economy). Six (6) simulation scenarios (considering 3 climate change-based scenarios and 3 adaptation options) were developed and run as part of proof-of-concept implementation of the DRST. Adaptation options tested systems response and recovery performance to shocks (hazard events). From the output maps and graphs, it can be seen that climate change impacts disaster resilience and that various adaptation options can be implemented to mitigate impacts and improve disaster resilience. The resilience framework is intended to support disaster resilience quantification and aid in the development of resilience-based assessment tools. The DRST is at the proof-of-concept stage and therefore does not provide sufficient level of detail or ground-truthing to make it an appropriate tool for real-world decision making. However with improvements, future iterations of the DRST can be used by emergency management professionals and decision makers to provide insight into the following key questions:

1. How are climate change influenced hydrometeorological hazards affecting Metro Vancouver?

2. How can municipalities in Metro Vancouver better plan for, and adapt to, future climate change-influenced hydrometeorological hazards?

3. How resilient is Metro Vancouver to climate change influenced hydrometeorological hazards?

The following is an example of how the implementation of the disaster resilience quantification framework and proof-of-concept DRST would be used to respond to the above questions:

How are climate change influenced hydrometeorological hazards affecting Metro Vancouver?

Increasing temperatures and changes in precipitation are two of the main climatic drivers of changes in water resources systems. Future changes are strongly linked to warming trends and the seasonality and magnitude of river flows. A warming climate with increased precipitation variability will likely increase exposure to sea level rise and riverine flooding in Metro Vancouver. This is consistent with the sea level rise projections in Agam (2014) and results of climate change influenced riverine flooding as presented in this dissertation.

How can municipalities in Metro Vancouver better plan for, and adapt to, future climate change-influenced hydrometeorological hazards?

Climate change influenced sea level rise and riverine flooding will continue to threaten coastal communities. With the pressures of increasing urbanization, development, and unique hydrometeorological hazards, coastal communities need to better plan, prepare, and respond to disasters. As a coastal city, Metro Vancouver can become more resilient to climate change influenced hydrometeorological disasters by implementing adaptation measures that will improve the robustness, redundancy, rapidity, and resourcefulness of key disaster management-related city systems. Two (2) adaptation options which could improve the resilience of Metro Vancouver are: enabling mobile treatment centres during a disaster and access to additional financial resources. Managed retreat, as implemented for a single DA in Pitt Meadows, does not contribute significantly to the overall resilience of Metro Vancouver. One (1) adaptation option which could improve the resilience of Pitt Meadows (municipality within Metro Vancouver) is managed retreat. Overall, managed retreat could also prove to be an effective measure for increasing disaster resilience at the Metro Vancouver level, however it would need to be implemented at a much larger scale for multiple DAs along the Fraser River.

How resilient is Metro Vancouver to climate change influenced hydrometeorological hazards?

Results suggest that Metro Vancouver exhibits a high degree of resilience at the Regional scale. However, this resilience is not distributed proportionately across the Region. In some DAs bordering the Fraser River, resilience drops nearly 20% in Scenario 2. This demonstrates the importance in selecting an appropriate focal scale for resilience assessment. To capture a holistic representation of disaster resilience, it is necessary to consider the influence across multiple scales. However, resilience is both relative and contextual and therefore selection of the focal scale will ultimately shape the assessment. Careful consideration should be paid to the selection of the focal scale when establishing research objectives, so that meaningful answers can be derived through the disaster resilience assessment process.

Chapter 6

6 CONCLUSIONS

This chapter summaries the methodology, main findings and contributions of the research. It also identifies some of the shortcomings of the resilience quantification methodology and its application to Metro Vancouver. Since the DRST was a pioneering effort in dynamic disaster resilience quantification, this chapter concludes with a discussion of possible modifications, extensions and other sets of recommendations for future work in the field of disaster management.

6.1 Summary of Methodology and Contributions to the Disaster Management Research Field

As described in Chapter 2, the climate is changing which will have significant impacts on the magnitude, frequency, and seasonality of hazards across the globe. It is anticipated that coastal megacities will be disproportionally affected by disasters in the future due to non-climatic factors such as urbanization and rapid population growth in combination with climatic factors such as increased exposure to climate change influenced hydrometeorological hazards including sea level rise and riverine flooding. Therefore, reducing the impacts of climate change-influenced hydrometeorological hazards on coastal cities was identified as the primary motivation for pursuing the research in this dissertation. To assess the current state of affairs, a review of existing disaster resilience definitions, quantification techniques, and assessment tools was presented in Section 2.3. The following is a summary of the issues and gaps identified in the review of resilience literature and resilience practice, and a description of how these gaps were addressed as part of this dissertation:

Issue 1: There is a growing recognition that resilience is temporally and spatially dynamic, however improvements are still needed to explicitly account for spatio-temporal dynamics in resilience quantification.

Chapter 3 presented a definition, methodological framework, and quantification method for disaster resilience assessment that is dynamic in both time and space and which enables the integration of multiple disaster resilience domains to provide a comprehensive description of disaster resilience (additional work published in Simonovic and Peck, 2013). This quantification method provides the ability to capture system improvements in the process of recovery (i.e. recovery levels exceeding pre-disaster levels). This is considered to be one of the key theoretical contributions of the work described in this dissertation.

Issue 2: Most existing resilience tools fail to identify thresholds as a significant contributor to the expression and assessment of dynamic disaster resilience and provide no means for its explicit inclusion in resilience quantification.

The dynamic resilience quantification expression and method presented in Chapter 3, Section 3.2.2 and the work of Simonovic and Peck (2013), was expanded conceptually and computationally to include dynamic disaster resilience quantification considering thresholds, which is described in Chapter 3, Section 3.2.3. This is considered to be one of the key theoretical contributions of the work described in this dissertation.

Issue 3: Improvements are still needed to explicitly quantitatively account for spatio-temporal dynamics in resilience assessment tools.

Disaster resilience is dynamic in time and space. Chapter 4 describes the implementation of the quantitative dynamic disaster resilience assessment methodology. A simulation tool was developed called the Disaster Resilience Simulation Tool (DRST) to provide for spatio-temporal dynamic disaster resilience assessment. It achieves this through the integration of system dynamics simulation, economic optimization, and geographic information systems (GIS) tools to account for complex, dynamic system interactions in the quantification of dynamic spatio-temporal resilience. The DRST generates tables and maps which can be used by disaster management professionals to identify where and when to implement “resilience building” measures. The benefits of tight-coupling GIS and system dynamics are published in a paper by the author in collaboration with others (Neuwirth et al., (2015)). This paper provided the foundation for the development of the DRST as presented in this dissertation. The DRST tool is considered to be one of the key application contributions of the work described in this dissertation to the field of disaster management.

6.2 Scope, Limitations, and Uncertainty

The research and applications contained herein offers one novel approach towards the dynamic expression and quantification of disaster resilience. As may be expected in any pioneering effort, there are a myriad of assumptions and limitations in this work, which can hopefully be addressed as part of future work. The following is a summary of some of the key assumptions and limitations of the work presented in this dissertation, separated into two (2) categories: key assumptions and limitations of the disaster resilience quantification framework; and limitations in the application of the framework to Metro Vancouver. Sources of potential errors and uncertainties are also described, primarily as it relates to the implementation of dynamic resilience quantification in the Metro Vancouver application.

Limitations in Disaster Resilience Quantification Framework

The quantification framework operates under the assumption that all systems maintain the same identity that they began with. Though thresholds were discussed, there are currently no methods proposed to accommodate systems which exhibit transformative behaviour if a threshold is crossed. Resilience as described in this dissertation, is considered as a systems' ability and capacity to adapt and adjust to shocks, and quickly return to a functioning state. Since this definition describes resilience in relation to the initial pre-shock functionality of the system, no attempts were made to describe transformative system behaviour as part of resilience assessment.

The metrics used to represent system resilience were based on stakeholder workshops and a review of disaster resilience literature but would benefit from ground-truthing and supporting evidence to confirm that the selected metrics are truly reflective of disaster resilient systems.

Limitations in the Application of the Framework (Metro Vancouver proof-of-concept)

The economics model as described in this research by Gertz (2015) is a valuable contribution to the field of natural disaster economics, however the existing optimization model does not properly account for iterative feedbacks between disaster resilience domains. If this model were deconstructed and rebuilt as a system as part of the dynamic simulation model, it would better be able to capture cross-domain relationships and system thresholds. In addition, the economics domain is currently represented as an optimization model, which operates to optimize system efficiencies in the various economic sectors. However, optimization of the elements in complex systems can actually reduce a systems' resilience to disturbances (Walker and Salt 2006). While not described any further in this dissertation, it is important to acknowledge this limitation which could be especially limiting for future work that considers resilience to multiple disturbances (shocks).

Hydrologic and hydraulic modelling limitations are inherent in the modelling algorithms, input data, and assumptions which are further described in Appendix G. Good engineering practice should ground-truth physical model parameters in the field. Although MFLNRO provided representative cross sections and model parameters were drawn from reliable engineering-based reports, no survey or ground truthing was completed as part of this dissertation.

The disaster resilience domains for Metro Vancouver are for illustrative purposes and form a proof-of-concept example. The expression of these domains remains underdeveloped and future research is recommended to identify additional potential resilience indicators within each of the disaster resilience domains. Furthermore, discussions with stakeholders revealed the ecological domain may play a significant role in disaster resilience and should be recognized and incorporated into future iterations of the Metro Vancouver DRST.

There remains limited operationalized research on domain capacities and what exactly contributes to disaster resilient cities (or regions). What's more, there are even fewer disaster resilience narratives for Metro Vancouver. This was acknowledged early on in the research process so a series of workshops was held between 2011 and 2015 with local stakeholders to help identify key disaster resilience domains and potential thresholds was held to address this limitation,. These stakeholder workshops successfully brought together individuals from various domains and spurred meaningful discussions on social, political, and infrastructure systems. Though there was valuable insight gained from these meetings, significant work remains in properly identifying key systems and thresholds.

A system dynamics approach to modelling cities and their component subsystems, makes the assumption of perfect mixing and homogeneity within system components and within each spatial unit (resolution of these units depends on the particular resilience domain and available data). For instance, spatial data as represented in the social resilience domain requires population data at the Dissemination Area (DA) level. This population is assumed to be uniformly distributed throughout the DA, so any description of the system at a finer resolution is not possible. This assumption applies to all resilience domains, across any number of system components. The use of Agent-Based Modelling (ABM) could resolve some of these limitations as it would capture the heterogeneity between entities and the structure of their interactions. However, ABMs are typically data intensive and face their own set of challenges including: the definition of component interactions; high data quantity requirements; high resolution, detailed data and; higher, sometimes prohibitive, model build and simulation times which subsequently may require the use of supercomputers.

Lastly, but perhaps most significantly, modelling and simulation is data intensive. The availability and quality of data required to develop and run spatio-temporal simulations is acknowledged as a serious limitation in this work. However, the author is of the belief that it's better to build simulation models based on a series of assumptions than to entirely abandon the effort altogether. The DRST, as with any other simulation model, should be considered a "living tool" which can continually be improved and updated to include new data and reflect new attitudes as the resilience landscape evolves.

Sources of Potential Errors and Uncertainties

It's also important to identify potential sources of errors and uncertainties to make more informed and relevant decision making and minimize the potential for maladaptation. Since this dissertation focused on developing a disaster resilience assessment framework and methodology for implementation, it may be considered as part of the pioneering efforts in disaster resilience quantification. Though this dissertation offers just one of multiple ways in which resilience can be quantified, it was intended to lay the foundation for future work in spatio-temporal dynamic disaster resilience assessment. Since the work presented in this dissertation may be considered cutting edge, there are many sources of potential errors and uncertainties which remain unresolved, including:

- Future climate change emissions trajectories used in hazard modelling;
- Uncertainties in the appropriateness of some of the data processing algorithms;
- The degree to which resilience performance metrics reflect real-world capacities and resilience;
- Spatial accuracy and attribute classifications of GIS data;
- Aggregation errors in incomplete temporal and spatial datasets; and
- Future system changes in societal and political priorities that were used to derive appropriate adaptation options and estimate funding mechanisms.

Complex issues (and subsequently complex systems) are often characterized by various types and sources of uncertainties. Common way to approach uncertainties in practice, include: sensitivity analyses and Monte Carlo simulations. Although neither of these methods was employed as part of this work, future iterations of the DRST would benefit from an explicit consideration and evaluation of uncertainties. Then the DRST can help identify the most robust strategies that perform well over a range of simulation scenarios. It is important to evaluate and communicate levels and sources of uncertainties so decision makers can understand the implications on their decisions and facilitate improved decision making. One way to help curb the impacts of uncertainty is by promoting adaptive capacity which helps prepare organizations to cope with a range of potential impacts.

6.3 Recommendations for Future Research

The research in this dissertation has already inspired additional work. The STDRM and generic resilience quantification model as provided in this dissertation was applied to research by Srivastav and Simonovic (2014) to simulate dynamic resilience of a railway exposed to flooding. The STDRM and dynamic resilience calculation inspired work by Irwin et al. (2016) to develop ResilSIM decision support tool, as applied to a case study in the City of London, ON. In 2016 the dynamic resilience description was expanded by Simonovic and Arunkumar (2016) to be applied to the operation of dams and reservoirs. Most recently, the STDRM and resilience calculation was applied to a multi-hazard resilience model of interdependent infrastructure systems by Kong and Simonovic (2018), Zhang et al. (2018a), Zhang et al. (2018b), Kong and Simonovic (2019), and Kong et al. (2019).

Although it is evident that the STDRM and resilience calculation has already progressed into research performed by others, there are many additional opportunities to improve and advance the work presented in this dissertation. As such, this section further focuses on four distinct sets of recommendations for future work: modifying the current DRST to permit simulation of other types of hazards; extension of the current DRST to include additional disaster impacts and domains; use of resilience modelling and simulation outputs; and lastly, more general recommendations for disaster resilience assessment.

6.3.1 Refinement of the DRST

A few of the next logical steps in the refinement of the DRST include: ground-truthing model assumptions; explicitly exploring model uncertainties; and evaluating the numerical model. Although each one of those tasks is a significant undertaking, one of the benefits provided by the DRST is that it’s relatively simple to modify model parameters and flexibility was built into the middleware program to accept new input data, as it becomes available. An additional benefit provided by the DRST is it can be used to improve decision-making under uncertainty since it can be easily altered to represent various modeling assumptions and simulation scenarios.

In addition, refinement of the DRST would be desirable to address research questions such as: What are possible adaptation options for other hazards?

The DRST application in BC considered high-flow large-scale flood events. Modelling low-peak, long-duration, high-volume events is recommended for future work as there may be significant impacts from these types of events and systems are likely to respond differently under these conditions.

Although BC is an area of high seismic activity, the impacts of seismic events on flood protection structures (e.g. dike damages or failures) are not considered in the scope of this work. However, a separate study by Golder Associates (2014) has estimated that damage from large-scale flooding due to seismic activity could reach $50 billion (CAD). Within delta areas in particular, there is a high likelihood of having coincidental high water and earthquake loadings (Golder Associates, 2014). The DRST was developed for assessing the impacts of climate change influenced riverine flooding and sea level rise. However, the tool could be adapted for additional types of applications. This particular example would require modification of the input hazard as well as a redefinition of resilience impacts to include the consequences of earthquakes and tsunamis.

If possible, it would be ideal for the DRST to be extended to simulate the behavior of multiple simultaneous hazards, or to run multiple hazards back-to-back and see the impacts on resilience.

6.3.2 Extension of the DRST

The current version of the DRST should be extended to provide a more complete representation of disaster resilience. An extension of the tool could help identify whether there are sufficient levels of detail in resilience quantification to be able to accurately capture the complexities of disaster resilience.

A more comprehensive definition of resilience impacts and capacities is required. This is an ongoing process that could become more refined. The DRST could benefit from the inclusion of environmental and biological impacts, which may have complex interactions and an influence on human health. Going forward, the DRST should be considered a living tool, constantly evolving to test new adaptation options which may change based on political and organizational priorities. As technology changes and as the resilience landscape changes, the model will require updating.

The impacts of estuarial flooding were not considered as part of this research, however additional research could be pursued to identify the influence of estuary systems in: (i) the definition of physical hazard, and (ii) to determine whether combined salt-freshwater environments plays a significant role in flooding impacts and disaster resilience. To achieve this would require a sophisticated understanding of estuary systems and how salt water affects environmental and physical (built) systems.

6.3.3 Resilience Outputs

The output of simulations using the DRST – and resilience models in general – could be used for more detailed disaster management decisions. For example, if simulation results determined that building additional disaster shelters was the best option to increase disaster resilience, the resilience maps could be used to identify the areas which may benefit most from addition of new disaster resilience shelters. Locations with low disaster resilience could be selected as candidates for building the new shelters. Furthermore, a disaster shelter site suitability analysis could be completed using spatial analysis techniques similar to those implemented in the DRST (spatial queries, attribute queries, and descriptive statistics) to determine the best locations to construct disaster shelters.

6.3.4 Model Evolution

To address some of the limitations of the proposed resilience modelling approach and SD model, a hybrid SD-ABM modelling method could be used to better describe some of the resilience domains, capture systems which operate on the individual agent level, and offer some beneficial trade-offs between these two modelling approaches. This could help capture cross-scale interactions for a more holistic description of resilience.

References

Acosta, J. D., Towe, V. L., Chari, R., Uscher-Pines, L., Sellers, C., & Chandra, A. (2015). The Hungrier Games: Disaster Resilience Skills for Youth [Toolkit]. Research ANd Development (RAND) Corporation. Retrieved from https://www.rand.org/well-being/community-health-and-environmental-policy/centers/resilience-in-action/community-resilience-toolkits.html

Acosta, J. D., Chandra, A., Xenakis, L., Varda, D. M., Eros-Sarnyai, M., Eisenman, D., … Sprong, S. (2015). Partnerships for Recovery Across The Sectors (PRACTIS) Toolkit [Toolkit]. Research ANd Development (RAND) Corporation. Retrieved from https://www.rand.org/well-being/community-health-and-environmental-policy/centers/resilience-in-action/community-resilience-toolkits.html

Acosta, J. D., Chandra, A., Towe, V. L., Zhao, Y., & Lu, Y. (2016). ENGAGED Toolkit: Improving the Role of Nongovernmental Organizations in Disaster Response and Recovery [Toolkit]. Research ANd Development (RAND) Corporation. Retrieved from https://www.rand.org/well-being/community-health-and-environmental-policy/centers/resilience-in-action/community-resilience-toolkits.html

Adger, W. N. (2007). Ecological and social resilience. In G. Atkinson, S. Dietz, & E. Neumayer (Eds.), *Handbook of Sustainable Development* (pp. 78–90). Cheltenham, UK: Elgar.

Agam, N. Development of Inundation Maps for the Vancouver Coastline Incorporating the Effects of Sea Level Rise and Extreme (2014). *Electronic Thesis and Dissertation Repository*, 2613.

Ahman, S., & Simonovic, S. P. (2000). System dynamics modeling of reservoir operations for flood management. *Journal of Computing in Civil Engineering*, *14*(3), 190–198.

Akanda, A. S., & Hossain, F. (2012). The Climate-Hater-Health Nexus in Emerging Megacities. *Eos*, *93*(37), 353–354. https://doi.org/10.1029/2012EO370001

Andre, A., Glen, A., Good, J., Gutsell, J., Hayat, I., Kershaw, J., Miller, J., Nash, J., & Relkoff, T. (2000). *Vulnerability of the Cellular Telecommunication Network in the Lower Mainland British Columbia*. Geography 452, Advanced Issues in Geographical Information Systems, Department of Geography, Simon Fraser University.

Anslow, F. (2017, January). BC On Track to Set New Temperature Record in 2016. *University of Victoria: Pacific Climate Impacts Consortium*.

Armington, P. (1969) A Theory of Demand for Products Distinguished by Place of Production, *International Monetary Fund Staff Papers, XVI,* 159-78.

Arnell, N., Liu, C., Compagnucci, R., Da Cunha, L., Hanaki, K., Howe, C., … Döll, P. (2001). Hydrology and Water Resources. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, & K. S. White (Eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability* (pp. 191–234). New York, NY: Cambridge University Press.

Atukorala, U., Hawson, H., Mylleville, B., & Williams, R. (2014). *Seismic Design Guidelines for Dikes, 2nd Edition*. Squamish, BC: Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), British Columbia.

Aven, T. (2011). On Some Recent Definitions and Analysis Frameworks for Risk, Vulnerability, and Resilience. *Risk Analysis*, *31*(4), 515–522. https://doi.org/10.1111/j.1539-6924.2010.01528.x

Ayyub, B. M. (2015). Practical Resilience Metrics for Planning, Design, and Decision Making. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *1*(2). https://doi.org/10.1061/AJRUA6.0000826

Balica, S. F., Wright, N. G., & van der Meulen, F. (2012). A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Natural Hazards*, *64*(1), 73–105. https://doi.org/10.1007/s11069-012-0234-1

Bathiany, S., Notz, D., Mauritsen, T., Raedel, G., & Brovkin, V. (2016). On the Potential for Abrupt Arctic Winter Sea Ice Loss. *Journal of Climate*, *29*(7), 2703–2719. https://doi.org/10.1175/JCLI-D-15-0466.1

Bennett, E. M., Cumming, G. S., & Peterson, G. D. (2005). A Systems Model Approach to Determining Resilience Surrogates for Case Studies. *Ecosystems*, *8*, 945–957. https://doi.org/10.1007/s10021-005-0141-3

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., … Unnikrishnan, A. (2007). Observations: Oceanic Climate Change and Sea Level. In *Climate Change 2007: The Physical Science Basis* (pp. 385–432). Cambridge, U.K.: Cambridge University Press.

British Columbia Ministry of Envrionment. (2016). *Indicators of Climate Change for British Columbia, 2016 Update*.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., … Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. https://doi.org/10.1193/1.1623497

Burn, D. H., & Whitfield, P. H. (2016). Changes in floods and flood regimes in Canada. *Canadian Water Resources Journal*, *41*(1–2), 139–150. https://doi.org/10.1080/07011784.2015.1026844

Campbell, J. E., & Shin, M. (2011). Geospatial Analysis I: Vector Operations. In *Essentials of Geographic Information Science v. 1.0* (pp. 167–185). Irvington, NY.

Cann, K. F., Thomas, D. R., Salmon, R. L., Wyn-Jones, A. P., & Kay, D. (2013). Extreme water-related weather events and waterborne disease. *Epidemiology and Infection*, *141*(4), 671–686. https://doi.org/10.1017/S0950268812001653

CARE: Climate Change and Resilience Platform (CCRP). (2018). Resilience Marker [Toolkit]. Retrieved from https://careclimatechange.org/cares-resilience-marker/

CARE: Climate Change and Resilience Platform (CCRP). (2018). *Resilience Marker Guidance note*.

CARE: Climate Change and Resilience Platform (CCRP). (2018). *Resilience Marker Vetting Form*.

Carrera, L., Standardi, G., Bosello, F., & Mysiak, J. (2015). Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling. *Environmental Modelling and Software*, *63*, 109–122. https://doi.org/10.1016/j.envsoft.2014.09.016

Chemtob, C. M., Nakashima, J. P., & Hamada, R. S. (2002). Psychosocial intervention for postdisaster trauma symptoms in elementary school children: A controlled community field study. *Archives of Pediatrics and Adolescent Medicine*, *156*(3), 211–216. https://doi.org/10.1001/archpedi.156.3.211

Clinton, H. R. (2006). *It takes a village*. New York, NY: Simon & Schuster.

Cochrane, H. C. (1974). *Social science perspectives on the coming San Francisco earthquake:Economic impact, prediction, and reconstruction*. Boulder, Colorado.

Cook, J., Nuccitelli, D., Green, S., Richardson, M., Winkler, B., Painting, R., … Skuce, A. (2016). Quantifying the consensus on anthropogenic global warming in the scientific literature. *Environmental Research Letters*, *8*(2), 1–7. https://doi.org/10.1088/1748-9326/8/2/024024

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, *18*(4), 598–606.

Cutter, S., Ahearn, J., Amadei, B., Crawford, P., Eidee, E. A., Galloway, G. E., … Zoback, M. Lou. (2013). Disaster Resilience: A National Imperative. *Environment: Science and Policy for Sustainable Development*, *55*(2), 25–29.

Cutter, S. L. (2016). The landscape of disaster resilience indicators in the USA. *Natural Hazards*, *80*(2), 741–758. https://doi.org/10.1007/s11069-015-1993-2

Datar, A., Liu, J., Linnemayr, S., & Stecher, C. (2011). The Impact of Natural Disasters on Child Health and Investments in Rural India. In *Social Science and Medicine* (Vol. 76).

de Bruijn, K., Buurman, J., Mens, M., Dahm, R., & Klijn, F. (2017). Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science and Policy*, *70*, 21–30. https://doi.org/https://doi.org/10.1016/j.envsci.2017.02.001

Dobbs, R., Remes, J., Manyika, J., Roxburgh, C., Smit, S., & Schaer, F. (2012). Urban world: Cities and the rise of the consuming class. In *McKinsey Global Institute*.

Dunlap, D. (2017, April 4). Preparing for the Future Using Lessons From Hurricane Sandy. *New York Times*.

Englum, L., & Grannis, J. (2017). Learning to Rebuild with Resilience. Retrieved October 17, 2018, from 100 Resilient Cities website: https://100resilientcities.org/learning-build-resilience/

Environment Canada. (2013). Canada's top ten weather stories of 2013. Retrieved January 5, 2019, from Environment and Climate Change Canada website: http://www.ec.gc.ca/meteo-Weather/default.asp?lang=En&n=5BA5EAFC-1&offset=3&toc=show

Environmental Systems Research Institute (ESRI). (2011). *ArcGIS Desktop version 10: ArcMap*. Redlands, CA, USA: Environmental Systems Research Institute.

Eum, H., Sredojevic, D., & Simonovic, S. P. (2010). Engineering Procedure for the Climate Change Flood Risk Assessment in the Upper Thames River Basin. *Journal of Hydrologic Engineering*, *16*(7), 608–612. https://doi.org/10.1061/(asce)he.1943-5584.0000346

Fan, L. (2013). Disaster as opportunity? Building back better in Aceh, Myanmar and Haiti. In *Humanitarian Policy Group (HPG) Working Paper*. London: Overseas Development Institute.

Federal Emergency Management Agency (FEMA). (1996). *Guide for All-Hazard Emergency Operations Planning*. Washington, D.C.

Federal Emergency Management Agency (FEMA). (2018). *National Flood Insurance Program (NFIP) Community Rating System (CRS) Brochure*. Washington, D.C.

Forrester, J. W. (2007). *System dynamics-a personal view of the first fifty years*. *22*(2/3), 345–358. https://doi.org/10.1002/sdr

Forrester, J. W. (1969). *Urban Dynamics*. Cambridge, Massachusetts: Massachusetts Institute of Technology (MIT) Press.

Frumkin, H. (Ed.). (2010). *Environmental Health: From Global to Local* (2nd ed.). San Francisco, CA: John Wiley & Sons, Inc.

Gastélum, J. R., Valdés, J. B., & Stewart, S. (2010). A System Dynamics Model to Evaluate Temporary Water Transfers in the Mexican Conchos Basin. *Water Resource Management*, *24*(7), 1285–1311.

General Algebraic Modeling System (GAMS) Development Corporation. (1987). *General Algebraic Modeling System (GAMS)*. Washington, D.C., USA.

Gertz, A. B., Davies, J. B., & Black, S. L. (2019). A CGE Framework for Modeling the Economics of Flooding and Recovery in a Major Urban Area. *Risk Analysis*, *39*(6), 1314–1341. https://doi.org/10.1111/risa.13285

Gertz, A. B., & Jim MacGee, S. (2015). *On the Economics of Climate Change and its Effects*. The University of Western Ontario.

Gesch, D. B. (2009). Analysis of Lidar Elevation Data for Improved Identification and Delineation of Lands Vulnerable to Sea-Level Rise. *Journal of Coastal Research*, (Special Issue 53), 49–58. https://doi.org/10.2112/SI53-006.1

Global Nutrition Cluster. (2008). A Toolkit for Addressing Nutrition in Emergency Situations. In *IASC Global Nutrition Cluster, UNICEF*. New York, NY.

Godschalk, D. R. (2003). Urban Hazard Mitigation: Creating Resilient Cities. *Natural Hazards Review*, *4*(3), 136–143. https://doi.org/10.1061/(asce)1527-6988(2003)4:3(136)

Goldmann, E., & Galea, S. (2014). Mental Health Consequences of Disasters. *Annual Review of Public Health*, *35*, 169–183. https://doi.org/10.1146/annurev-publhealth-032013-182435

Goldstein, B. E., Wessells, A. T., Lejano, R., & Butler, W. (2015). Narrating Resilience: Transforming Urban Systems Through Collaborative Storytelling. *Urban Studies*, *52*(7), 1285–1303. https://doi.org/10.1177/0042098013505653

Gopinath, G., Swetha, T. V., & Ashitha, M. K. (2014). Automated extraction of watershed boundary and drainage network from SRTM and comparison with Survey of India toposheet. *Arabian Journal of Geosciences*, *7*, 2625–2632. https://doi.org/10.1007/s12517-013-0919-0

Grannis, J., Arroyo, V., Hoverter, S., Goetz, M., Bennett, A., DeWeese, J., … Deas, M. (2016). *Rebuilding with Resilience: Lessons from the Rebuild by Design Competition After Hurricane Sandy*. Washington, D.C.: Georgetown Climate Center.

Grossmann, W. D., & Eberhardt, S. (1992). Geographical information systems and dynamic modelling: Potentials of a new approach. *The Annals of Regional Science*, *26*, 53–66. https://doi.org/10.1007/BF01581480

Guha, A., & Lawrence, G. A. (2013). *Estuary Classification Revisited*. *43*, 1566–1571. https://doi.org/10.1175/JPO-D-12-0129.1

Gupta, M., Velasquez, G., Nag, S., Panda, A., Kuberan, R., Hari, K., & Suryono, R. (2010). *Building back better for next time*. Bangkok, Thailand: UNISDR Secretariat Asia and Pacific.

Haimes, Y. Y. (2011). Responses to Terje Aven's paper: On Some Recent Definitions and Analysis Frameworks for Risk, Vulnerability, and Resilience. *Risk Analysis, 31*(5), 689–692. https://doi.org/10.1111/j.1539-6924.2011.01587.x

Hallegatte, S. (2008). An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina. *Risk Analysis*, *28*(3), 779–799. https://doi.org/10.1111/j.1539-6924.2008.01046.x

Hamman, J. J., Nijssen, B., Bohn, T. J., Gergel, D. R., & Mao, Y. (2018). The Variable Infiltration Capacity model version 5 (VIC-5): infrastructure improvements for new applications and reproducibility. *Geoscientific Model Development*, *11*, 3481–3496. https://doi.org/10.5194/gmd-11-3481-2018

Hammond, M. J., Chen, A. S., Butler, D., Djordjevic, S., & Manojlovic, N. (2013). A framework for flood impact assessment in urban areas. *Floods: From Risk to Opportunity*, 41–47.

Henry, K. (2016). *Reaching Resilience: CARE Bangladesh Strategy to Disaster Risk Reduction and Climate Change Adaptation*. Dhaka, Bangladesh: CARE Bangladesh.

Henstra, D. (2012). Toward the Climate-Resilient City: Extreme Weather and Urban Climate Adaptation Policies in Two Canadian Provinces. *Journal of Comparative Policy Analysis: Research and Practice*, *14*(2), 175–194. https://doi.org/10.1080/13876988.2012.665215

Heymann, D. (2016). Explanation of Terms. In *Control of Communicable Diseases Manual*. https://doi.org/10.2105/CCDM.2745.156

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., … Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety*, *145*, 47–61. https://doi.org/10.1016/j.ress.2015.08.006

Infrastructure Canada. (2018). Climate Lens [Toolkit]. Retrieved from https://www.infrastructure.gc.ca/pub/other-autre/cl-occ-eng.html

Infrastructure Canada. (2018). *Climate Lens General Guidance Version 1.1*. Retrieved from https://www.infrastructure.gc.ca/alt-format/pdf/guidelines-lignes-directrices/climate-lens-general-guidance-2018-05-28.pdf

Inter-Agency Standing Committee (IASC). (2008). Nutrition Cluster A Toolkit for Addressing Nutrition in Emergency Situations. *Nutrition*, (June).

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (C. . Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, … L. L. White, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2000). *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, R. K. Pachauri, & L. A. Meyer, Eds.). Geneva, Switzerland: IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Core writing team, R. . Pachauri, & A. Reisinger, Eds.). Geneva, Switzerland: IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, … P. M. Midgley, Eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change* (V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, … T. Waterfield, Eds.). In Press: IPCC.

Irwin, S., Schardong, A., Simonovic, S. P., & Nirupama, N. (2016). ResilSIM-A Decision Support Tool for Estimating Resilience of Urban Systems. *Water, 8*(9), 377. https://doi.org/10.3390/w8090377

Jevrejeva, S., Jackson, L. P., Riva, R. E. M., Grinsted, A., & Moore, J. C. (2016). Coastal sea level rise with warming above 2 °C. *Proceedings of the National Academy of Sciences*, *113*(47), 13342–13347. https://doi.org/10.1073/pnas.1605312113

Joerin, J., Shaw, R., Takeuchi, Y., & Krishnamurthy, R. (2012). Assessing community resilience to climate-related disasters in Chennai, India. *International Journal of Disaster Risk Reduction*, *1*, 44–54. https://doi.org/10.1016/j.ijdrr.2012.05.006

Jones, E., & Faas, A. J. (Eds.). (2016). *Social Network Analysis of Disaster Response, Recovery, and Adaptation*. Oxford, UK and Cambridge, MA, USA: Butterworth-Heinemann.

Keim, M. E. (2008). Building Human Resilience: The Role of Public Health Preparedness and Response As an Adaptation to Climate Change. *American Journal of Preventive Medicine*, *35*(5), 508–516. https://doi.org/10.1016/j.amepre.2008.08.022

Kelman, I. (2015). Climate Change and the Sendai Framework for Disaster Risk Reduction. *International Journal of Disaster Risk Science*, *6*, 117–127. https://doi.org/10.1007/s13753-015-0046-5

Kerle, N., & Müller, A. (2013). Megacities and Natural Hazards. In P. T. Bobrowsky (Ed.), *Geographic Information Systems (GIS) and Natural Hazards* (pp. 660–664). https://doi.org/10.1007/978-1-4020-4399-4_231

Kerr Wood Leidal Associates (KWA) Ltd. (2011). *Coastal Flood Mapping Guidelines and Specifications, Final Report*. Surrey, BC: Ministry of Forests, Lands & Natural Reosurce Operations.

Kesavan, P. C., & Swaminathan, M. S. (2006). Managing extreme natural disasters in coastal areas. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *364*, 2191–2216. https://doi.org/10.1098/rsta.2006.1822

Khan, S., Yufeng, L., & Ahmad, A. (2009). Analysing complex behaviour of hydrological systems through a system dynamics approach. *Environmental Modelling and Software*, *24*, 1363–1372. https://doi.org/10.1016/j.envsoft.2007.06.006

Khyrina, A. F. A. S., Burairah, H., & Abd Samad, H. B. (2012). A Systems Thinking in Natural Disaster Management: Evacuation Preparedness. *Advances in Economics, Risk Management, Political and Law Science*, 384–389.

Kjeldsen, T. R., & Rosbjerg, D. (2004). Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems. *Hydrological Sciences Journal*, *49*(5), 755–767. https://doi.org/10.1623/hysj.49.5.755.55136

Klise, K. A., Moriarty, D., Bynum, M. L., Murray, R., Burkhardt, J., & Haxton, T. M. (2019). *Water Network Tool for Resilience (WNTR) User Manual* (EPA/600/R-17/264). Washington, D.C.: US Environmental Protection Agency.

Kong, J., & Simonovic, S. P. (2018). A model of interdependent infrastructure system resilience. *International Journal of Safety and Security Engineering*, *8*(3), 377–389. https://doi.org/10.2495/SAFE-V8-N3-377-389

Kong, J., Simonovic, S. P., & Zhang, C. (2019). Sequential Hazards Resilience of Interdependent Infrastructure System: A Case Study of Greater Toronto Area Energy Infrastructure System. *Risk Analysis*, *39*(5), 1141–1168. https://doi.org/10.1111/risa.13222

Kong, J., & Simonovic, S. P. (2019). Probabilistic Multiple Hazard Resilience Model of an Interdependent Infrastructure System. *Risk Analysis : An Official Publication of the Society for Risk Analysis, Risk Analysis*. https://doi.org/10.1111/risa.13305

Kreibich, H., & Bubeck, P. (2013). Natural Hazards: Direct Costs and Losses Due to the Disruption of Production Processes. In *Global Assessment Report on Disaster Risk Reduction 2015*. Postdam, Germany.

Kuzņecova, T., & Romagnoli, F. (2014). System Dynamics approach within the context of city resilience and urban metabolism. *9th International Conference "Environmental Engineering."* Vilnius, Lithuania.

Lentz, E. E., Thieler, E. R., Plant, N. G., Stippa, S. R., Horton, R. M., & Gesch, D. B. (2016). Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. *Nature Climate Change*, *6*, 696–700. https://doi.org/10.1038/nclimate295

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research*, *99*(D7), 14415–14428. https://doi.org/10.1029/94JD00483

Lin, W., Chou, W., Lin, C., Huang, P., & Tsai, J. (2005). Automated suitable drainage network extraction from digital elevation models in Taiwan's upstream watersheds. *Hydrological Processes*, *20*(2), 289–306.

Lohmann,D, Raschke, E., Nijssen, B. & Lettenmaier, D.P. (1998). Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, *Hydrological Sciences Journal*, 43:1, 131-141, DOI: 10.1080/02626669809492107

Luther, L. (2008). *CRS Report for Congress, Disaster Debris Removal After Hurricane Katrina: Status and Associated Issues*. USA: Congressional Research Service.

Luther, L. (2011). *CRS Report for Congress, Managing Disaster Debris: Overview of Regulatory Requirements, Agency Roles, and Selected Challenges*. USA: Congressional Research Service.

Malilay, J., Henderson, A., McGeehin, M., & Flanders, W. D. (1997). Estimating Health Risks from Natural Hazards Using Risk Assessment and Epidemiology. *Risk Analysis*, *17*(3), 353–358. https://doi.org/10.1111/j.1539-6924.1997.tb00873.x

Masud, M. B., Soni, P., Shrestha, S., & Tripathi, N. K. (2016). Changes in Climate Extremes over North Thailand, 1960–2099. *Journal of Climatology*, 1–18. https://doi.org/10.1155/2016/4289454

McBean, G., & Rodgers, C. (2010). Climate hazards and disasters: the need for capacity building. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(6), 871–884. https://doi.org/10.1002/wcc.77

Metro Vancouver. (2017). About Us. Retrieved July 22, 2018, from http://www.metrovancouver.org/about/Pages/default.aspx

Metro Vancouver. (2018). *Climate 2050 Strategic Framework*. Burnaby, BC: Metro Vancouver.

Metro Vancouver. (2010). *Corporate Climate Action Plan*. Burnaby, BC: Metro Vancouver.

Ministry of Forests Lands Natural Resource Operations (MFLNRO). (2014). *Fraser River Design Flood Level Update - Hope to Mission, Final Report*. Surrey, BC.

Nan, C., & Sansavini, G. (2017). A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering and System Safety*, *157*, 35–53. https://doi.org/10.1016/j.ress.2016.08.013

Nastev, M., & Todorov, N. (2013). Hazus: A standardized methodology for flood risk assessment in Canada. *Canadian Water Resources Journal*, *38*(3), 223–231. https://doi.org/10.1080/07011784.2013.801599

National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory: California Institute of Technology. (2015). NASA Holds Media Briefing on Carbon's Role in Earth's Future Climate. Retrieved March 8, 2019, from www.jpl.nasa.gov/news/news.php?feature=4749

National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory: California Institute of Technology. (2009). Global Climate Change Vital Signs of the Planet: The Causes of Climate Change. Retrieved June 17, 2019, from https://climate.nasa.gov/causes/

National Oceanic and Atmospheric Administration (NOAA). (2017). *Detailed Method for Mapping Sea Level Rise Inundation*. Office for Coastal Management: National Oceanic and Atmospheric Administration.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources*, *32*, 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348

Neuwirth, C., Peck, A., & Simonović, S. P. (2015). Modeling structural change in spatial system dynamics: A Daisyworld example. *Environmental Modelling and Software*, *65*, 30–40. https://doi.org/10.1016/j.envsoft.2014.11.026

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness. *American Journal of Community Psychology*, *41*(1–2), 127–150. https://doi.org/10.1007/s10464-007-9156-6

Northwest Hydraulic Consultants (NHC). (2008). *Fraser River Hydraulic Model Update, Final Report*. Surrey, BC: Ministry of Envrionment.

O'Neill, H. K., McLean, A. J., Kalis, R., & Shultz, J. M. (2016). Disaster averted: Community resilience in the face of a catastrophic flood. *Disaster Health*, *3*(3), 67–77. https://doi.org/10.1080/21665044.2016.1219575

Organisation for Economic Co-operation and Development (OECD). (2014). *Guidelines for Resilience Systems Analysis*. OECD Publishing.

Orr, D. (2014). Systems Thinking and the Future of Cities. *The Solutions Journal*, *5*(1), 54–61.

Pacific Climate Impacts Consortium (PCIC). (2014). Gridded Hydrologic Model Output. Retrieved May 26, 2019, from http://www.pacificclimate.org/

Pant, R., Barker, K., & Zobel, C. (2014). Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors. *Reliability Engineering & System Safety*, *125*, 92–102.

Paton, D., & Johnston, D. (2006). *Disaster Resilience: An Integrated Approach*. Springfield, Illinois, USA: Charles C Thomas Publishing Ltd.

Patz, J. A., Frumkin, H., Holloway, T., Vimont, D. J., & Haines, A. (2014). Climate Change: Challenges and Opportunities for Global Health. *Journal of the American Medical Association*, *312*(15), 1565–1580. https://doi.org/10.1001/jama.2014.13186

Peacock, W.G., Brody, S., Seitz, W., Merrell, W., Vedlitz, A., Zahran, S., Harriss, R., Stickney, R., (2010). Advancing Resilience of Coastal Localities: Developing Implementing, and Sustaining the Use of Coastal Resilience Indicators: A Final Report. *Hazard Reduction and Recovery Center*.

Peck, A., Neuwirth, C., & Simonovic, S.P. (2014). Coupling System Dynamics with Geographic Information Systems: CCaR Project Report Water Resources Research Report no. 086, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 60 pages. ISBN: (print) 978-0-7714-3069-5; (online) 978-0-7714-3070-1.

Peck, A. & Simonovic, S.P. (2013). Coastal Cities at Risk (CCaR): Generic System Dynamics Simulation Models for Use with City Resilience Simulator. Water Resources Research Report no. 083, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 55 pages. ISBN: (print) 978-0-7714-3024-4; (online) 978-0-7714-3025-1.

Pomeroy, J. W., Stewart, R. E., & Whitfield, P. H. (2015). The 2013 flood event in the South Saskatchewan and Elk River basins: Causes, assessment and damages. *Canadian Water Resources Journal*, *41*(1–2), 105–117. https://doi.org/10.1080/07011784.2015.1089190

Radić, V., & Hock, R. (2011). Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. *Nature Geoscience*, *4*, 91–94. https://doi.org/10.1038/ngeo1052

Radzicki, M. J., & Robert, T. (1997). *Introduction to System Dynamics: A systems approach to understanding complex policy issues*. United States Department of Energy.

Ramezankhani, A., & Najafiyazdi, M. (2006). A System Dynamics Approach on Post-Disaster Management: A Case Study of Bam Earthquake, December 2003. *Proceedings of the 26th International Conference of the System Dynamics Society*.

Rose, A. (2017). *Defining and Measuring Economic Resilience* (Integrated). Singapore: Springer.

Sanders, P., & Sanders, F. (2004). Spatial urban dynamics: a vision on the future of urban dynamics. In *Paper presented at the 22nd International Conference of the System Dynamics Society*. Oxford.

Schnorbus, M., Werner, A., & Bennett, K. (2014). Impacts of climate change in three hydrologic regimes in British Columbia, Canada. *Hydrological Processes*, *28*, 1170–1189. https://doi.org/10.1002/hyp.9661

Sharifi, A. (2016). A critical review of selected tools for assessing community resilience. *Ecological Indicators*, *69*, 629–647. https://doi.org/10.1016/j.ecolind.2016.05.023

Sharma, D., & Babel, M. S. (2013). Application of downscaled precipitation for hydrological climate-change impact assessment in the upper Ping River Basin of Thailand. *Climate Dynamics*, *41*(9–10), 2589–2602. https://doi.org/10.1007/s00382-013-1788-7

Shaw, R., Takeuchi, Y., Joerin, J., Fernandez, G., 2010. Climate and Disaster Resilience Initiative Capacity-Building Program. Kyoto University, Kyoto, Japan.

Shepherd, A., Wingham, D., Wallis, D., Giles, K., Laxon, S., & Sundal, A. V. (2010). Recent loss of floating ice and the consequent sea level contribution. *Geophysical Research Letters*, *37*(13), 1–5. https://doi.org/10.1029/2010GL042496

Shrestha, R. R., Schnorbus, M. A., Werner, A. T., & Berland, A. J. (2012). Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin, British Columbia, Canada. *Hydrological Processes*, *26*, 1840–1860. https://doi.org/10.1002/hyp.9283

Shrestha, S. (2014). Assessment of water availability under climate change scenarios in Thailand. In *Climate Change Impacts and Adaptation in Water Resources and Water Use Sectors* (pp. 9–23). https://doi.org/10.1007/978-3-319-09746-6

Shrubsole, D., Brooks, G., Halliday, R., Haque, E., Kumar, A., Lacroix, J., … Simonovic, S. P. (2003). An Assessment of Flood Risk Management in Canada. *ICLR Research Paper Series, No. 28*, 71.

Siddiqi, Y., & Salem, M. (2012). A Social Accounting Matrix for Canada. *Statistics Canada, Analytical Studies Branch, Economic Analysis (EA) Research Paper Series*, *2012*.

Simonovic, S. (2009). *Managing Water Resources: Methods and Tools for a Systems Approach*. Paris, France and London, UK: UNESCO Publishing.

Simonovic, S. P., & Peck, A. (2013). Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities Quantification Framework. *British Journal of Environment and Climate Change*, *3*(3), 378–401. https://doi.org/10.9734/bjecc/2013/2504

Simonovic, S., & Arunkumar, R. (2016). Comparison of static and dynamic resilience for a multipurpose reservoir operation. *Water Resources Research*, *5*(3), 8630–8649. https://doi.org/10.1002/ 2016WR019551

Simonovic, S., & Arunkumar, R. (2016). Comparison of static and dynamic resilience for a multipurpose reservoir operation. *Water Resources Research*, *52*(11), 8630–8649. https://doi.org/https://doi.org/10.1002/2016WR019551

Simonovic, S. P., Irwin, S., & Schardong, A. (2016). Resilience simulation tool (ResilSIM) [Toolkit]. London, ON. Retrieved from https://resilsim-uwo.ca/About

Srivastav, R., & Simonovic, S. P. (2014). *Simulation of Dynamic Resilience : A Railway Water Resources Research Report Simulation of Dynamic Resilience : A Railway Case Study*. London, ON: Western University.

Statistics Canada. (2018). Dissemination Area (DA): Plain Language Definition. Retrieved November 22, 2018, from Statistics Canada Illustrated Glossary website: https://www150.statcan.gc.ca/n1/pub/92-195-x/2011001/geo/da-ad/da-ad-eng.htm

Steinfeld, C. M. M., Kingsford, R. T., & Laffan, S. W. (2013). Semi-automated GIS techniques for detecting floodplain earthworks. *Hydrological Processes*, *27*, 579–591. https://doi.org/10.1002/hyp.9244

Stenström, P. (2004). Hydraulics and mixing in the Hudson River estuary: A numerical model study of tidal variations during neap tide conditions. *Journal of Geophysical Research: Oceans*, *109*(C4). https://doi.org/10.1029/2003JC001954

Towe, V. L., Chandra, A., Acosta, J. D., Chari, R., Uscher-Pines, L., & Sellers, C. (2015). Community Resilience: Learn and Tell Toolkit [Toolkit]. Research ANd Development (RAND) Corporation. Retrieved from https://www.rand.org/well-being/community-health-and-environmental-policy/centers/resilience-in-action/community-resilience-toolkits.html

United Nations (UN). (1997). *United Nations Framework Convention on Climate Change Chapter XXVII: Environment*, *Kyoto Protocol*. Kyoto, Japan: United Nations.

United Nations (UN). (1992). *United Nations Framework Convention on Climate Change Treaty Chapter XXVII. Environment*. New York, NY: United Nations.

United Nations Department of Economic and Social Affairs (UN DESA). (2018). Revision of World Urbanization Prospects. Retrieved May 11, 2019, from United Nations Department of Economic and Social Affairs website: https://population.un.org/wup/Publications/

United Nations International Strategy for Disaster Reduction (UNISDR). (2005). Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters. In *Extracted from the final report of the World Conference on Disaster Reduction (A/CONF.206/6)*. Geneva, Switzerland; Nairobi, Kenya and Bangkok, Thailand.

UNDRR. (2017). Disaster Resilience Scorecard for Cities. *The United Nations Office for Disaster Reduction*, (Version 2.2), 56.

United Nations Office for Disaster Risk Reduction (UNDRR). (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction* (Vol. 71). https://doi.org/https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf

University of Western Ontario (UWO): Facility for Intelligent Decision Support. (2016). About the ResilSIM tool. Retrieved January 4, 2019, from https://resilsim-uwo.ca/About

US Army Corps of Engineers (USACE). (2011). *HEC-GeoRAS: GIS Tools for Support of HEC-RAS using ArcGIS, HEC-GEORAS User's Manual version 4.3.93*. Davis, CA, USA: US Army Corp of Engineers Hydrologic Engineering Center.

US Army Corps of Engineers (USACE). (2010). *HEC-RAS River Analysis System: Hydraulic Reference Manual version 4.1*. Davis, CA, USA: US Army Corp of Engineers Hydrologic Engineering Center.

US Environmental Protection Agency. (2018). Water Network Tool for Resilience (WNTR) [Toolkit]. Washington, D.C., USA. Retrieved from https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHSRC&dirEntryId=337793

Ventana Systems Inc. (2009). *Vensim DSS*. Massachusetts, USA.

Walker, B., & Salt, D. (2012). *Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function*. Washington: Island Press.

Walker, B., & Salt, D. (2006). *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Washington, D.C.: Island Press.

Watson, J., Gayer, M., & Connolly, M. (2007). Epidemics after Natural Disasters. *Emerging Infectious Diseases*, *13*(1), 1–5.

Watters, J. (2014). *Disaster Recovery, Crisis Response, and Business Continuity: A Management Desk Reference*. Berkeley: Apress.

Wenzel, F., Bendimerad, F., & Sinha, R. (2007). Megacities - megarisks. *Natural Hazards*, *42*(3), 481–491. https://doi.org/10.1007/s11069-006-9073-2

Werner, A. T. (2011). *BCSD Downscaled Transient Climate Projections for Eight Select GCMS over British Columbia, Canada*. Victoria, BC: Pacific Climate Impacts Consortium, University of Victoria.

Wong, P. P., Losada, I. J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K. L., … Sallenger, A. (2014). Coastal systems and low-lying areas. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, … L. L. White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 361–409). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

World Health Organization (WHO). (2018). Drowning: Key facts.

World Health Organization (WHO). (2003). *Climate change and human health: risk and responses* (A. J. McMichael, D. H. Campbell-Lendrum, C. F. Corvalán, K. L. Ebi, A. K. Githeko, J. D. Scheraga, & A. Woodward, Eds.). Geneva, Switzerland.

World Health Organization (WHO). (2013). *Building Back Better: Sustainable Mental Health Care after Emergencies*. Geneva, Switzerland: World Health Organization.

Xie, H., & Rao, R. (2014). A system dynamics model for medical staff allocation in post-Wenchuan earthquake relief. *Proceedings - 2014 IEEE Workshop on Advanced Research and Technology in Industry Applications, WARTIA 2014*, 307–311. https://doi.org/10.1109/WARTIA.2014.6976258

Zeleňáková, M., Blišťan, P., Alkhalaf, I., Gaňová, L., & Zvijáková, L. (2016). Assessment of environmental damages in case of flood in Bodva River basin, Slovakia. *International Journal of Safety and Security Engineering*, *6*(3), 498–507. https://doi.org/10.2495/SAFE-V6-N3-498-507

Zhang, C., Kong, J., & Simonovic, S. P. (2018a). Restoration resource allocation model for enhancing resilience of interdependent infrastructure systems. *Safety Science*, *102*, 169–177. https://doi.org/10.1016/j.ssci.2017.10.014

Zhang, C., Kong, J., & Simonovic, S. P. (2018b). Modeling joint restoration strategies for interdependent infrastructure systems. *Public Library of Science (PLoS) ONE*, *13*(4), 18. https://doi.org/10.1371/journal.pone.0195727

Appendix A

An Introduction to Spatial Data, Spatial Data Tools, and their use in the Development of the DRST

Spatial data and the representation of disaster resilience as dynamic in both time and space required the acquisition, understanding, and use of various types and formats of spatial data and data analysis tools. This Appendix provides a brief introduction to various types of spatial data and describes the various formats of data used in the development of the Disaster Resilience Simulation Tool. It covers the following topics:

- An introduction to spatial data;
- Spatial data types; and
- Spatial reference systems.

The various spatial data described in this Appendix was manipulated using several spatial analysis tools. The following Appendix therefore also lists and describes the suite of spatial analysis tools implemented in the Disaster Resilience Simulation Tool. These tools were accessed via the ArcGIS dynamic link library (DLL) and implemented with the use of Python scripts. Note that some of these tools are only available with an active ArcGIS Spatial Analyst or Network Analyst License:

- Extract Tools (clip, select, split)
- Overlay Tools (union, intersect, erase)
- Proximity Tools (buffer, cost-distance)
- Reclass Tools (lookup, reclassify)
- Geometric Network Tools (create geometric network, set flow direction, trace geometric network)

When the extract, overlay, proximity, and reclassify spatial tools are executed in a sequence, it is referred to as *geoprocessing*. The DRST incorporates geoprocessing into its preparation of spatial resilience inputs for various (economic, engineering, health, and social) model domains. The DRST geoprocessing sequences are executed in a Python middleware program.

An Introduction to Spatial Data: Spatial data is used to represent features in the real world. Digitally, these pieces of data are organized and stored together as layers. There are many different forms of spatial data including tables, shapefiles, markup files (such as KML), etc. Although spatial data comes in many diverse formats (Table 8) it shares the similar characteristic of being linked to a location which is typically defined by a set of coordinates (latitude and longitude). With this location information, data can be mapped, typically using geographic information system (GIS) software. Mapped data can then be represented as thematic layers stacked on top of each other to gain a better understanding of the spatial landscape and features at a particular location (Figure 55). Furthermore, the spatial relationships between map features can be explored using spatial analysis techniques.

To effectively organize spatial data, features are often grouped together in datasets and spatially represented as layers. Map layers are thematic representations of different types of geographic information which may include: discrete features, continuous surfaces, object attributes, and imagery (Table 8). The DRST makes use of all of these types of data in order to represent various features and phenomena in resilience calculations and, where necessary, converts between these representations based on the intended use of the data. This spatial data was essential for resilience mapping. The remainder of this section identifies more specifically the key characteristics of spatial data, the preparations of spatial data, and analysis of spatial data for use in the DRST.

Table 8: Thematic representations of geographic data

Discrete Features	Object Descriptions and Attributes	Imagery	Continuous Surfaces
Points	Symbols	Aerial	Elevations
Lines	Colours	Satellite	DEMs
Polygons	Labels abc def ghi	LANDSAT	TINs

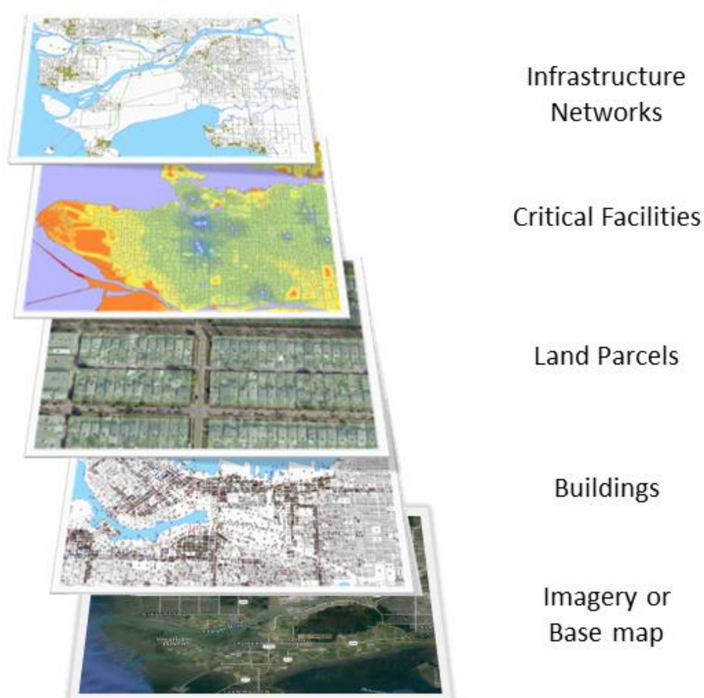


Figure 55: Spatial data as layers

Spatial Data Types: The two (2) most common types of spatial data structures are vectors and rasters. Spatially discrete features are typically represented using vector data (points, lines, and polygons) (Figure 56a) while spatially continuous phenomena are often represented using raster data (Figure 56b). However, it is possible to represent spatially discrete features as both vector or raster data (Figure 57). Similarly, a feature dataset (for example, houses) could be modeled discretely as vector or raster data, and could furthermore be represented as any one of the vector formats (Figure 58). The reasons for selecting one data structure over another may include:

i) Format of the original dataset;

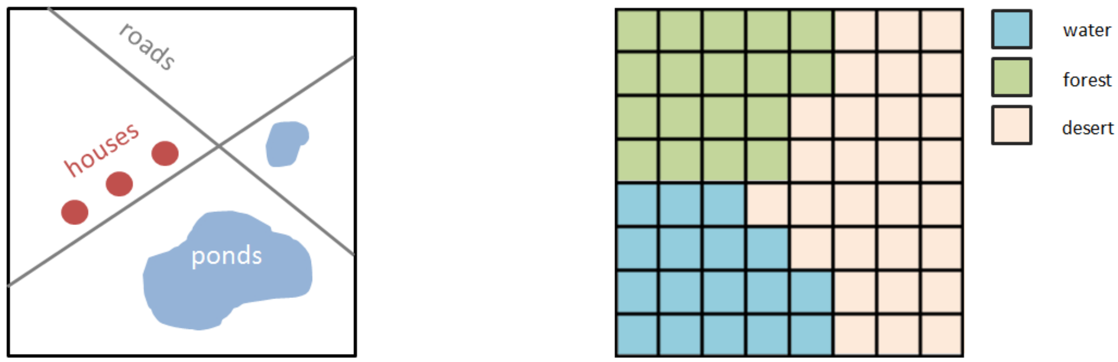
ii) Size of the dataset;

iii) Accessibility;

iv) Available computer storage; and

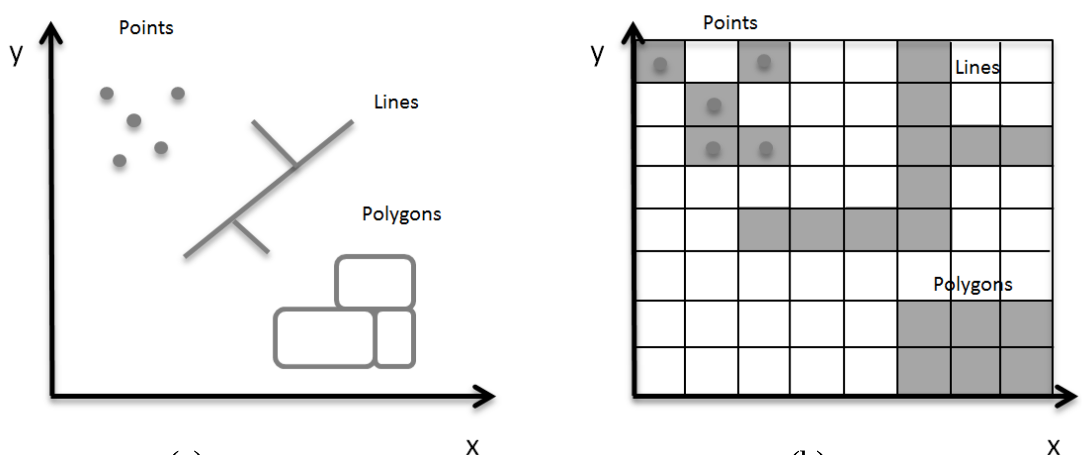
v) Desired level of precision.

The selection of the best conceptual model (the way in which features are represented), is therefore driven by the intended use of the data.



(a) (b)

Figure 56: Two types of spatial data structures representing (a) spatially discrete features as vector data; and (b) spatially continuous data as raster data



(a) (b)

Figure 57: Representation of spatially discrete features as (a) vector data; and (b) raster data

Figure 58: Spatially discrete features (houses) represented in various vector formats (a) points; (b) lines; and (c) polygons

Spatial Reference Systems: Every spatial dataset is mapped using a reference coordinate system. There are two types of coordinate systems: geographical coordinate systems and projected coordinate systems.

Geographic coordinate systems (GCSs) represent the location of features on the earth's surface relative to the earth's center. Projected coordinate systems (PCSs) are the location of features defined on a 2D planar representation of the earth's surface. PCSs are always based on a GCS, which in turn uses an approximation of the earth's shape as a spheroid. Locations referenced using GCSs are defined by a latitude and longitude relative to a global datum.

Each coordinate system may be defined by different units of measurement (feet, meters, or degrees), shifts, and reference datum, adding to the complexity of working with multiple GIS datasets. Any distances and measurements made between datasets with different coordinate systems are not necessarily equal. Therefore, one of the first steps in working with spatial data is to make datasets compatible by ensuring they are share similar spatial reference information. To achieve this, datasets commonly require geographic datum transformations to convert coordinates between two geographic coordinate systems. Failure to correctly transform datasets could cause misalignments anywhere from a few centimeters to a few hundred meters.

Mathematical transformations help translate the data from a spheroid (the approximate shape of the Earth) to a flat 2D surface (a map). A transformation is required to go from a GCS to PCS because reality is distorted in some way when translating 3D positions onto 2D maps. Map projections "roll out" the 3D shape of the Earth onto a 2D surface based on a particular shape; conical, cylindrical, and planar are some of the most common shapes used in map projections. Each projection preserves different spatial properties, therefore reducing the distortion of the projection in different ways. Selecting the appropriate projection is driven by the questions and analytical goals of the spatial analysis.

GCSs commonly used in Canada include: North American Datum 1927 (NAD 1927), North American Datum 1983 (NAD 1983), and Canadian Spatial Reference System 98 (CSRS98). PCSs commonly used in Canada include: Universal Trans Mercator (UTM), 10

Degree Transverse Mercator (10TM), and Albers Equal Area Conic. Since the DRST relies on spatial data collected from multiple sources, GCS and PCS transformations were required. Ensuring that datasets are geographically compatible by having all input and output layers mapped in the same working environment is one of the first procedures executed by the DRST.

Vertical coordinate systems are also important to spatial analysis when considering the representation of elevations or depths. The units of measurement in vertical coordinate systems are always linear (feet or meters). The z-axis direction may be positive in the upwards direction (representing positive elevation values) and negative in the downwards direction (representing depths below the reference point). However, it is possible that some vertical coordinate systems define the z-axis upwards direction as negative and the downwards z-direction as positive. Thus, it is important that the vertical coordinate systems of datasets using elevations or depth data be compatible. Since the DRST uses spatial elevation and depths as part of the analysis, the datasets had to satisfy this criterion.

To ensure compatible coordinate systems between all of the spatial data, one of the first things the DRST does is set these characteristics in the spatial geoprocessing environment.

Extract Tools: Extract analysis is a form of geographic analysis which selects and cuts features and attributes from spatial datasets. Data can be selected using SQL queries or by location and a new feature dataset created from these selections. The DRST uses extract analysis to reduce the size of datasets and select features used elsewhere in the resilience analysis. Extract operations used in the DRST include: clip, select, and split (Figure 59).

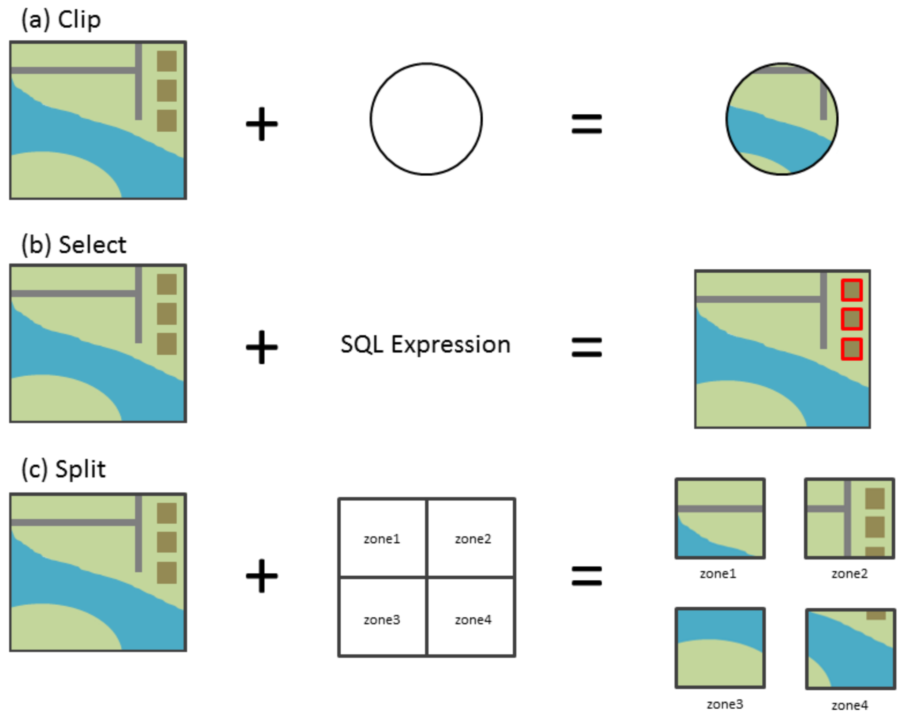


Figure 59: Extract analysis tools (a) clip, (b) select, and (c) split

Overlay Tools: Overlay analysis is a form of geographic analysis which uses data layering to join two or more spatial data features to help identify the spatial relationships between them. The DRST uses overlay analysis to combine multiple datasets, modify geometry, and provide new information to answer a collection of research questions important to resilience assessment. For example, spatial analyses help the DRST resolve questions such as: "which infrastructure lies in the floodplain?"; "what is the depth of flooding at this particular location?"; and "which areas have a high incidence of poverty?" among others. Overlay analysis can help provide answers to these types of questions. Overlay operations include: union, intersect, and erase (Figure 60). Many overlay operations are executed in the DRST.

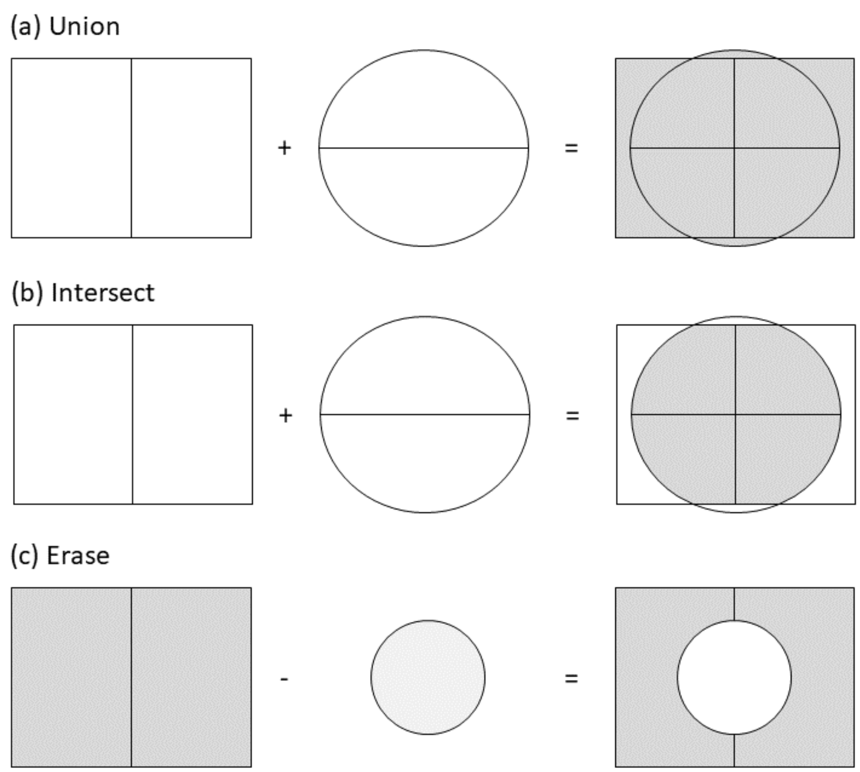


Figure 60: A subset of the overlay analysis tools
(a) union; (b) intersect; and (c) erase

Proximity Tools: Proximity analysis is a form of geographic analysis which uses data layering to identify spatial relationships between data to help the DRST resolve questions such as: "what is near what?" Proximity analyses involve the use of buffers, distances, directions, routes, and allocations to identify how close features are to each other; the nearest and farthest features from a source; and the shortest distance between two or more features. Proximity analysis tools can be divided into vector (feature) and raster-based tools. The primary raster-based proximity analysis tool used by the DRST is called *cost-distance*. Cost-distance analysis uses the relative spatial location of features to measure distances. This tool uniquely considers that distance can be evaluated in terms of cost (such as difficulty, dollar cost, energy expenditure, time, etc.), instead of traditional distance units (meters, feet, etc.). The algorithm behind the tool then calculates the cumulative least cost path to the cell(s) of interest (Figure 61).

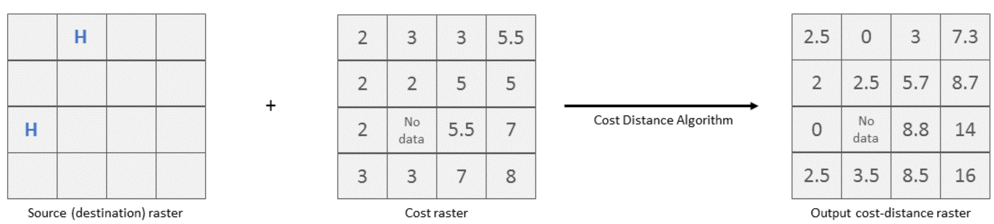


Figure 61: Cost distance proximity analysis

Reclass Tools: The reclassify tool is part of the *Reclass* toolset. This tool changes the values in raster cells according to a set of criteria, typically specified as a range. For example, if a raster map holds values between one (1) and one hundred (100), these values may be reclassified as numbers within the range one (1) to twenty (20), twenty-one (21) to forty (40), forty-one (41) to sixty (60), sixty-one (61) to eighty (80), and eighty-one (81) to one-hundred (100) (Figure 62). Reclassification is typically performed to simplify raster data and calculations so raster data will better suit future spatial analysis needs. The reclassification tool is used in multiple instances of the DRST for the purposes of data pre-processing, data analyses, and data post-processing.

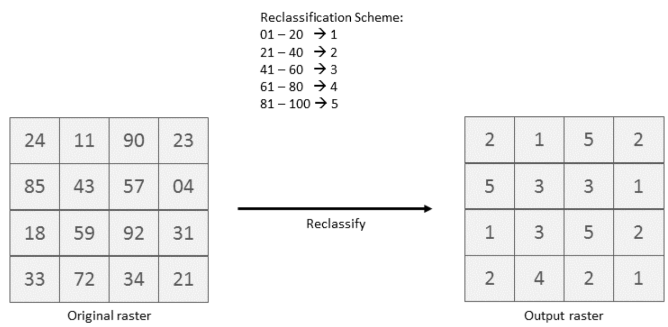


Figure 62: Spatial raster reclassification

Geometric Network Tools: Creating, managing, and tracing a geometric network is possible using tools in the *Geometric Network* toolset. A geometric network can be used to represent real-world network infrastructure systems such as water distribution systems, sewer systems, electrical distribution systems, and other utilities. Geometric networks can be modelled and analyzed to determine network loops, circuits, or directional tracing. First, a network needs to be created (using edges, junctions, and connectivity rules) that closely represents the real world system. An example of a simplified geometric network schematic is shown in Figure 63. Connectivity in geometric network is based on the geometric coincidence of features and therefore to ensure connectivity, *snapping* tools are often used during the network building process.

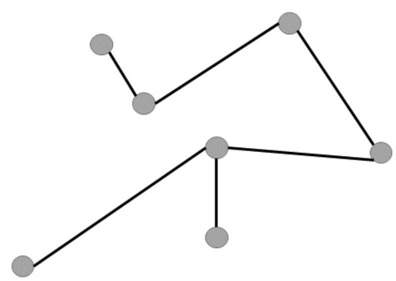


Figure 63: Schematic of a geometric network

Once a geometric network has been established, it is necessary to set the network flow direction. This can be based on either: (i) the digitized direction, or (ii) a set of sources and sinks. An example schematic of flow directions is presented in Figure 64.

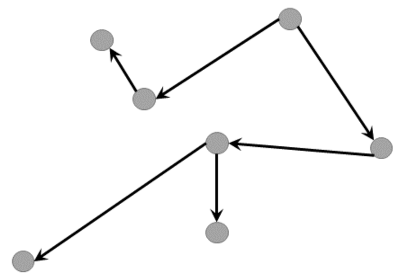


Figure 64: Schematic of geometric network with flow direction

Upon setting flow direction, it is necessary to identify flags (starting points for the tracing operations), barriers (interruption/blocking points for the tracing operations), and weightings (the cost to travel through junctions and/or edges) as conceptualized in Figure 65.

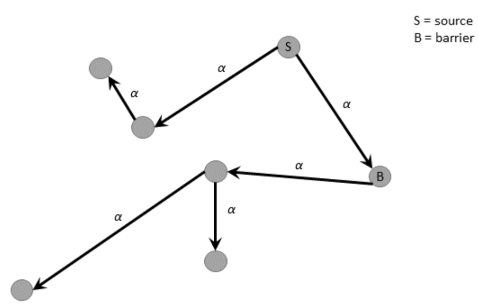


Figure 65: Flags (sources), barriers, and weights

Once the geometric network build has been completed, it is necessary to establish the desired tracing task. Tracing operations can be performed on the geometric network in various ways including: find ancestors, find connected or disconnected, find loops, find accumulation, find path, and trace upstream or downstream. An example of results from a trace downstream operation is shown in Figure 66.

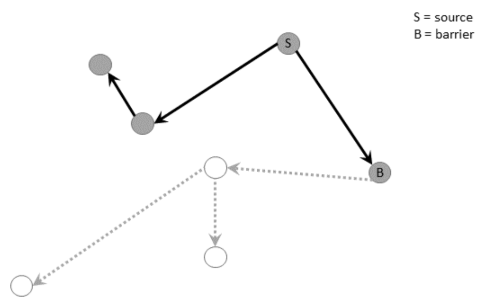


Figure 66: Conceptual results from a trace downstream operation in a geometric network

A geometric network was created in ArcGIS to represent power transmission network as part of the implementation of social domain in the DRST. It uses the trace downstream operation to identify all network features that lie downstream of a given point in the network. The trace operation is executed at each time step to determine outages in the transmission network during a flood event.

It should be also be noted, however, that the implementation of geometric network tracing in ArcMap differs from the way in which is needs to be programmed in the Python middleware program. Although geometric network tracing tools (as part of ArcPy) are used, the way in which barriers, flags, and tracing is executed does not map directly from the use of the tool within the ArcMap interface. To see how this tool was implemented in a Python environment, the reader is referred to the documentation of the Python middleware program provided in Appendix F (electronically).

Appendix B
VIC Hydrologic Model Equations

The following is a list of the basic mathematical equations used in the VIC hydrologic model. This model was used to simulate climate change influenced streamflows for the Fraser River Basin. The VIC model is based on the original work of Liang et al. (1994), which has since been updated to VIC 5 model Hamman et al. (2018) to include improvements in the flexibility and accuracy of the model, but remains fundamentally built on the equations below. The snow accumulation and ablation models were created consider the work of Andreadis et al. (2009). The climate change influenced hydrologic simulations were completed by Pacific Climate Impacts Consortium (PCIC) using the VIC model.

Model	Equation(s)	Parameters: Description	Equation No.
Evapotranspiration	Comprised of: 1) Evaporation from each vegetation class 2) Transpiration from each vegetation class 3) Evaporation from bare soil Total Evapotranspiration: $E = \sum_{n=1}^{N} C_v[n] * (E_c[n] + E_t[n]) + C_v[N+1] * E_1$	n: surface cover class $C_v[n]$: fraction of vegetation cover for nth (1, 2, …, N) surface cover class $[N+1]$: represents bare soil class $C_v[N+1]$: fraction of bare soil area $E_c[n]$: evaporation from the canopy layer $E_t[n]$: evaporation due to transpiration E_1: evaporation from bare soil (soil layer 1)	C- 1

Interception (canopy layer water balance)	$$\frac{dW_i[n]}{dt} = P - E_c[n] - P_t[n]$$ when $$0 \le W_i[n] \le W_{im}[n]$$ and $$W_{im}[n] = K_L * LAI[n, month]$$	P: precipitation rate $P_t[n]$: throughfall of precipitation $W_i[n]$: amount of water intercepted by the canopy $W_{im}[n]$: maximum amount of water intercepted by the canopy K_L: constant of 0.2mm $LAI[n, month]$: leaf area index for the n[th] type of surface cover class for a particular month	C- 2
Drainage (soil layer 1 to soil layer 2)	$$Q_{12}[n] = K_s \left(\frac{W_1[n] - \theta_r}{W_1^c - \theta_r} \right)^{\frac{2}{B_p}+3}$$	K_s: saturated soil conductivity θ_r: residual moisture content B_p: pore size distribution index	C- 3

Runoff	Comprised of: 1) Direct surface runoff 2) Subsurface runoff (baseflow) Total Runoff: $$Q = \sum_{n=1}^{N+1} C_v[n] * (Q_d[n] + Q_b[n])$$	$C_v[n]$: fraction of vegetation cover for n[th] (1, 2, …, N) surface cover class $Q_d[n]$: direct surface runoff for cover class n of vegetation $Q_b[n]$: subsurface runoff for cover class n of vegetation	C- 4
Direct Surface Runoff (vegetation cover)	$$Q_d[n] * \Delta t = P_t[n] * \Delta t - W_1^c + W_1^-[n]$$ for $i_0 + P_t[n] * \Delta t \geq i_m$ otherwise, $$Q_d[n] * \Delta t = P_t[n] * \Delta t - W_1^c + W_1^-[n] + W_1^c \left[1 - \frac{i_0 + P_t * \Delta t}{i_m}\right]^{1+b_i}$$	Δt: time step W_1^c: maximum soil moisture content of soil layer 1 $W_1^-[n]$: the soil moisture content in layer 1 at the beginning of the time step i_0: point infiltration capacity	C- 5

	for $i_0 + P_t[n] * \Delta t \le i_m$	i_m: maximum infiltration capacity b_i: infiltration shape parameter	
Subsurface Runoff (vegetation cover)	$Q_b[n] = \frac{D_s D_m}{W_s W_2^c} W_2^-[n]$ for $0 \le W_2^-[n] \le W_s W_2^c$ otherwise, $Q_b[n] = \frac{D_s D_m}{W_s W_2^c} W_2^-[n] + \left(D_m - \frac{D_s D_m}{W_s}\right)\left(\frac{W_2^-[n] - W_s W_2^c}{W_2^c - W_s W_2^c}\right)^2$ for $W_2^-[n] \ge W_s W_2^c$	D_m: maximum subsurface flow D_s: fraction of maximum subsurface flow W_2^c: maximum soil moisture content of soil layer 2 W_s: fraction of maximum soil moisture content of soil layer 2 $W_2^-[n]$: soil moisture content of soil layer 2 at the beginning of the time step Note: $D_s \le W_s$	C- 6
Aerodynamic Flux	Net radiation:	$H[n]$: sensible heat flux ρ_w: density of water	C- 7

	$$R_n[n] = H[n] + \rho_w L_e E[n] + G[n] + \Delta H_s[n]$$	L_e: latent heat of vaporization $\rho_w L_e E[n]$: is latent heat flux $G[n]$: ground heat flux $\Delta H_s[n]$: change in energy storage in the layer, per unit time, per unit area	
Snow	Ground snowpack (2-layer): $$\rho_w c_s \frac{dWt_s}{dt} = Q_r + Q_s + Q_e + Q_p + Q_m$$	c_s: specific heat of ice ρ_w: density of water T_s: temperature of the surface layer Q_r: net radiation flux Q_s: sensible heat flux Q_e: latent heat flux Q_p: energy flux advected to the snowpack by rain or snow	C- 8

	Intercepted snow: $$I = fP_s$$	Q_m: energy flux given to the pack I: snow water equivalent intercepted P_s: snowfall f: efficiency of snow inception (typically taken as 0.6)	
Flow Routing	Linearized St. Venant: $$\frac{\partial Q}{\partial t} = D\frac{\partial^2 Q}{\partial x^2} - C\frac{\partial Q}{\partial x}$$	Where C and D are optimized for each grid box	C- 9

Some important assumptions and limitations of the VIC model include:

- Land surface is modeled as a grid of large uniform cells
- Sub-grid heterogeneity (e.g. elevation, land cover) is handled via statistical distributions
- Inputs are time series of sub-daily meteorological drivers (precipitation, air temperature, wind speed, long wave radiation, short wave radiation, atmospheric pressure, and vapor pressure) and daily land cover data (albedo, LAI, canopy cover fraction)
- Land-atmosphere fluxes, and the water and energy balances at the land surface are simulated at a daily or sub-daily time step
- Water can only enter a grid cell via the atmosphere
- The portions of surface and subsurface runoff that reach the local channel network within a grid cell are assumed to be much greater than the portions that cross grid cell boundaries into neighboring cells. Grid cells are simulated independently of each other, there is no communication between grid cells and as such, non-channel flow between grid cells is ignored
- Once water reaches the channel network, it is assumed to stay in the channel (it cannot flow back into the soil)

  Routing of stream flow is performed separately from the land surface simulation, using a separate model

Appendix C
HEC-RAS Hydraulic Modelling Equations

The following is a list of the fundamental mathematical equations used as a basis for hydraulic modelling using the United States Army Corps of Engineers (USACE) HEC-RAS software. This model was used to simulate climate change influenced inundation for the Fraser River Basin. Hydraulic model development and simulation was performed by the author. Results were calibrated to four Water Survey of Canada (WSC) streamflow gauges on the Fraser River network. Results were validated based on cross sections and flow data provided by the Ministry of Forest Lands and Natural Resource Operations (MFLNRO) of British Columbia. Please note that HEC-RAS version 4.2.1 was used to perform hydraulic modelling and 1D unsteady flow simulation. Parameters were primarily derived from open data sets available online through Land Information Ontario (LIO), Data BC, UBC's GIS Data Catalogue, and Western University's GIS Library.

Unsteady Flow Principle	Equation	Parameters	Equation No.
Continuity Equation	$$\frac{\partial A}{\partial t}+\frac{\partial S}{\partial t}+\frac{\partial Q}{\partial x}-q_l=0$$ functional form: $$\Delta Q+\frac{\Delta A_c}{\Delta t}\Delta x_c+\frac{\Delta A_f}{\Delta t}\Delta x_f+\frac{\Delta S}{\Delta t}\Delta x_f-\bar{Q}_l=0$$	A: cross-sectional area t: time S: storage (from non-conveying portions of cross section) Q: flow x: distance along the channel q_l: lateral inflow per unit distance A_c, A_f: cross sectional area of the channel and floodplain, respectively x_c, x_f: length of the channel and floodplain, respectively, between two cross sections $\bar{Q}_l$: average lateral inflow	D- 1
Momentum Equation	$$\frac{\partial Q}{\partial t}+\frac{\partial (VQ)}{\partial x}+gA\left(\frac{\partial z}{\partial x}+S_f+S_h\right)=0$$ functional form: $$\frac{\Delta(Q_c\Delta x_c+Q_f\Delta x_f)}{\Delta t\Delta x_e}+\frac{\Delta(\beta VQ)}{\Delta x_e}+g\bar{A}\left(\frac{\Delta z}{\Delta x_e}+\bar{S}_f+\bar{S}_h\right)=0$$	g: acceleration due to gravity S_f, S_h: friction slope and local slope, respectively V: velocity Q_c, Q_f: flow in the channel and floodplain, respectively Δx_e: equivalent flow path β: velocity distribution factor z: water surface elevation	D- 2
Momentum Equation (at a junction)	Functional form:	ξ: fraction of momentum entering the receiving stream Q_l: lateral inflow V_l: average velocity of lateral inflow	D- 3

	$$\frac{\Delta(Q_c \Delta x_c + Q_f \Delta x_f)}{\Delta t \Delta x_e} + \frac{\Delta(\beta V Q)}{\Delta x_e} + g\bar{A}\left(\frac{\Delta z}{\Delta x_e} + \bar{S}_f + \bar{S}_h\right) = \xi \frac{Q_l V_l}{\Delta x_e}$$		
Flow Distribution Factor (ratio of conveyance)	$$\phi = \frac{Q_c}{Q_c + Q_f}$$ Functional form (assuming S_f is the same for channel and floodplain): $$\phi_j = \frac{K_c}{K_c + K_f}$$	K_c: conveyance in the channel K_f: conveyance in the floodplain * under the assumption that friction slope is the same for the channel and the floodplain	D- 4

*Additional equations and finite difference approximations for the terms in the momentum and energy equations used in the solution of 1D unsteady flow models can be found in USACE (2010). Some important assumptions and limitations of the 1D unsteady flow HEC-RAS models include:

- Water surface is horizontal at any cross section perpendicular to flow; in other words, the water surface elevation is the same for the channel and floodplain at any given cross section
- At a junction, the water surface computed at the downstream side is used for cross sections just upstream; for steeper rivers where this is not really a good assumption, an energy balance can be performed to compute upstream water surface elevations
- When solving momentum balance equation at a junction, water surface elevations at the cross sections on each tributary just upstream of the junction are assumed to be equal to each other (as an approximation)

Appendix D
GAMS Programming and Documentation

The following Appendix is included to provide additional details and materials to support the thesis text. This Appendix first describes the functionality of the economic domain of the DRST (GAMS model) and then provides the GAMS code used as part of the DRST. The code was developed by Aaron Gertz as part of his PhD thesis *On the Economics of Climate Change and its Effects* (2015) and additional details pertaining to the development of the program can be found in the paper:

Gertz, Aaron B. and James B. Davies. *A CGE Framework for Modelling the Economics of Flooding and Recovery in a Major Urban Area, Economic Policy Research Institute.* EPRI Working Papers, 2015-2. London, ON: Department of Economics, University of Western.

Description of the Economic Model of the DRST (GAMS optimization model)

The GAMS software has its own programming language, also referred to as GAMS language. Therefore, a GAMS model is a collection of GAMS statements (Figure 67).

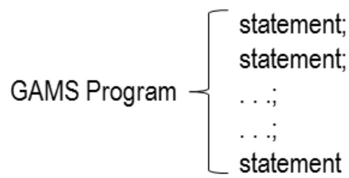


Figure 67: Structure of a GAMS program

Formulating an optimization model requires definition of indices, given data, decision variables, constraints, and an objective function. These terms were used to describe the CGE model described in the thesis text. However, in the GAMS environment, this terminology is a little different and these entities are referred to as follows: indices are called *sets*, given data are called *parameters*, decision variables are called *variables,* and constraints and the objective function are called *equations*. The economic optimization problem is formulated with sets, parameters, variables, and equations in a GAMS model file, which defines the CGE model (Figure 68). The GAMS model file was developed by (Gertz et al., 2019) and slightly modified by the author for integration into the DRST. The GAMS model file used in the DRST is provided in the remainder of this Appendix.

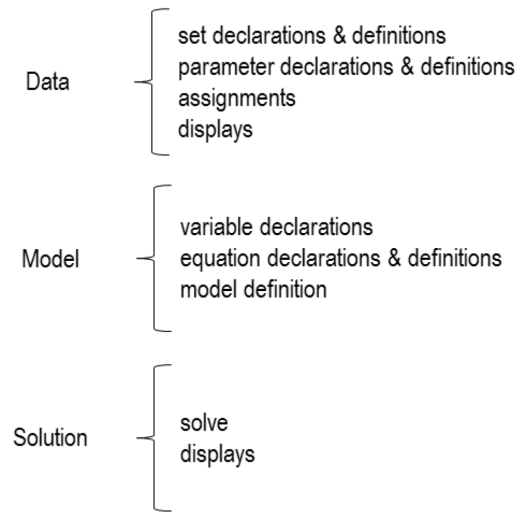


Figure 68: Organization of GAMS program

When a well-defined operational GAMS model file is sent to the GAMS program, the optimization model is formulated and solved. The GAMS program uses mathematical optimization techniques to solve the objective functions (*equations*) subject to constraints (also *equation*s). The program then outputs results in the form of text files which contain optimization solutions and variable values. The three allowable forms of data into a GAMS model include: lists, tables, and direct assignments. The DRST makes use of all three fundamentally different formats, however the primary data input format is tables, including matrices.

GAMS software is file-based and offers open architecture in which the user can create or edit files using their preferred word processor. Since GAMS files require no special editor, the input and output files can be easily integrated with other programs. This is useful for the implementation of the DRST, since some of the input files become modified in the event of a flood. The DRST invokes GAMS using a Python script. The object-oriented GAMS Python API provides access to GAMS from within a Python program. This is used to bridge between the economics modelling, SD simulations, and GIS analysis components of the DRST. The Python script developed as part of this research provides the functionality and automation for all three modelling, simulation, and optimization tools from the convenience of a single program.

```
$TITLE Model Van: dynamic model of Vancouver economy.

$ONTEXT

$OFFTEXT

TABLE BENCH(*,*)  Benchmark financial flows (e.g. an input-output table)

$ondelim
$include VAN_20x20_all_adj.csv
$offdelim

TABLE E_CAP(*,*)  Exposed capital to flooding by industry

$ondelim
$include exposed_capital.csv
$offdelim

SET    T      Time periods          /1*220/,
       TFIRST(T),
       TLAST(T),
       TAID(T),
                 I      Produced goods        /BS11, BS21, BS22, BS23, BS31, BS41, BS44,
                         BS48, BS51, BS52, BS54, BS56, BS61, BS62, BS71, BS72, BS81,
                         GS61, GS62, GS91/,
       F      Factors of production   /L, K/,
       TX     Taxes                 /ST, CIT, LIT, KIT/
       FD     Final demand sectors    /W, G, INVP, INVG, E, M/;


ALIAS (I,J), (F,FF);
```

```
TFIRST(T) = YES$(ORD(T) EQ 1);
TLAST(T) = YES$(ORD(T) EQ CARD(T));

SCALAR  TS      TIMESTEPS IN 1 YEAR                    /4/
        DR      DAMAGE RATE OF EXPOSED CAPITAL         /0.25/
        LRK     TEMP LOSS RATE OF CAPITAL              /0/
        LRL     TEMP LOSS RATE OF LABOUR               /0/
        YA      YEARS OVER WHICH AID IS SPREAD         /2/
        AIDP    FRACTION OF DAMAGE COVERED BY AID /0.75/
        DELTA   DEPRECIATION                           /0.05/
*       DELTA   DEPRECIATION                           /0.10/
        R       INTEREST RATE                          /0.0762713752792/
*               R       INTEREST RATE /0.1303876789703/
                *for g = 0.05
*               R       INTEREST RATE /0.1164652147643/
                *for delta = 0.1
        G       GROWTH RATE                            /0.02/
*       G       GROWTH RATE                            /0.05/
        RK0     INITIAL RETURN TO CAPITAL;

TAID(T) = YES$(ORD(T) LE YA*TS);

PARAMETERS
   QREF(T)     Quantities,
   PREF(T)     Prices,

  Q0(I)        Benchmark gross domestic output,
   ID0(J,I)    Benchmark Intermediate demands,
  FS0(F,I)     Benchmark factor supplies,
   VL(I)       Benchmark labour earnings,
```

VK(I) Benchmark CAPITAL EARNINGS,
TAX(TX,I) Tax revenues,
TR(TX,I) Tax rates,

C0(I) Benchmark household demand,
GOVD(I) Benchmark government demand,
INVP(I) Benchmark distribution of goods in private investment,
INVG(I) Benchmark distribution of goods in gov't investment,
INV(I) Benchmark distribution of goods in total investment,
E0(I) Benchmark exports,
M0(I) Benchmark imports,
TAXC(FD) Consumption taxes on final demand,
STR(FD) Consumption tax rates,

W0 Benchmark private consumption (and welfare index),
G0 Benchmark government consumption,
CA0 Trade deficit or surplus,

K0(I) INITIAL CAPITAL STOCK,
I0(I) INITIAL INVESTMENT for sector I,
I0_TOT Sum of I0(I),
INV_TOT INITIAL TOTAL INVESTMENT (no tax),
FRAC_INV(I) FRACTION OF INVESTMENT going to SECTOR I,

K_L(I) Pct loss of capital during flood,
L_L(I) Pct loss of labour during flood,
K_D(I) Pct capital damage after flood,
AID(T) Flood aid per time period,

Inv_ts(T,I) Actual Investment by sector,
GDP(T) GDP,

```
  GR(T)      GDP growth rate,
  LAB(T,I)   Labour,

 ESUB(I)     Armington elasticity of substitution;

R = R/TS;
G = G/TS;
DELTA = DELTA/TS;



QREF(T) = (1 + G) ** (ORD(T) - 1);
PREF(T) = (1/(1 + R)) ** (ORD(T) - 1);

*Input-output
Q0(I) = BENCH(I,I);
ID0(J,I) = MAX(0, -BENCH(J,I));
VL(I) = -BENCH("L",I);
VK(I) = -BENCH("K",I);
TAX(TX,I) = -BENCH(TX,I);

*Final Demand
C0(I) = -BENCH(I,"W");
GOVD(I) = -BENCH(I,"G");
INVP(I) = -BENCH(I,"INVP");
INVG(I) = -BENCH(I,"INVG");
INV(I) = INVP(I) + INVG(I);
E0(I) = -BENCH(I,"E");
M0(I) = BENCH(I,"M");
TAXC(FD) = -BENCH("ST",FD);

INV_TOT = SUM(I, INV(I));
```

```
FRAC_INV(I) = INV(I)/INV_TOT;


W0 = BENCH("W","W");
G0 = BENCH("W","G");
CA0 = BENCH("FX","CONS");

*Input taxes
TR("ST",I) = TAX("ST",I)/sum(J,ID0(J,I));
TR("CIT",I) = TAX("CIT",I)/VK(I);
TR("LIT",I) = TAX("LIT",I)/VL(I);
TR("KIT",I) = TAX("KIT",I)/VK(I);

STR("INVP") = (TAXC("INVP")+TAXC("INVG"))/INV_TOT;

*Output taxes
STR("W") = TAXC("W")/W0;
STR("G") = TAXC("G")/G0;
STR("E") = TAXC("E")/(sum(I,E0(I))+TAXC("E"));
STR("M") = TAXC("M")/(sum(I,M0(I))+TAXC("M"));

*Capital, investment and rate of return calculations
RK0 = (DELTA + R)*(1+STR("INVP"));
K0(I) = VK(I)/RK0;
I0(I) = (DELTA + G) * K0(I);
I0_TOT = sum(I,I0(I));

*Damages and losses plus aid
FS0("L",I) = VL(I);
FS0("K",I) = K0(I);
K_L(I) = LRK*E_CAP(I,"KLOSS");
```

```
L_L(I) = LRL*E_CAP(I,"LLOSS");
K_D(I) = DR*E_CAP(I,"KDAM");
AID(T)$TAID(T) = AIDP*SUM(I,K_D(I)*K0(I))/(YA*TS);


ESUB(I) = 3;


$ONTEXT
$MODEL:Van

$SECTORS:
    X(T,I)  ! Activity level for sector I
    W(T)    ! Activity level for sector W (welfare index)
    GC(T)   ! Activity level for sector GC (government consumption bundle)
    KN(T,I) ! Investment sector
    K(T,I)  ! Capital accumulation
    M(T,I)  ! Imports
    E(T,I)  ! Exports
    ARM(T,I) ! Armington goods

$COMMODITIES:
    P(T,I)   ! Price index for commodities
    PL(T,I)  ! Price index for primary factor L
    PK(T,I)  ! Price index for primary factor K
    PW(T)    ! Price index for welfare (expenditure function)
    PG(T)    ! Price index for government bundle
    RK(T,I)  ! Rental rate for capital
    PKT(I)   ! Post-terminal capital constraint
    FR(T)    ! Real exchange rate
    PF(T,I)  ! Price index for foreign commodity
```

```
        PA(T,I)  ! Price index for Armington good

$CONSUMERS:
        CONS     ! Income level for consumer household
        GOVT     ! Income level for government

$AUXILIARY:
        TK(I)    ! Terminal Capital Stock

$PROD:X(T,I) s:0  va:0.4
        O:P(T,I)       Q:Q0(I)
        I:PA(T,J)      Q:ID0(J,I)     P:(1+TR("ST",I))  A:GOVT T:TR("ST",I)
        I:PL(T,I)      Q:VL(I)        P:(1+TR("LIT",I)) A:GOVT T:TR("LIT",I) va:
        I:RK(T,I)      Q:K0(I)        P:(RK0*(1+TR("KIT",I)+TR("CIT",I)))          A:GOVT
T:TR("KIT",I) A:GOVT T:TR("CIT",I) va:

$PROD:K(T,I)
       O:PK(T+1,I)       Q:((1-DELTA)*K0(I))
       O:PKT(I)$TLAST(T) Q:((1-DELTA)*K0(I))
       O:RK(T,I)         Q:K0(I)
        I:PK(T,I)        Q:K0(I)

$PROD:KN(T,I)
       O:PK(T+1, I)      Q:I0(I)
       O:PKT(I)$TLAST(T) Q:I0(I)
        I:PA(T,J)        Q:(FRAC_INV(J)*I0(I))          P:(1+STR("INVP"))          A:GOVT
T:STR("INVP")

$PROD:M(T,I)
       O:PF(T,I)       Q:((1+STR("M"))*M0(I))        A:GOVT  T:STR("M")
        I:FR(T)         Q:M0(I)
```

```
$PROD:E(T,I)
    O:FR(T)       Q:((1+STR("E"))*E0(I))      A:GOVT  T:STR("E")
    I:PA(T,I)     Q:E0(I)

$PROD:ARM(T,I) s:ESUB(I)
    O:PA(T,I)     Q:(Q0(I)+M0(I))
    I:P(T,I)      Q:Q0(I)
    I:PF(T,I)     Q:M0(I)

$PROD:W(T) s:1
    O:PW(T)       Q:W0                        A:GOVT  T:STR("W")
    I:PA(T,I)     Q:C0(I)

$PROD:GC(T) s:0
    O:PG(T)       Q:G0                        A:GOVT  T:STR("G")
    I:PA(T,I)     Q:GOVD(I)

$DEMAND:CONS s:1
    D:PW(T)       Q:(sum(I,C0(I))*QREF(T)) P:PREF(T)
    E:PL(T,I)     Q:(FS0("L",I)*QREF(T))
    E:PK(TFIRST,I) Q:FS0("K",I)
    E:FR(T)       Q:(CA0*QREF(T))
    E:FR(T)       Q:AID(T)
    E:PKT(I)      Q:(-1)   R:TK(I)

$DEMAND:GOVT s:1
    D:PG(T)       Q:(sum(I,GOVD(I))*QREF(T)) P:PREF(T)

$CONSTRAINT:TK(I)
    SUM(T$TLAST(T), KN(T,I)/KN(T-1,I) - X(T,I)/X(T-1,I)) =G= 0;
```

```
$REPORT:
*       V:L_out(T,I)    I:PL(T,I)     PROD:X(T,I)
*       V:VK_out(T,I)   I:RK(T,I)     PROD:X(T,I)
*       V:W_out(T)      D:PW(T)       DEMAND:CONS
        V:W_in(T,I)     I:PA(T,I)     PROD:W(T)
*       V:G_out(T)      D:PG(T)       DEMAND:GOVT
        V:G_in(T,I)     I:PA(T,I)     PROD:GC(T)
        V:K_out(T,I)    I:PK(T,I)     PROD:K(T,I)
        V:I_fin(T,I)    O:PKT(I)      PROD:KN(T,I)

$OFFTEXT


$SYSINCLUDE mpsgeset Van

*DISPLAY TAX, TAXC, TR, STR, INV_TOT, I0, I0_TOT, VK, RK0, K0, M0, E0, CA0;
DISPLAY TAID, AID;

X.L(T,I)  =  QREF(T);
W.L(T)    =  QREF(T);
GC.L(T)   =  QREF(T);
KN.L(T,I) =  QREF(T);
K.L(T,I)  =  QREF(T);
M.L(T,I)  =  QREF(T);
E.L(T,I)  =  QREF(T);
ARM.L(T,I) =  QREF(T);
TK.L(I)  = K0(I) * (1 + G) ** CARD(T);

P.L(T,I) = PREF(T);
PF.L(T,I) = PREF(T);
```

```
FR.L(T) = PREF(T);
PL.L(T,I) = PREF(T);
PA.L(T,I) = PREF(T);
PK.L(T,I) = (1+STR("INVP"))*(1+R)*PREF(T);
PW.L(T) = PREF(T);
PG.L(T) = PREF(T);
RK.L(T,I) = RK0*PREF(T);
PKT.L(I) = SUM(TLAST, PK.L(TLAST,I)/(1+R));

*Van.ITERLIM = 0;
*$INCLUDE Van.GEN
*SOLVE Van USING MCP;

Van.workfactor = 100;

FS0("K",I) = (1 - K_D(I))*K0(I);
Van.ITERLIM = 100000;
$INCLUDE Van.GEN
SOLVE Van USING MCP;

*GDP and growth rate calculations
Inv_ts(T,I) = K_out.L(T+1,I) - (1 - delta)*K_out.L(T,I);
Inv_ts(T,I)$TLAST(T) = I_fin.L(T,I);
GDP(T) = sum(I,W_in.L(T,I) + G_in.L(T,I) + Inv_ts(T,I)) - CA0*QREF(T) - AID(T);
GR(T) = 100*(GDP(T+1) - GDP(T))/GDP(T);
GR(T)$TLAST(T) = G*100;
LAB(T,I) = FS0("L",I)*QREF(T);


FILE OUTPUT /output.dat/;
FILE OUTPUT_TS /output_ts.dat/;
```

```
*FILE OUTPUT_D_AID /output_ts_aid.dat/;
output.nd = 5;
output_ts.nd = 5;


PUT OUTPUT;
PUT @2, 'T', @8, 'I', @19, 'X', @31, 'P', @43, 'E', @55, 'M', @66, 'PF', @79, 'K', @90,
'RK', @103, 'L', @114, 'PL'/;
LOOP(T,
LOOP(I,
PUT @1, T.TL, @5, I.TL, @9, X.L(T,I), @20, P.L(T,I), @32, E.L(T,I), @44, M.L(T,I),
@56, PF.L(T,I), @68, K_out.L(T,I), @80, RK.L(T,I), @92, LAB(T,I), @104,
PL.L(T,I)/));

PUT OUTPUT_TS;
PUT @2, 'T', @13, 'GDP', @27, 'W', @38, 'PW', @51, 'G', @62, 'PG', @74, 'FX', @86,
'GR'/;
LOOP(T,
PUT @1, T.TL, @4, GDP(T), @16, W.L(T), @28, PW.L(T), @40, GC.L(T), @52,
PG.L(T), @64, FR.L(T), @76, GR(T)/);

*PUT OUTPUT_D_AID;
*PUT @2, 'T', @13, 'AID'/;
*LOOP(T,

*PUT @1, T.TL, @4, AID(T)/);
```

Appendix E

Data to Support the Application of Resilience Quantification Framework for Metro Vancouver, British Columbia, Canada

The following Appendix is included to support the application of the resilience quantification framework to Metro Vancouver, BC. The following is a list of the data used in the creation of the model, the source of the data, and a brief description of the dataset. Supporting data files are included as part of the electronic submission, note that some of these files, while spatial in nature, are saved as matrices and require post-processing to visualize the data. Note also that there is overlap between some of the data files. This is because multiple variables and variable attributes may be contained in a single .shp or database file.

Table 9: Description of Model Input Data

Model Domain	Data Name	Data Type	Data Source(s)	Data Description	File Location in Electronic Submission & Note(s)
All	Base imagery	Aerial Photo	DataBC	Detailed aerial imagery for the Metro Vancouver area	Input geodatabase
	Digital Elevation Model (DEM)	Spatial	DataBC	High resolution digital elevations data	Hydraulics Folder
	Dissemination Areas	Spatial	Statistics Canada Census Data	Dissemination Area boundaries for Metro Vancouver	Input geodatabase
	Municipal boundaries	Spatial	GeoBase	Boundaries for each of the 21 municipalities in Metro Vancouver	Input geodatabase
Economic	Input-Output table	Numerical	Gertz (2015)	Input-output table that is used by GAMS in economic modelling	Economics folder
	Roll number	Numerical and Spatial	BCA	The identifier (ID) for each piece of infrastructure, used to link spatial and numerical data	Input geodatabase
	Buildings by industry	Numerical	BCA	An industry categorization of each building, by address	Input geodatabase
Engineering	Building value	Numerical	BCA	The reconstruction value of each building, by address	Input geodatabase * Note, real values not provided due to confidentiality
	Building type	Numerical	BCA	The building type (ex. Split-level, two-story, …), by address	Input geodatabase
	Stage-Damage curves	Numerical	FEMA (2015)	Depth-damage curves (depth v. % damage) for each type of structure. Slight	Curves built directly into Python program.

				modifications made to the FEMA curves to reflect Canadian conditions	Can reference .py file
	Power supply	Spatial	BC Hydro	Power supply to BC	Input geodatabase
Health	Public healthcare facilities	Spatial	BCA & DataBC	The location, construction value, and type of public hospital care facilities in BC	Input geodatabase
	Road network	Spatial	DataBC	The location, construction material and classification (ex. Highway, local, …) of roads in Metro Vancouver	Input geodatabase
Social	Population	Spatial	Statistics Canada	Population estimates based on the Canadian Census at the Dissemination Area level	Input geodatabase
	Cell towers	Database; converted to Spatial	Innovation, Science, and Economic Development Canada's Spectrum Management System	Locations, providers, frequency, height, and additional attributes of cellular tower services in Canada	Input geodatabase
Physical	Climate change emissions scenarios	Alpha-numeric	IPCC (2007) & IPCC (2014)	The emission scenarios used to derive the climate change influenced hazards; flooding and SLR, respectively	See IPCC reports
	GCMs	Alpha-numeric	PCIC	The GCMs used to derive climate change-influenced hazards	See PCIC documentation
	Hydrologic modelling results (Hydraulic modelling upstream boundary conditions)	Numerical	PCIC	The hydrologic modeling based on various emissions scenarios and GCMs	Hydraulics folder

Hydraulic modeling downstream boundary conditions	Numerical	MFLNRO & Agam (2014)	The SLR boundary conditions under various climate change scenarios	Hydraulics folder
Hydraulic modeling parameters	Numerical	MFLNRO	Manning's roughness coefficients	Hydraulics folder
Hydraulic modeling river geometry	Spatial	DataBC / digitization by A. Peck	River channel, tributaries, banks, flow direction, slopes, etc. On-screen digitization by A. Peck using DEMs and aerial photos	Input geodatabase
Hydraulic modeling calibration streamflows	Numerical	Water Survey of Canada (WSC)	Four streamflow / level gauges on the Fraser River for model calibration	Hydraulics folder
Hydraulic modeling validation cross-sections	Numerical	MFLNRO	A few cross sections along the Fraser River for model validation	Hydraulics folder

Appendix F
Disaster Resilience Simulation Tool (DRST) and Python Code

The following Appendix is included to provide additional details and materials to support the dissertation text. In this Appendix, the Python code for the DRST is provided. The code includes Vensim functions, ArcGIS functions, and GAMS functions. The code was written from scratch using online supporting documentation provided by ESRI and Ventana Systems. The majority of the code was written within the Spyder Python Development Environment. It should be noted that for the Python script to run, compatible versions of all three software must be installed on a single computer running Windows. The specific software versions used in developing the DRST are as follows:

- Windows 7 Professional SP1
- Vensim DSS v. 5.10e
- ArcGIS ArcMap 10.1
- GAMS 24.2.3

The reader is referred to the associated files on USB / electronic submission for the *.py* scripts, input files, and DRST tool with a graphical user interface. Supporting details on the use of the DRST can be found in Appendix H.

Note: For confidentiality purposes, the building assessment values were modified for this electronic submission. Therefore, to reproduce the results as presented in this dissertation, would require the user to obtain MPAC data and repopulate the assessment value data column in the associated GIS buildings file. As a placeholder, the buildings file included as part of this submission has had the assessment value for all buildings set to a constant value. The DRST still executes properly with this placeholder data, but will therefore not replicate exactly the results as presented

Appendix G
Fraser River Hydraulic Modelling Assumptions and Limitations

The following Appendix is included to provide additional details and materials to support the thesis text. This Appendix provides important assumptions, limitations, and recommendations for the hydraulic model of the Fraser River and its tributaries.

Hydraulic Model Assumptions

A model is a simplified representation of a real-world system. In this case, a hydraulic model is used to simulate the Fraser River and its tributaries. The current 1-D hydraulic modelling methodology is generally well accepted in the engineering community and HEC-RAS software is the current standard for hydraulic analyses used by the USACE. The current model, however, is therefore not directly compatible with the current Ministry model which uses the proprietary MIKE11 hydraulic modelling software. In order to better understand the hydraulic HEC-RAS model – specifically as it relates to the geometry file – the following are some of the assumptions that were made:

1) Split flow estimations

Split flows are the locations (or junctions) where one main branch of a river splits downstream into two or more branches. Split flows in the HEC-RAS model were handled in a similar fashion as the approach used by MFLNRO. The split flows in the model were estimated as percentages of main stem flows (Figure 69). There is currently no strong data to support these estimates, as attempts to use transducers to measure average flows at key split flow locations was abandoned after a few unsuccessful attempts as indicated in MFLNRO (2014). As such, the following split flow assumptions were made:

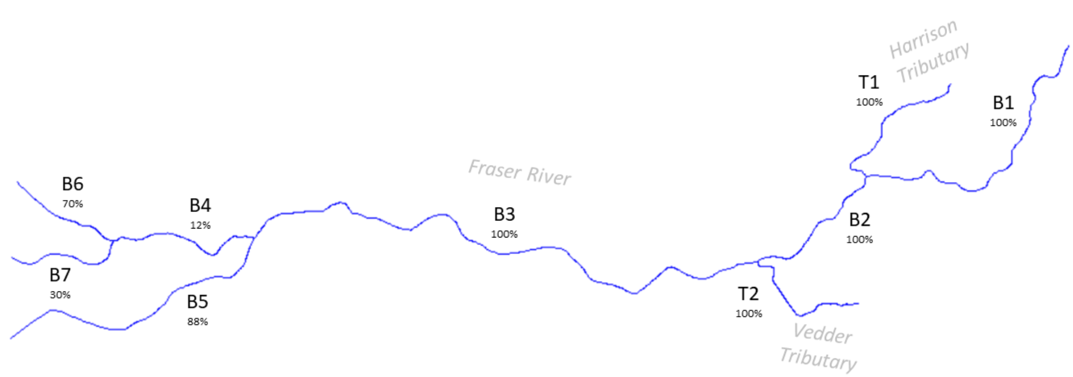


Figure 69: Flow split assumptions for the Fraser River and its tributaries

2) Not all sources of flooding were considered

Hydraulic HEC-RAS model considers the downstream boundary conditions as tide level plus climate change influences via sea level rise. Upstream conditions were driven by climate change-influenced streamflow data provided by PCIC. However, there was no considerations given to storm surge or tsunami caused inundations. At the time of writing, design criteria and parameters for tsunami mapping in BC were not yet developed and were not included in the hydraulic analysis.

Hydraulic Model Limitations

Some of the limitations in the hydraulic modelling include:

1) Inherent limitations of 1-D modelling

HEC-RAS is 1-D modelling software: but in some areas of the modeled region the flow patterns are strongly 2- and 3- dimensional (MFLNRO, 2014); the lower gravel reach has highly complex flows which may not be able to be accurately simulated by a 1-D flow model (MFLNRO, 2014). The Ministry has made some modifications to their model to try and address this limitation, but the complexity, data requirements, and time commitments were too significant to address this limitation in the HEC-RAS model used for this research and was considered out of the scope of this dissertation.

2) Exclusion of over-water infrastructure

Bridges and other over-water infrastructure were excluded from hydraulic modelling due to time constraints and lack of detailed data. This is a very significant limitation, as some of this infrastructure is extremely significant to emergency preparedness, response and recovery activities. For example, the Jacob Haldi Bridge spans the Bedford Channel of the Fraser River, connecting Fort Langley and McMillan Island. This island is home to the Kwantlen First Nations people and the bridge is the only mainland access road to the entire island (Figure 70). By not considering this over-water infrastructure, the potential back-water effects the bridge may cause will be neglected in addition to potential inundation effects on this bridge.

Figure 70: Jacob Haldi Bridge from Fort Langley to McMillan Island, BC (Google Maps, 2014)

3) Absence of sensitivity analysis to changes in bathymetry

No sensitivity analysis of model to changes in bathymetry or changes in channel bed elevations which may be especially important in the sandy/gravel reaches of the Fraser downstream of Mission. However, this is also a limitation of the current MFLNRO hydraulic model. This limitation becomes more severe when applied to the climate change scenarios combined with estimates of SLR. There are 1-D sediment transport simulation capabilities available in HEC-RAS, however due to time limitations and lack of available sediment transport data, it was excluded from this research.

4) High-level Model Calibration and Validation

The hydraulic model calibration and validation is limited. The hydraulic model used in this research was only calibrated for 2007 flows, and was not validated. Flow estimations based on climate change scenarios will be magnitudes higher than observed and therefore flows will be outside the observed/calibration/validation range which makes the actual accuracy of the hydraulic model difficult to assess.

5) Limitations in Model Accuracy

The hydraulic model is based on many assumptions and estimations of data, and therefore should not be used for any other purposes than for simulations and analysis using the DRST. Given these limitations, it is important to acknowledge that there will be significant differences between the HEC-RAS model simulated values and recorded observations at river gauge stations.

Despite the aforementioned assumptions and limitations, it should be noted that the inundation maps generated in this hydraulic analysis should be sufficient for making relative comparisons of climate change impacts for the region of Metro Vancouver. The maps generated from hydraulic analysis include estimates of future precipitation and runoff events and incorporate regional SLR projections which is used as input into the proposed DRST for the purposes of assessing the impacts of climate change on Metro Vancouver. Since all scenarios are run using the same river geometry and characteristics, in relative terms they should be adequate for relative comparisons between all of the DRST simulation scenarios.

Hydraulic Modelling Recommendations

The following is a list of recommendations for anyone interested creating their own hydraulic model and performing hydraulic simulation to generate inundation maps. Although some of the recommendations are specific to modelling the Fraser River and its tributaries, many of them could be generalized and extended in pursuit of any hydraulic modelling effort in a large basin characterized by complex over-bank urban areas.

1) If the Ministry ever releases their MIKE11 model for open use then the proposed HEC-RAS model should be abandoned and the Ministry's MIKE11 model should be adopted. The Ministry's model will be more detailed and more accurate.

2) 1-D modelling is not sufficient for modelling complex urban environments such as the Metro Vancouver delta region. Therefore, future studies should consider 2-D modelling and simulation to more accurately project river flows.

3) Continued monitoring and station measurements would continue to help verify model projections.

4) For any future proposed over-water infrastructure or land use changes which may significantly modify roughness values of the right overbank, left overbank, or channel, the hydraulic model should be updated to accommodate for these new channel geometries and the simulations should be run again to determine if there are significant changes in flow patterns (and corresponding floodplains).

5) Similarly, if the Ministry releases any more detailed information on their hydraulic analysis, the current HEC-RAS model should be updated.

6) The current hydraulic analysis does not include dike breach analysis. In the proposed HEC-RAS modelling, dikes may be overtopped, but does not account for any other failure mechanisms including, but not limited to: foundation failures, slope failures, liquefaction, erosion or piping. This would be good material for a separate study to determine if the current levees are at risk from other modes of failure which may cause localized flooding.

7) The DRST uses inundation maps generated using GIS tools (ArcMap's HEC-GeoRAS extension) and HEC-RAS v.4 software. Since then, newer versions of HEC-RAS have been released. At the time of writing, the current version is 5.0.7. Version 5 software was released by USACE in 2016 and offers improved functionality over version 4. Version 5 has moved away from reliance on ArcGIS software and HEC-RAS v.5.x offers integrated GIS support, directly within the HEC-RAS interface in a tool called RasMapper. Due to the significant pre- and post-processing requirements for combined use of HEC-RAS v.4.x and HEC-GeoRAS, it is highly recommended that the most recent release of HEC-RAS be used to prepare inundation maps, going forward.

8) Inundation maps developed using the HEC-RAS model presented as part of this work are intended to support this research only and should not be used for any real design or future planning purposes; they are rough estimations developed to illustrate the methodology developed as part of this research and are in no way endorsed by the MFLNRO or any other BC department or agency.

Appendix H
Disaster Resilience Simulation Tool (DRST)
Graphical User Interface (GUI)

The Disaster Resilience Simulation Tool can be executed by running the *resilienceGUI.py* file (included as part of the electronic submission). To do this, the user must have Python 2.x installed on their machine. Note: if the user has ArcMap 10.x installed with the default configuration settings, **then Python should already be installed on the machine**. There are two ways in which the Python script can be executed: calling a Python interpreter directly, or within an interactive Python shell. For most users, this will be accomplished through either the Python command line, IDLE (Python GUI that is installed as part of ArcGIS installation), or Spyder (common open-source cross-platform development environment; the one used in the development of this tool).

Once the python *resilienceGUI.py* file has been executed, the user will be presented with the GUI input screen (Figure 71).

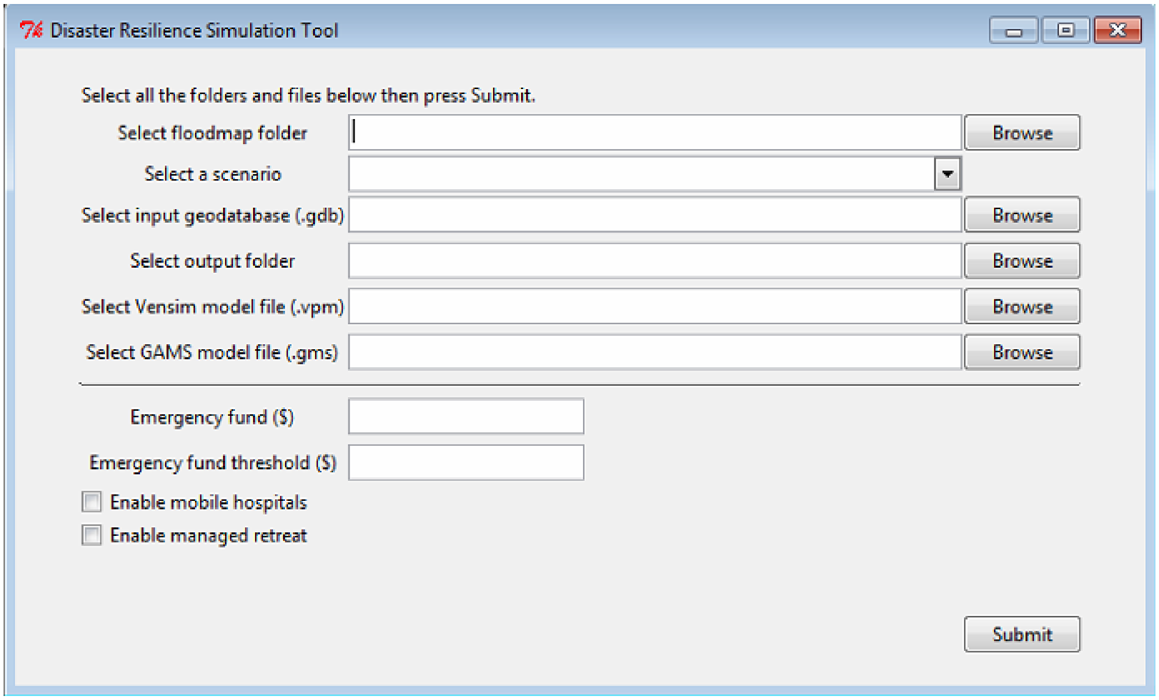


Figure 71: DRST graphical user interface (GUI) screen

This is where the user is prompted to select various simulation inputs and options. Some of these fields may be populated with default data, which can be modified by the user. It is recommended that the user completes the information in a top-down sequence as presented in the GUI. A description of the simulation options is as follows:

Select floodmap folder: This is where the user can select the location that the continuous modelling flood inundation maps are stored. The user can navigate to any accessible folder on their computer, however for performance reasons it is recommended that this folder be saved to a local (C:\) drive.

Select a scenario: This object allows the user to select one of the flood map scenarios. This dropdown list populates with the flood map scenarios from the folder identified by *select floodmap folder*. Only the options in the specified floodmap folder are available.

Select input geodatabase (.gdb): This is where the user can select the (ESRI) geodatabase that contains all of the input files. The extension of this file should be .gdb.

Select output folder: This is the where the user can specify an output folder. The output folder will contain all of the output files generated during the simulation. This is where maps and tables will be stored. Note that if the user wishes to run multiple simulations, a new output folder should be specified for each simulation so that files are not accidentally overwritten.

Select Vensim model file (.vpm): This is where the user can select the Vensim model to be run as part of the simulation. In this research, there is only one model to run, but this input option allows the model to be stored anywhere on the user's computer. Note that this file is .vpm which is a published Vensim model file, and not the traditional .mdl format. The tool comes with the published model file (.vpm), however if for any reason the user wishes to make modifications to the Vensim model directly, the .mdl file can be opened in Vensim, modified, and then subsequently needs to be republished (to .vpm format) before it can be run as part of the DRST. For more information on publishing Vensim models, the user is referred to Vensim help documentation available through the Vensim GUI or online at: https://www.vensim.com/documentation.html.

Select GAMS model file (.gms): This is where the user can specify the location of the GAMS model to be run as part of the simulation. In this research, there is only one model to run, but this input option allows the user to navigate to the stored file anywhere on the user's computer.

The following are a set of simulation options available to the user at the beginning of the simulation:

Emergency funds ($): This is where the user can specify the amount ($) of emergency funding available during a simulation. The entry must be of type integer with a value greater than or equal to zero. The format should be continuous digits with no commas, no spaces, and no special characters. If the user wishes to make an infinite source of funding available during a simulation, this can be proxied by entering a very large number (for example, 999999999999). If the user wishes for no funding sources to be made available during a simulation, then the user should enter a value of zero (0).

Emergency fund threshold ($): This is where the user can specify the amount ($) of damage that triggers the use of the emergency funds during a simulation. The entry must be of type integer with a value greater than or equal to one. The format should be continuous digits with no commas, no spaces, and no special characters. If the user wishes to provide access to the emergency funds immediately, the user should enter a value of one (1). If the user does not want emergency funds to ever become available, the user can proxy this situation by entering a very large number (for example, 999999999999).

Enable mobile hospitals: This is where the user can specify whether to implement a mobile hospital station during a simulation. The radio button can be toggled on/off for yes/no. If toggled off, no mobile hospitals will be added during the simulation. If toggled on, then a mobile hospital is placed within Metro Vancouver during the simulation. The mobile hospital will be added to the simulation at time step 6. Currently, the user does not have control over when or where the mobile hospital is deployed during a simulation. Once the mobile hospital is deployed, it is assumed to remain in place for the remainder of the simulation.

Enable managed retreat: This is where the user can specify whether to implement managed retreat during a simulation. The radio button can be toggled on/off for yes/no. If toggled off, managed retreat does not occur during the simulation. If toggled on, then the managed retreat of Pitt Meadows area is assumed to have taken place before the simulation has started. Currently, the user does not have control over when or where the managed retreat occurs during a simulation. Once managed retreat has occurred, it is assumed the land is uninhabited for the remainder of the simulation.

Once all of the input files and folders, output locations, and simulation options have been set, the user can press the *Submit* button and the simulation will proceed. The user should not click on the interface during a simulation – this can cause instabilities which may cause the model to crash. The user will be prompted once the simulation is complete and output files will be saved in the output folder.

Additional notes:

- The user should confirm system and software requirements (per Appendix F) to ensure the Python program is able to run on their machine.
- The user should be careful not to modify the names of any of the input files contained within the DRST inputs geodatabase; this may result in undesirable behaviour and the program may crash.
- The program creates intermediate files which are saved to a default folder automatically generated by the program in the same location as specified by the user in the GUI for saving model outputs. These files represent intermediate maps and tables which were created during the simulation. However, they get overwritten at each time step (primarily to save disk space) so files in the intermediate folder will be representative of the simulation at the last time step only.
- Simulation times are about 4 – 6 hours, though times may vary depending on the user's system hardware and processing capabilities.

It is recommended that the user have at least 64GB of free space on their machine to run the DRST and save simulation outputs.

Appendix I

Curriculum Vitae

Name	Angela M. Peck
Post-Secondary Education	The University of Western Ontario, Canada Ph.D. Candidate 2011 – Present The University of Western Ontario, Canada Civil and Environmental Engineering 2011, M.E.Sc. The University of Western Ontario, Canada Civil and Environmental Engineering 2008, B.E.Sc.
Engineering Employment	Associated Engineering (AE) Civil Designer, Infrastructure Division Climate Change Subject Matter Expert 2017 - Present
Awards & Achievements	Alexander Graham Bell Canada Graduate Scholarship (NSERC CGS D), Jan 2012 - Dec 2014 Nominated for Teaching Assistant Award, 2011 Ontario Graduate Scholarship (OGS), 2009 – 2010 DeMarco Family Green Technologies Award, 2008 The University of Western Ontario Entrance Scholarship, 2004
Teaching Experience	Instructor, 2017 Winter CEE 9567b: GIS Applications to Water Resources Management Instructor, 2016 Winter CEE 9567b: GIS Applications to Water Resources Management CEE 2219b: Computational Tools for Civil Engineers Certificate in University Teaching and Learning, 2015 – Present

Completion of Advanced Teaching Program (ATP), 2015

Teaching Assistant, 2008 – 2015
Department of Civil and Environmental Engineering, The University of Western Ontario, London, Canada

Undergraduate courses:
CEE 2218: Civil Engineering Systems
CEE 3324: Surveying
CEE 3361: Water Resources Management
CEE 4461: Natural Disasters
ES 4498: Engineering Ethics

Graduate courses:
CEE 9510: Engineering Planning and Project Management

Specialized Training

ESRI Earth Imagery at Work (2017)
ESRI Going Places with Spatial Analysis (2016)
NASA ARSET Applied Remote Sensing Training (2016, 2018)

Publications

I. Articles published or accepted in refereed journals

Neuwirth, C., Hofer, B. and **Peck, A.** (2015). Spatiotemporal Processes and their Implementation in Spatial System Dynamics Models. *Journal of Spatial Science*, 12pp. Doi: 10.1080/14498596.2015.997316.

Neuwirth, C., **Peck, A.** and Simonovic, S.P. (2015). Modeling Structural Change in Spatial System Dynamics: A Daisyworld Example, *Environmental Modelling & Software*, 65:30-40.

Simonovic, S.P. and **Peck, A.** (2013). Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities – Quantification Framework. *British Journal of Environment and Climate Change*, 3(3): 378-401.

Peck, A., Bowering, E. and Simonovic, S.P. (2013). A flood risk assessment to municipal infrastructure due to changing climate part II: case study. *Urban Water Journal*. Doi:10.1080/1573062X.2013.781760.

Bowering, E., **Peck, A.** and Simonovic, S.P. (2013). A flood risk assessment to municipal infrastructure due to changing climate part I: methodology. *Urban Water Journal*. Doi:10.1080/1573062X.2012.758293.

Peck, A., Prodanovic, P. and Simonovic, S.P. (2013). Rainfall Intensity Duration Frequency Curves Under Climate Change: City of London, Ontario, Canada. *Canadian Water Resources Journal*, 37(3), 177-189.
Karmakar, S., Simonovic, S.P., **Peck, A**., and Black, J. (2010). An Information System for Risk-Vulnerability Assessment to Flood. *Journal of Geographic Information System*, 2, 129-146.

II. Other Refereed Contributions (* indicates oral presenter)

Peck, A.*, and Simonovic, S.P. (2016). Use of Resilience in Adaptation to Climate Change Caused Natural Disasters. Adaptation Canada 2016, Ottawa, ON, April 12-14.

Peck, A.*, and Simonovic, S.P. (2015). Climate Change Influenced Riverine Flooding and Sea Level Rise on Canada's West Coast. Canadian Society for Civil Engineering (CSCE) 22^{nd} Hydrotechnical Conference, Montreal, QC, April 30-May1.

Neuwirth, C.*, and **Peck, A.** (2013). A Conceptual Spatial System Dynamics (SSD) Model for Structural Change in Grassland Farming. In Piantadosi, J., Anderssen, R.S., and Boland, J. (eds) MODSIM2013, 20^{th} International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, December 2013, pp. 628-634.

Peck A.*, Bowering, E.*, and Simonovic, S.P. (2010). Assessment of Climate Change Risk to Municipal Infrastructure: A City of London Case Study. Canadian Society for Civil Engineering (CSCE) Annual General Meeting and Conference, 11th International Environmental Specialty Conference, Winnipeg, MB, June 9-12.

Bowering E.*, **Peck A.*,** and Simonovic, S.P. (2009). A Methodology for Risk Assessment of Municipal Infrastructure due to Climate Change: A Case Study of London, Ontario. Proceedings of the American Geophysical Union (AGU) Annual Fall Meeting, San Francisco, CA, December 14-18.

Peck, A.*, Black, J., Karmakar, S., and Simonovic, S.P. (2008). A Web-based Flood Information System. CD Proceedings, 4th International Symposium on Flood Defence: Managing Flood Risk, Toronto, Ontario, Canada, May 6-8.

III. Non-Refereed Contributions
Peck, A., Neuwirth, C. and Simonovic, S.P. (2014). Coupling System Dynamics with Geographic Information Systems: CCaR Project Report. Water Resources Research Report no. 086, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 60 pages. ISBN: (print) 978-0-7714-3069-5; (online) 978-0-7714-3070-1.

Peck A. and Simonovic, S.P. (2013). Coastal Cities at Risk (CCaR): Generic System Dynamics Simulation Models for Use with City Resilience Simulator. Water Resources Research Report no. 083, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 55 pages. ISBN: (print) 978-0-7714-3024-4; (online) 978-0-7714-3025-1.

Peck, A., Bowering, E. and Simonovic, S.P. (2011). City of London: Vulnerability of Infrastructure to Climate Change, Final Report. Water Resources Research Report no. 074, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 66 pages. ISBN: (print) 978-0-7714-2895-1; (online) 978-0-7714-2902-6.

Peck, A., Bowering, E., and Simonovic, S.P. (2010). Draft Report (Outcome 5, 6 & 7): Impact of Climate Change to Municipal Infrastructure: A City of London Case Study. Project Report, the City of London, ON, September 2010.

Simonovic, S.P. and **Peck, A.** (2010). Updated Rainfall Intensity Duration Frequency Curves for the City of London Under the Changing Climate. Water Resources Research Report no. 065, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada. ISBN: (Print) 978-0-7714-2819-7; (Online) 978-0-7714-2820-3.

Bowering, E., **Peck, A.,** and Simonovic, S.P. (2009) Status Report 1 – Project Definition Report. The City of London, ON. March 2009.

Peck, A., Karmakar, S., and Simonovic, S.P. (2007). Physical, Economical, Infrastructural and Social Flood Risk - Vulnerability Analyses in GIS. Water Resources Research Report no. 057, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada. ISBN: (Print) 978-0-7714-2662-9; (Online) 978-0-7714-2663-6.

IV. Other Contributions

Keynote Speaker, 5th International Conference on Geoinformation Technologies for Natural Disaster Management (GiT4NDM). Mississauga, Ontario, October 9-11, 2013.

Panel Member, Translating Climate Model Outputs into Engineering Parameters for the Transportation Sector, Climate Adaptation Futures: Second International Climate Change Adaptation Conference 2012. Tucson, AZ, May 29-31, 2012.