Floods: Mapping Vulnerability in the Upper Thames Watershed under a Changing Climate

CFCAS Project:
Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions

Project Report XI

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TABLE OF CONTENTS

1. INTRODUCTION

Extreme events or natural hazards such as floods, droughts, and windstorms are acute examples where climate and socio-economic systems interact resulting in lives lost, economic damages, and disruption of lives, infrastructure, and ecosystems. Vulnerability assessments have been undertaken to understand the "potential for loss" or "vulnerability"; traditionally they focused on the nature of the hazard and who and what are exposed (Cutter 2001). More recently, vulnerability assessments have explored the social, economic, and political conditions that are likely to affect the capacity of individuals or communities to cope with or adapt to hazard(s) (Cutter 1996). The vulnerability profile of a community is not only dependent on external environmental conditions – the hazard(s) and internal biophysical characteristics of the system influencing susceptibility but is also socially constructed by the attributes of individuals and social groups within the system and external human system factors such as policies and institutions which affect the capacity to respond or adapt (Füssel 2007). From a hazards perspective, vulnerability assessments provide insights into responses necessary to prevent loss of life, damages, or in worst cases disasters (Cutter 1996). From a climate change perspective, capturing the differential elements of vulnerability is a prerequisite for developing adaptation policies that will promote equitable and sustainable development (Vogel and O'Brien 2004).

Flooding is the most common natural hazard affecting Canada today (Wianecki and Gazendam 2004a; ICLR 2007). According to Emergency Preparedness Canada's Disaster Database, there have been a total of 168 flooding disasters reported in Canada between 1900 and June 1997, 37 of which occurred in Ontario (Shrubsole et al. 2003). Over this period, the number of flooding disasters has increased, with more than 70% of the flooding events occurring after 1959. The likely causes are due to a shift in climate, increasing development on the floodplain, and improved record keeping and reporting practices (Shrubsole et al. 2003). Over 65% of the recorded flooding events were the result of snowmelt runoff, storm rainfall events, or a combination of both (Brooks et al. 2001 in Shrubsole et al. 2003); and 40% of the flooding occurred in April and May coinciding with spring snowmelt (Shrubsole et al. 2003). Other causes of flooding include ice jams, catastrophic outbursts, urban stormwater runoff, and dam/structural failure.

Flooding is also the most costly natural hazard for Canada in terms of property damage and loss (PSEPC 2005a; ICLR 2007). Significant flooding events reported by Public Safety and Emergency Preparedness Canada (PSEPC) occurred in 1996 in the Saguenay River, Quebec ($1.5 billion); in 1950 in the Red River, Manitoba ($1.09 billion); in 1954 in Ontario from Hurricane Hazel ($1.03 billion); and in 1999 in the Red and Assiniboine Rivers, Manitoba ($815 million) (2005b). These damage figures are reported in 2000 Canadian (CDN) dollar amounts.

A preliminary analysis of floods occurring between 1990 and 2003 in Ontario suggests that the frequency of flood events is increasing (Wianecki and Gazendam 2004b). Flood damage to personal property and community disruption is also rising but fatalities are decreasing (Wianecki and Gazendam 2004a). This increase in flood damage can be explained by rapid population growth and development, land use changes, an increase in property values, and ageing infrastructure, as well as an increase in the frequency of flood events (Wianecki and Gazendam 2004a). Data also indicate a shift in the timing of floods. The Water Network examined Ontario's flood history from the period 1680-1989 and found that all of the floods occurred in March and April during springmelt; since 1991, flooding has shifted to a year-round phenomena influenced by ice jams, rain, and thunderstorms (Wianecki and Gazendam 2004b).

In recent years, a number of communities in Ontario have experienced significant damages from severe flooding events related to intense precipitation events. They include:

- an August 19, 2005 storm in the Toronto Region, where 100-150 mm of rain fell within one hour causing an estimated $10-11 million in municipal costs for repairing roads and infrastructure. Insurance claims were estimated at $350 million (TRCA 2006).
- the July 14-15, 2004 Peterborough storm, where 250 mm of rain fell in 41 hours. Insurance claims for private and commercial property damage were over $87 million as roads were flooded, sewer systems backed up, and 4,500 homes and many commercial buildings were damaged (Klaassen and Seifert 2004).
- Hurricane Francis on September 9, 2004, where 100-150 mm of rain fell in 12 hours on eastern Ontario resulting in $58 million in claims but no lives lost. In comparison, Hurricane Hazel in 1954 resulted in $1 billion 2004 CDN in damages and 81 lives lost. The storm affected transportation, sewage treatment, and electrical infrastructure systems (Klaassen and Seifert 2004).
- the 49th Parallel storm occurring over the period June 8-11, 2002 was a significant severe rainstorm (with total rainfalls of 200-400 mm) that produced flooding and record streamflows in north-western Ontario, south-eastern Manitoba, and northern Minnesota. In north-western Ontario, there were $31 million in damages including $3 million to infrastructure. There were 11 homes seriously damaged, railway lines impacted, and 13 First Nation communities affected (Acres International Limited 2003; Murphy et al. 2003).
- a storm in Peterborough on June 12, 2002 with 200 mm of rain in 11 hours resulted in $17 million in damages (Klaassen and Seifert 2004).
- a storm in the Grand River watershed on June 13-14, 2004 that deposited 200 mm of rain (more than 150 mm of rain fell in less than 6 hours on June 14), and resulted in significant flooding with roads washed out, basements flooded, and significant soil erosion (Klaassen and Seifert 2004).

Human-caused climate change, due to rising concentrations of greenhouse gases, is very likely to increase the intensity of precipitation enhancing the potential risk of flash flooding and urban flooding and increasing community exposure to this hazard (Kundzewicz et al. 2007; Meehl et al. 2007). With warming, the waterholding capacity of the atmosphere increases and the additional water vapour enhances the risk of heavy precipitation events (Allen and Ingram 2002; Hegerl et al. 2007; Trenberth et al. 2007). Already, global observations show changes in the amount, intensity, frequency, and type of precipitation with widespread increases in the heaviest events (95th and 99th percentiles) in the mid-latitudes over the last 50 years even where total precipitation has decreased. The number of heavy daily precipitation events that lead to flooding has also increased but not everywhere (Trenberth et al. 2007). In North America, total annual precipitation is projected to increase due to climate change (Christensen et al. 2007). Climate modelling shows that precipitation intensity is also projected to increase (Meehl et al. 2007). A greater proportion of total precipitation will be concentrated in heavy precipitation events and the intensity of these events will rise when total precipitation increases (Hegerl et al. 2007). The increase in precipitation extremes is greater than changes in mean precipitation (Kharin and Zwiers 2005). Future flood damage from more intense precipitation events will depend on the capacity of populations and communities to adapt.

There are numerous studies that have addressed contemporary vulnerability of Canadian communities to flooding from the natural hazards perspective of understanding flood exposure and the number of people and structures affected (e.g. Roy et al. 2001; Nirupama and Simonovic 2007) but few that explore the socio-economic aspects of flooding vulnerability (Morris-Oswald and Simonovic 1997; Enarson 1999; Enarson and Scanlon 1999; Natural Hazard Center 1999). In the climate change impacts and adaptation field, vulnerability is in its early conceptual development with some vulnerability assessments in developing and developed countries on coastal flooding and agricultural effects for example (Wu et al. 2002; Leichenko et al. 2004; O'Brien et al. 2004a). In Canada, some studies have assessed the effects of climate change on flooding hazard (Roy et al. 2001; Cunderlik and Simonovic 2005; Huang et al. 2005) but there are no vulnerability assessments that explore the changing exposure of a community to flooding due to climate change and the social aspects of vulnerability that influence the capacity to cope or adapt.

This vulnerability assessment uses a place-based approach (Cutter et al. 2000) and examines the changing exposure of an urban area to riverine flooding due to climate change scenarios, and the socio-economic and physical attributes of the place that influence the capacity to cope or ability to adapt to flooding. This assessment is a component of the research project, "*Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions*" funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), which is a collaboration between the Universities of Waterloo and Western Ontario, Environment Canada, and the Upper Thames River Conservation Authority (UTRCA). The main objectives of the project are to 1) develop water resources risk and vulnerability assessment tools, 2) assess climatic vulnerability of the Upper Thames river basin, and 3) recommend guidelines for vulnerability reduction and hazard mitigation in order to improve the understanding of the processes leading to hydrological hazards, including floods and drought.

This vulnerability assessment builds upon the climate change scenario-generating techniques and hydrologic modelling developed in other components of the CFCAS research project (Figure 1) and explores the vulnerability of the Upper Thames River watershed, specifically the Forks of the Thames River area in London, Ontario, to current and future flooding scenarios resulting from intense rainfall events. While the original scope of the project included an examination of drought risk, drought scenarios were not wholly developed for the vulnerability assessment. Therefore, this report focuses solely on vulnerability to flooding. A profile of vulnerability is developed by assessing:

- biophysical properties or system attributes, here infrastructure, that are susceptible to perturbation, and
- socio-economic characteristics of the community that influence response capacity or adaptation to flooding.

In addition to traditional measures of determining the number of people and structures affected, this assessment uses indices to measure the vulnerability of the Forks of the Thames River area in London, Ontario to flooding hazard in a changing climate. A Geographic Information System (GIS) is used to map the changing flood exposure and integrate the socio-economic data into vulnerability indicators and map their spatial distribution in the Forks of the Thames study area.

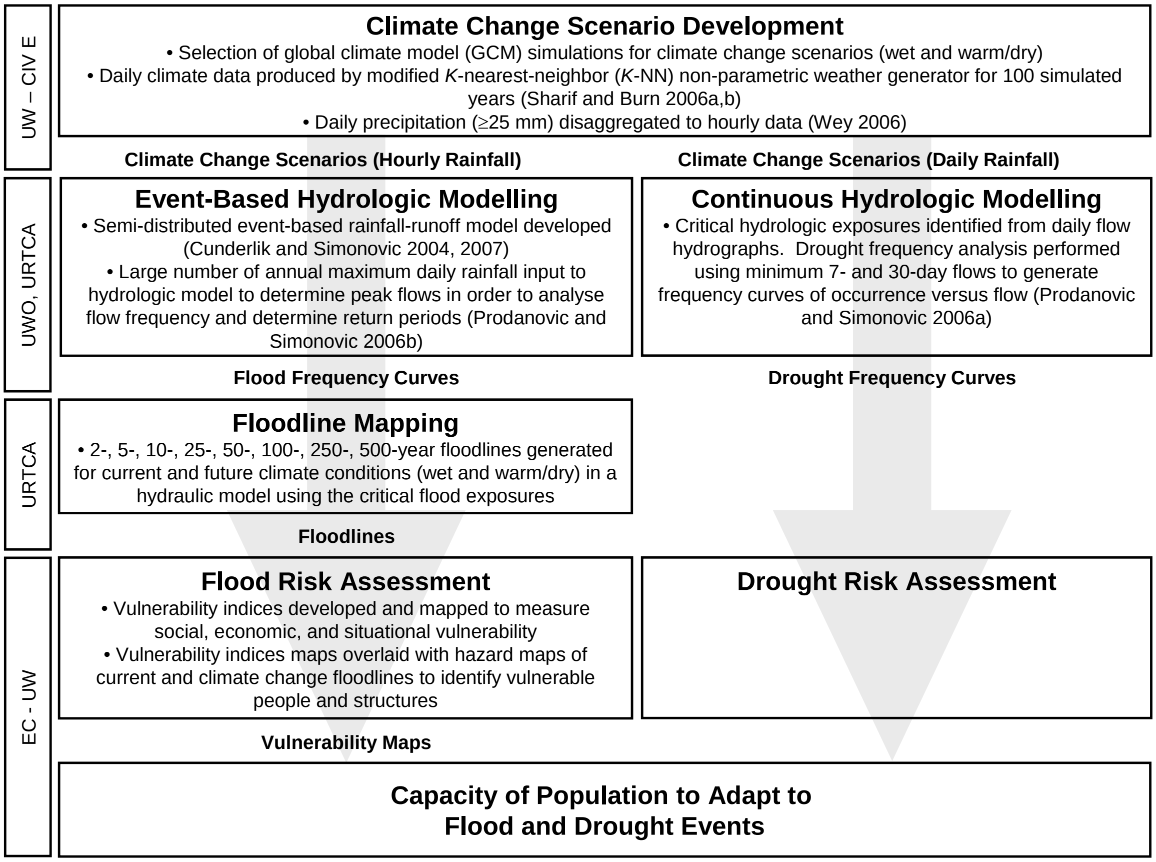

Figure 1 Diagram outlining the components of and associated leads for the "*Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions*" project; where, EC = Environment Canada; UW = University of Waterloo; CIV E = Department of Civil Engineering; UWO = University of Western Ontario; UTRCA = Upper Thames River Conservation Authority.

2. THE STUDY AREA

The Upper Thames watershed, located in south-western Ontario (Figure 2a), covers an area of 3,432 km^2 (UTRCA 2006a). The watershed has a population of 485,000 with the majority living in the City of London (UTRCA 2006a). The watershed is predominately agriculture, representing 78% of the total area. Forest and urban areas cover another 21% of the watershed (12% and 9%, respectively) while the remaining watershed is classified as quarries and water (UTRCA 2002). There are two main branches of the Thames River (Figure 2b). The north branch flows southerly from the top of the watershed near Mitchell, and the south branch flows south-westerly from the eastern portion of the watershed near Woodstock. This study focuses on the Forks of the Thames, the confluence of the north and south branches of the Thames River near the centre of the City of London (Figure 2c). From the Forks, the Thames River continues to flow west, past the town of Delaware through the Lower Thames River watershed eventually draining into Lake St. Clair, north of Tillbury.

Flood History

Historically, the Thames River has experienced several severe flooding events and associated damages (Wianecki and Gazendam 2004b; Helsten and Davidge 2005). Aboriginals and early European settlements located on the extensive floodplain of the Thames to take advantage of the river's abundant resources and to utilize the river as a transportation corridor. The first written account of flooding along the Thames occurred in 1791, and although floods have occurred regularly after that, flooding was not as severe and development continued on the floodplain for the next century. Then in July 1883, severe flooding along the Thames River killed 17 people in London and caused extensive damage, prompting the City of London to build a series of dykes to protect properties in low-lying areas along the river (UTRCA 2006b).

The dykes did not prove effective when the worst flooding event occurred in April 1937 after nearly six inches (approximately 152 mm) of rain fell in five days over south-western Ontario. On April 26, the North Thames rose 15' (4.5 m) near Fanshawe in a few hours resulting in extensive flooding of many areas along the river in the City (Figure 3). The South Thames branch rose 13'9" (4.2 m) and continued to rise as the north branch was falling. On April 27, the river rose to a record 21'6" (6.5 m) above mean summer level and just below the confluence, the flood water level reached 23' (7 m) above normal summer level with the Springbank dam closed. The flood resulted in \$3 million (1937 CDN) in property damage, destroyed 1,100 homes, and killed five people (UTRCA 2006c). Many roads, bridges, and dams were heavily damaged within the watershed. Flooding also occurred in 1947, when flood water overtopped the dyke on the North Branch, but was not as severe as in 1937. As a result of these flooding events, a series of dams (Fanshawe, Wildwood, and Pittock Dams) were constructed to control flooding and prevent similar events from occurring in the future. More recently, less severe floods have occurred in the watershed in March 1977, September 1986, September 1997, and July 2000 (Figure 4) but they did not breach the dykes protecting the city (UTRCA 2006b,d).

Figure 4 Flooding at the Forks of the Thames in July 2000 (UTRCA 2006b).

Figure 2 The Forks of the Thames study area located in the Upper Thames Watershed in south-western Ontario.

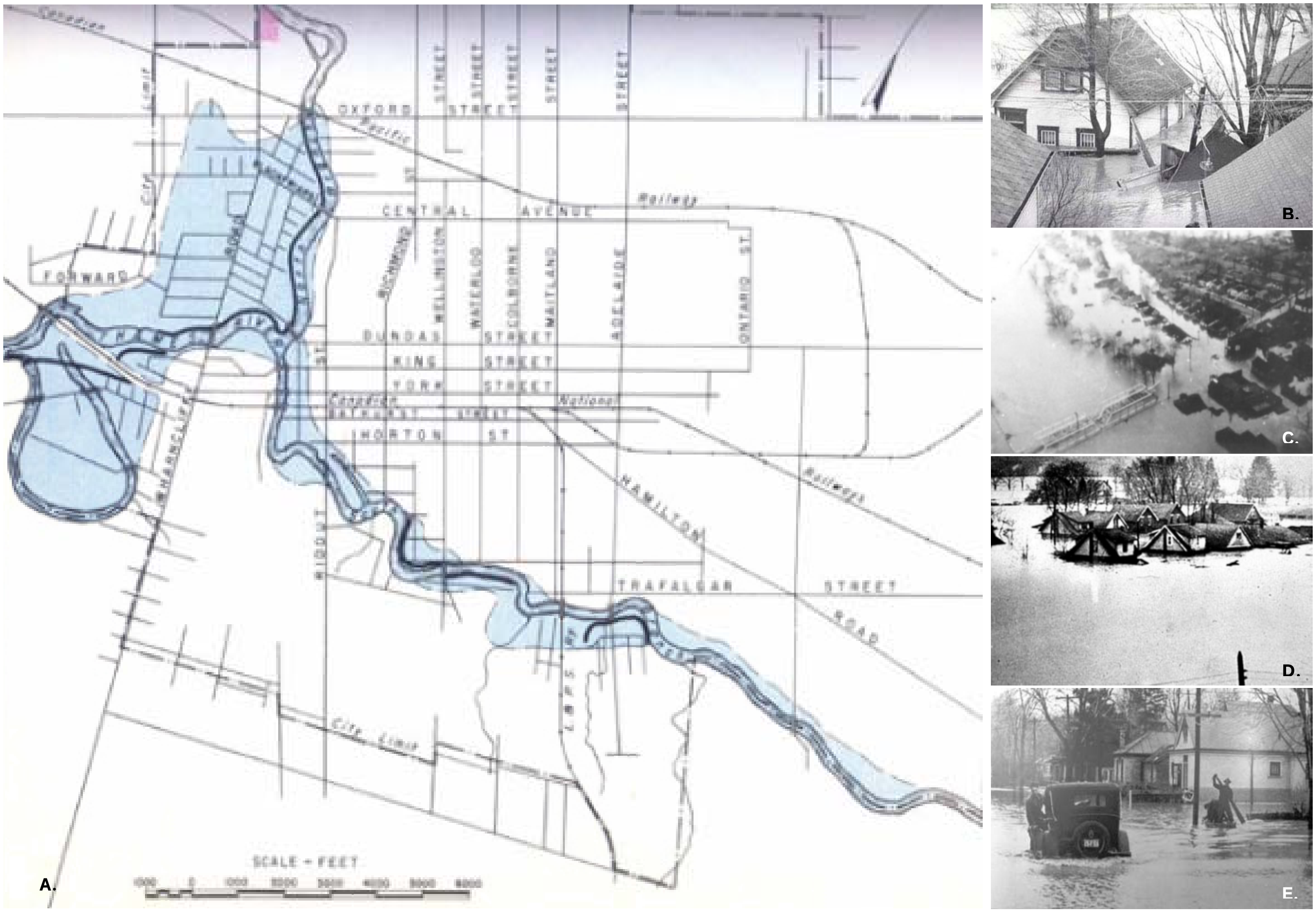

Figure 3 Impacts of the 1937 Flood in London; a) the extent of flooding at the Forks of the Thames (flooded area highlighted in blue); and flooded homes b) along Front Street, c) on Front Street by the Wellington Road Bridge over the South Thames, d) in the Cove, and e) in west London (URTCA 2006c).

3. CAPACITY TO ADAPT TO FLOODS

A discussion of the vulnerability literature follows. The concept of vulnerability is described. Different perspectives on assessing vulnerability from the classic or natural hazards approach to a social sciences approach and vulnerability of place will be introduced. Indicators of vulnerability, specifically related to flooding, will be described. The section concludes with a description of GIS and its usefulness in conducting vulnerability assessments.

Vulnerability

Vulnerability, a key concept in human-environment research, is multi-dimensional and its conceptualization has developed over time (Dow 1992; Dow and Downing 1995; Cutter 1996; Hewitt 1997; Jones and Shrubsole 2001). It reflects the contribution from a wide range of disciplines including global environmental change (Liverman 1990), engineering (Hashimoto et al. 1982), anthropology (Finan et al. 2002), hazards and disaster studies (Cutter et al. 2000; Jones 2004), and climate change (Kelly and Adger 2000; Smit et al. 2001). As a result there are competing and often contradictory definitions but broadly vulnerability means "the potential for loss" (Cutter 1996; O'Brien et al. 2004b). This study draws upon the theoretical underpinnings of the natural hazards and disaster, and climate change assessments fields (Cutter et al. 2000; Flax et al. 2002; Wu et al. 2002). Traditional natural hazards and disaster studies explore the biophysical aspects of vulnerability – exposure to a hazard, distribution of hazardous conditions, effects on people and structures, estimation of the potential damages, and identification of adjustments available to individuals and society (Burton et al. 1993; Cutter et al. 2000). Another conceptualization – social vulnerability – has gained prominence in the literature. Vulnerability is socially constructed. It is related to characteristics that influence an individual's or group's ability or inability to anticipate, cope with, resist, and recover from or adapt to any external stress such as the impact of flooding (Blaikie et al. 1994; Kelly and Adger 2000; Montz and Evans 2001). Relevant socio-demographic characteristics include age, socio-economic status, experiences, gender, race, and wealth. The research has evolved again to a "vulnerability of place" approach which integrates biophysical and social vulnerability within a particular geographic region; the approach not only considers the hazards themselves but the unique contexts within which they were imbedded (Cutter et al. 2000). Vulnerability is directly related to the degree of exposure and inversely related to the capacity to cope and recover or adapt (Finan et al. 2002). Therefore, not only is it important to identify high risk areas, it is critical to identify vulnerable populations, understand what causes people to be vulnerable, and assess the measures that can reduce vulnerability (Blaike et al. 1994). Vulnerability can be reduced by identifying, helping, and empowering those who are most vulnerable (Hewitt 1997).

In the hazards and disaster field, there was growing recognition that there was a need to reorient emergency management systems to be more proactive in reducing losses (life and property) and future hazard impacts through mitigation, preparedness, response, and recovery rather than focusing on rescue and post-event clean-up. This was based on the growing recognition that the degree to which populations are vulnerable to hazards is not merely dependent on the exposure to the hazard – proximity to the source of the threat or the physical nature of the hazard – but it is also socially constructed and based on social, economic, and political factors that have a role in defining vulnerability. Some population subgroups because of disparities in wealth, socioeconomic status, and housing have an increased potential for losses due to hazards as they have less ability to adapt – cope or respond. Access to resources, be they economic, social, or political, are fundamental to the adaptation process and differential access to resources to mobilize to adapt influences vulnerability of households, individuals, and communities. Adaptation relies on human and financial capital (knowledge and money) and changes and readjustments in social organization (investments in social and political capital) to reduce vulnerability (Blaikie et al. 1994).

In the climate change context, vulnerability is the degree to which a system is susceptible to or unable to cope with adverse effects of climate change including variability and extremes; it is a function of the character, magnitude, rate of variation of exposures, sensitivity, and adaptive capacity (Smit et al. 2001). In climate change research, vulnerability and adaptation are key concepts. If climate vulnerability is an undesirable state of risk faced by an individual or group, adaptation can be seen as the sets of system changes, or behavioural responses, that seek to diminish this vulnerability (Finan et al. 2002). Climatic extremes such as flooding and a suite of socio-economic system characteristics are interwoven to produce patterns of vulnerability and adaptive capacity. Political, economic, and social conditions as well as physical and geographic phenomena create vulnerability for certain populations/communities (Finan et al. 2002).

Füssel (2007) has tried to reconcile and integrate the conceptualizations of vulnerability from a variety of schools of research to inform climate change impact assessment and vulnerability research. The dimensions of vulnerability are summarised in the conceptual framework outlined in Figure 5. There are four vulnerability factors based on whether they are internal or external to the system/community being studied and whether they are focused on socio-economic or biophysical characteristics. This study touches upon three quadrants of the vulnerability domain and include the internal socio-economic and biophysical properties that make a system or community vulnerable as well as external biophysical factors. In this application, the external biophysical domain assesses the flooding hazard and maps the various floodlines associated with the climate scenarios. The internal biophysical domain characterizes the infrastructure (e.g. housing stock) which gives rise to

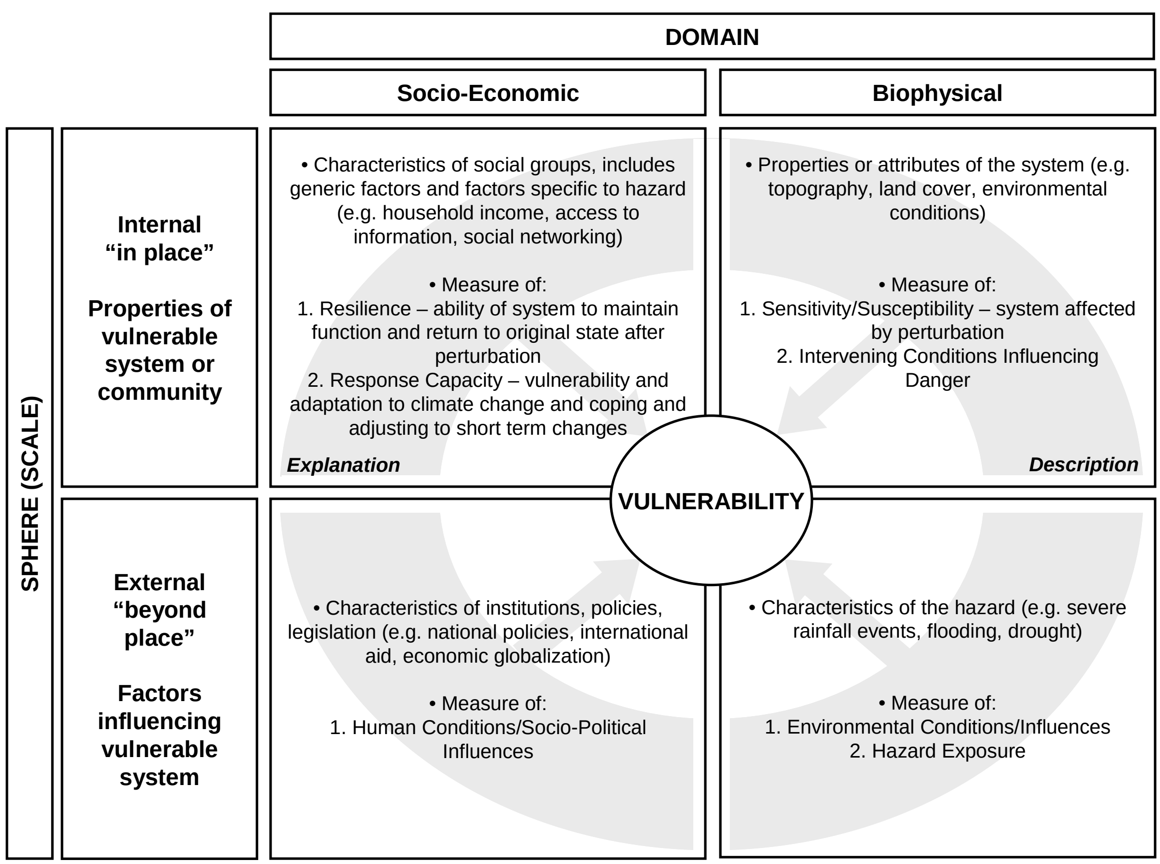

Figure 5 A conceptual diagram of the four key components that can be used to define vulnerability (modified from Füssel 2007)

situational vulnerability. In the internal socio-economic domain, socio-economic indicators are developed to help explain the capacity to adapt to flooding. The assessment does not consider external macro-level issues related to social structures, economics, political structures, environmental conditions, and organizational conditions acting on the community represented in the external socio-economic sphere.

Vulnerability Assessments

"Vulnerability is not … a predetermined state, but instead is usually socially constructed, contextual, dynamic, and driven by various causal agents and processes … capturing the differential elements of vulnerability is a prerequisite for the formulation and implementation of policies that will promote equitable and sustainable development" (Vogel and O'Brien 2004). Climate change impacts research and vulnerability assessments specifically as well as hazards research, have adopted the use of indicators to develop a better understanding of the socio-economic and biophysical factors contributing to vulnerability. Indicators can be used as proxies for diverse situations, they can be developed for virtually any scale (e.g. household, system, state) and the characteristics often coincide with determinants of adaptive capacity (Cutter et al. 2000; Vogel and O'Brien 2004; Phillips et al. 2006). Adger et al. (2004) identified nine categories of indicators of vulnerability to climate change including economic well-being, health and nutrition, education, physical infrastructure, institutions/governance/conflict, geographic, and demographic factors, dependence on agriculture, natural resources and ecosystem, and technical capacity. Cutter et al. (2003) listed factors that have gained consensus among social scientists as contributing to social vulnerability to environmental hazards. These factors include: lack of access to resources (including information, knowledge, and technology); limited access to political power and representation; social capital, including social networks and connections; beliefs and customs; building stock and age; frail and physically limited individuals; and type and density of infrastructure and lifelines.

The methods used to construct vulnerability maps in climate change and current climate studies are reviewed in Tables 1 and 2, respectively.

Indicators of Vulnerability

For mapping vulnerability to flooding in the Forks of the Thames, a survey of the literature identified a range of factors that are relevant to developing socio-economic and biophysical vulnerability indicators (Table 3). Indicators ranged from age and gender, to ethnicity, social status, homeownership (renter), income, geographic location, education, health status and special needs, and household arrangement (Lowry et al. 1995; Cutter et al. 2000; Health Canada 2001; Montz and Evans 2001; Flax et al. 2002; Wu et al. 2002; Jones 2004; Chakraborty et al. 2005; Phillips et al. 2006; Rygel et al. 2006). A combination of socio-economic factors, such as being elderly, a female or a minority and situational variables such as being a renter or having special needs compounds and increases vulnerability (Phillips et al. 2006). Some indicators and the rational for their contribution to vulnerability are described in more detail below.

Table 1 Methodologies for constructing vulnerability maps in climate change studies.

Data	Exposure (Biophysical)	Coping Ability (Socio-economic)	Vulnerability
Assess vulnerability of coastal communities to current and future riverine flooding and coastal storm surges in New Jersey (Wu et al. 2002)			
• Storm surge and flood data • Land use cover • 1990 US Census of Population and Housing (block unit) • Current and future climate conditions	• Storm surge heights and winds from the National Hurricane Center's (NHC's) SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model; assigned risk scores from 1 to 5 for Category 1-4 storm surge and low risk zone • Q3 flood data from the Federal Emergency Management Agency (FEMA) with Velocity Zone, 100- and 500-year floodplains, and low-risk zone; assigned risk scores from 1 to 4 • Added the storm surge and flooding risk scores then divided summary score evenly into 4 risk categories • Compared land use cover to flood risk zones spatially (area and percent change for very high, high, moderate and low risk flood risk zones)	• Social vulnerability indicators relate to cultural beliefs and norms, lack of access to resources and political will • Standardized vulnerability indices ranging from 0 to 1; no weights • Composite index is arithmetic mean of vulnerability indices of all variables • Mapped total social score in quartiles of low, moderate, high and very high	• Combined the flood hazard zone and social vulnerability layers together for overall flood vulnerability map (quartiles of the product of the regrouped flood hazard scores (0 to 4) and social vulnerability score (0 to 1)) • Areal interpolation when hazard zones crossed census blocks to estimate population and structures within each zone (assumed even distribution) • Identified the number of critical facilities within each flood risk zone • Also applied future sea level rise and future development scenarios
Assess risk of high temperature events in southern Québec (Vescovi et al. 2005)			
• Climate data • Climate projections • Demographic projections	• Indices for mean number of days and mean number of episodes per year for temperature thresholds	• Created four social sub-indices for age (over 65), poverty (low income earners), social isolation (single person households), education (people older than 20 with less than 13 years education) • Indices were centred and summed	• Combined hazard and social vulnerability with weighted sum in GIS
Map cumulative stresses of water vulnerability to shortages and contaminations in the Canadian Prairies (Grosshans et al. 2005)			
• 2001 Canada Agricultural Census • 2001 Municipal Water Use Data • Ecodistrict data • Soil landscape of Canada • Climate change projections (precipitation change)	• Water availability stresses (precipitation surplus/deficit, soil available water holding capacity, percent are of fresh water) • Indicators were normalized (standardized), summed, then renormalized to values between 0 and 100	• Water use stresses (hectares of seeded land with irrigation, human water flow, livestock water use) • Water quality stresses (livestock, cropped land with chemicals applied, population) • For each theme, indicators were normalized, summed, then renormalized	• The normalized three themed-stresses were summed together then renormalized for total composite index • No weights were used in analysis • Classified maps based on natural breaks
Vulnerability of agriculture to multiple stressors (climate change, globalization) in India (O'Brien et al. 2004a; Leichenko et al. 2004)			
• 1991 Census data • Centre for Monitoring of Indian Economy's (CMIE's) Infrastructure Development Index	• Averaged biophysical indicators (soil cover and degradation, groundwater exploitation, flooding)	• Averaged social and technological indicators (occupational status, literacy, infrastructure development, gender discrimination) • Normalized values based on United Nations Development Program's Human Development Index	• Averaged each set of variables and then combined together for district level base index, which was then combined with climate sensitivity index and trade sensitivity index • Final two maps overlaid to determine hot spots

Table 2 Methodologies for constructing vulnerability maps in current/historical climate studies.

Data	Exposure (Biophysical)	Coping Ability (Socio-economic)	Vulnerability
All-hazard assessment of vulnerability along coast of South Carolina (Cutter et al. 2000)			
• 1990 US Census of Population and Housing (block unit) • Archival material (newspapers, etc.) • FEMA's Q3 flood data • NHC's SLOSH model	• Identified hazards and estimated rate of occurrences for chemical releases, drought (Palmer Drought Severity Index - PDSI), earthquakes, floods (100- and 500-year flood lines), hail, hurricane surges, hurricane wind, thunderstorm wind, tornados, wildfire • All rate of occurrence layers combined into single composite of intersecting polygons and summed • Scores classed into deciles	• Social vulnerability indicators relate to lack of resources, information and knowledge; lack of access to political power and representation; certain beliefs and customs; weak buildings and individuals; infrastructure and lifelines • Standardized indices to ratio of variable in each census block by total number in county then dividing by maximum range (resultant score ranges from 0 to 1); mean house value standardized using the difference between county and block value plus absolute of maximum value divided by maximum value • Index variables summed to get composite index and placed into deciles	• Biophysical layer multiplied by the social vulnerability layer for vulnerability of place; no weights • Vulnerability values classified into quantiles • Determined the percentage of each social indicator in each specific hazard zone (overlay) • Areal interpolation when hazard zones crossed census blocks to estimate population and structures within each zone (assumed even distribution) • Overlaid infrastructure layer with place-vulnerability for mitigation planning
Assess spatial variability of biophysical risk and social vulnerability for effective evacuation planning in urbanized coast in Florida (Chakraborty et al. 2005)			
• NHC Risk Analysis Program • Flood insurance maps • 2000 US Census of Population and Housing (block unit)	• Calculated and mapped the probability of rate of occurrence for hurricanes and tropical storms and flooding and summed the two individual probabilities for total geophysical risk index	• Social vulnerability indices related to evacuation assistance need (population and structure, differential access to resources, population with special evacuation needs) • Standardized vulnerability indices ranging from 0 to 1; no weights • Composite index is arithmetic mean of vulnerability indices of all variables • Index values for three characteristic groups plus one combined	• Similar to Cutter et al. 2000 • Multiplied geophysical risk index by social vulnerability for evacuation index for overall evacuation assistance need; classified into five categories • No weights applied since literature does not agree on relative contributions of variables
Compare methods and approaches of defining social vulnerability to flash flooding in Syracuse, New York (Montz and Evans 2001)			
• US Census data or national equivalent	• n/a	• Used Lowry et al. 1995 approaches for social vulnerability • Converted variables to density values based on area of census block (age, gender, population density but not income); with and without weights • Scaled (standardized) variables ranging from 0 to 1; with weights	• Sum of density values (no weights) for total social vulnerability score • Weighted sum of density values • Weighted scaled sum (included income); scaled each variables from 0 (no impact) to 10 (high impact/vulnerability) • Weights 0.273 for age, gender; 0.091 for population density and income
Vulnerability assessment of natural hazards in Rhode Island (Odeh 2002)			
• Historical hazard data • Geographic and environmental data (e.g. topography, soils) • Demographic data • Critical facilities • Economic Data	• Hazard scores for each hazard type were the product of the frequency (probability each year), scope (geographic area covered) and intensity (level of intensity of hazard) scores • Each sub-score was assigned values ranging from 0 (no impact) to 5 (most impact)	• Exposure scores for each census tract were the product of the exposure types score and the importance factor • Exposure types were critical facilities (schools, hospitals, etc.); social vulnerability (population density, percentage of non-whites, families below poverty line, elderly, public assistance, no vehicles,	• Combined risk is the product of the exposure and hazard scores in four ways • Multiplied individual hazard scores by individual exposure scores (vulnerability of select hazards/exposures) • Multiplied sum of hazard by sum of exposure scores (state-wide aggregated scores)

Table 2 (continued) Methodologies for constructing vulnerability maps in current/historical climate studies.

Data	Exposure (Biophysical)	Coping Ability (Socio-economic)	Vulnerability
		renters, non-English speakers); environmental threats (rare species habitat, scenic vistas); economic value (value of construction, agricultural lands, etc.) • Exposure type assigned values ranging from 0 (no exposure) to 5 (highest exposure) • Importance factor based on occupancy factor	• Multiplied individual hazard scores by sum of exposure scores (vulnerability for each hazard type, considering sum of all exposures) • Multiplied individual exposure scores by sum of hazard scores (vulnerability for each exposure type, considering sum of all hazards)
Analyse community vulnerability to hazardous material releases in Sonora / Arizona (Lowry et al. 1995)			
• Hazardous waste model • 1990 US Census and 1990 Mexican Census data • Colegio de la Frontera Norte (COLEF) research	• Location of industrial facilities and surface and sewer transmission of hazardous material • Digitized facility location from aerial photographs, addresses and field verification • Buffered transmission lines; least cost pathway for elevation • Applied linear scale index ranging from 0 to 10 for each GIS layer	• Sensitive population (under 18 and over 65) and population density layers • Sensitive institutions were buffered • Economic/infrastructure vulnerability from mean house index (US) and minimum monthly salary and home construction (Mexico) • Applied linear scale index ranging from 0 to 10 for each GIS layer	• Combined hazard and human-related data sets; assigned weights based on composite mapping analysis (CMA); multiplied scaled index values for each layer by weights • Weights 0.273 for age, gender; 0.091 for population density and income • Sum of the weighted individual indices for the human component plus the weighted indices for the hazard component • Also tested different weights for summing the human and hazard components together • Estimated population within each zone and identified vulnerable locations
Construction of a social vulnerability index for hurricane storm surges in Virginia (Rygel et al. 2006)			
• SLOSH model • 2000 US Census (block unit)	• Storm-surge flood-risk zones for hurricanes	• Principal component analysis • Combined three component (poverty, immigrants, old age/disabilities) scores with simple and weighted averages (weights determined using Pareto ranking)	• Did not combine two components together
Community vulnerability assessment tool for hazard mitigation with three case studies (North Carolina, Hawaii and Rhode Island) (Flax et al. 2002)			
• Historic data • GIS layers of hazards, critical facilities, economic activities, environment • Census data	• Risk maps for all identified risks in study area; each map then overlaid in GIS to create multi-hazard map • Hazard zones assigned scores from 1 to 5; 0 for no risk	• Analyses special consideration areas (areas with high concentrations of poverty, elderly, minorities, single-parent households, rental dwellings, no high school diploma, public assistance recipients, non-English speaking populations, no vehicle, etc.)	• Overlay special consideration areas on risk areas • Determines vulnerabilities of critical facilities, economic activities and the environment along with mitigation opportunities within the community vulnerability assessment tool
• **Assess vulnerable populations to multiple hazards in Greater Vancouver (Jones 2004)**			
• 1996 Canada Census of Population • Hazard data • Street network file	• Eight physical (flood, earthquake, landslide, wildlife) and technological (poor drinking water, excessive noise, industrial landfills, air-borne industrial pollution) hazards were mapped in GIS and assigned risk zone scores (high, medium, low, etc.)	• Literature review and principal component analysis to select indicators related to age, ethnicity, social status and household arrangement • Variables were standardized from 0 to 1; with no weights • Individual scores were summed for composite index and mapped in quintiles • Also tested various scaling and weighting schemes	• Overlaid each hazard layer with the social vulnerability layers to determine coincidences

Table 3 Social and biophysical vulnerability indicators used in vulnerability assessments.

Author and Purpose	Indicator Theme (Category)	Individual Indicator (Variable)	Justification	Method of Selection	Data Sources
DEVELOPED COUNTIES (UNITED STATES, CANADA, UNITED KINGDOM)					
Climate Change Studies					
Grosshans et al. 2005 • Maps the cumulative threats to Prairie water resources • Historic and future climate conditions	• Water availability stress	• Precipitation surplus/deficit • Soil available water holding capacity • Total percent of area of fresh water	• n/a	• n/a	• Canadian Soil Information System (CanSIS) and National Ecological Framework for Canada • 2001 Canada Census of Agriculture • Environment Canada's (EC's) 2001 Municipal Water Use Database
	• Water use stress	• Total percent of seeded land with irrigation • Total human water flow • Total livestock water use			
	• Water quality stress	• Total livestock • Total percent of land with agricultural chemicals applied • Total percent of land with fertilizer, herbicide insecticide, fungicide applied • 2001 population			
	• Agricultural soil and water conservation	• Seeded land with no/zero tillage • Farms with cropland having grass waterways • Farms with cropland with windbreaks or shelterbelts			
	• Water conservation policy	• Industrial, commercial advice • Public advert • Water efficiency equipment installation • Lawn watering bylaws • Water conservation programs underway			
	• Water availability and use	• Precipitation coefficient of variability • Future precipitation change scenarios			
Wu et al. 2002 • Assesses vulnerability of coastal communities to riverine and coastal storm surge flooding in New Jersey • Current and future climate conditions	• Social vulnerability (ability to cope)	• Total population • Total housing units • Number of females • Number of non-white residents • Number of people under 18 • Number of people over 60 • Number of female-headed single-parent households • Number of renter-occupied housing units • Median house value	• Indicators provide initial metric for operationalizing social vulnerability but does not fully explain underlying causes of vulnerability • Fundamental causes of vulnerability related to cultural beliefs/norms, lack of access to resources, political power • Demographic and housing characteristics amplify or reduce vulnerability	• Literature review	• 1990 US Census of Population (block unit)

Table 3 (continued) Social and biophysical vulnerability indicators used in vulnerability assessments.

Author and Purpose	Indicator Theme (Category)	Individual Indicator (Variable)	Justification	Method of Selection	Data Sources
Current/Historical Climate Studies					
Chakraborty et al. 2005 • Assesses spatial variability of biophysical risk and social vulnerability in Florida • Current climate conditions	• Population and structure	• Total population • Number of housing units • Number of mobile homes	• Populations requiring evacuation assistance	• Literature review	• 2000 US Census of Population and Housing data (dis-semination areas)
	• Differential access to resources	• Population below poverty level • Occupied housing units with no telephones • Occupied housing units with no vehicles			
	• Population with special evacuation needs	• Institutionalized population in group quarters • Population age 5 years or older • Population aged over 85 years • Population (over 5 years of age) with disabilities			
Cutter et al. 2000 • All-hazard assessment of vulnerability along coast of South Carolina • Current climate conditions	• Population and structure	• Total population • Total housing units	• Evacuation difficulties in areas with higher concentration of people	• Literature review	• 1990 US Census of Population (block unit)
	• Differential access to resources	• Number of females, • Number of non-whites • Number of people under 18 • Number of people over 65	• Lack of access to resources and differential exposure • Physical weakness, thus difficult to move; more susceptible to health complications from hazard		
	• Wealth or poverty	• Mean house value	• Poor lack resources, live in poor-quality housing, cannot recover quickly		
	• Level of physical structural vulnerability	• Number of mobile homes	• More structurally vulnerable		
Flax et al. 2002 • Develops vulnerability assessment tool and applies to four case study locations • Current climate conditions	• Special consideration areas	• Poor • Elderly • Minority • Single-parent households • Rented dwellings • No high school diploma • Public assistance recipients • Non-English speaking populations • No vehicle available	• Need special care or have difficulty with disaster response and recovery • Lack resources for prevention and mitigation	• n/a	• 1990 and 2000 US Census of Population (census tracts)
Jones 2004 • Assess vulnerable populations to multiple hazards in Greater Vancouver • Current climate conditions	• Age	• Population under 19 • Population over 65	• Lack physical resources • Old reluctant to leave homes • Slower recovery times	• Literature review and principal component analysis	• 1996 Canada Census of Population
	• Ethnicity	• Population who belong to visible minority • Population without English or French as mother-tongue	• Often poorer and live in poorer-quality built homes • Communication barriers • Slower recovery times		

Table 3 (continued) Social and biophysical vulnerability indicators used in vulnerability assessments.

Author and Purpose	Indicator Theme (Category)	Individual Indicator (Variable)	Justification	Method of Selection	Data Sources
	• Social Status	• Household income • Population with at most high school education • Rented private household properties	• Disadvantaged, more likely poor with limited resources		
	• Household arrangement	• Single-parent families • Private households with one person • Private households with more than six people	• Disadvantaged, more likely poor with limited resources		
Lowry et al. 1995 • Assesses vulnerability to hazardous material releases in Arizona • Current climate conditions	• Sensitive population	• Population density under 18 years • Population density over 65 years • Population density between 18 and 65 years	• n/a	• Literature review	• 1990 US Census of Population • 1990 Mexican Census of Population
	• Economic condition	• Mean home value (US) • Index derived from minimum monthly salary and home construction (percent with potable water and sewage) (Mexico)	• Poor warning systems, lack of effective transportation in emergency		
Montz and Evans 2001 • Constructs social vulnerability indices for flash flooding in New York • Current climate conditions	• Age	• Population under 15 and over 65	• More vulnerable	• Literature review of base information and other analyses of vulnerability	• US Census of Population (or national equivalent)
	• Gender	• Single female head of household			
	• Economic status	• Median household income			
	• Population size	• Population density			
Phillips et al. 2005 • Identifies at risk populations for more effective emergency preparedness and response in Alabama • Current climate conditions	• n/a	• Income • Gender • Race and ethnicity • Age • Geographic location • Homeownership • Education • Health status • Special needs	• Lack of key resources (health, education, income, transportation) increases vulnerability • Vulnerable populations also receive, perceive and interpret risk differently	• Surveys; frequencies, cross tabulations, correlation analysis	• Surveys
Rygel et al. 2006 • Constructs vulnerability indices for hurricane storm surges in Virginia • Current climate conditions	• Poor	• Poverty	• Less money on preventative measures, emergency supplies, recovery efforts; limited access to lifelines, live in poorly built homes; higher mortality rates	• Literature review and principal component analysis	• 2000 US Census of Population (block unit)
		• Gender	• Women more likely live in poverty; care-givers to others first before seeking safety; hold low status jobs that disappear after disaster		
	• Immigrants	• Race and ethnicity	• Minorities more likely poor; language barriers		

Table 3 (continued) Social and biophysical vulnerability indicators used in vulnerability assessments.

Author and Purpose	Indicator Theme (Category)	Individual Indicator (Variable)	Justification	Method of Selection	Data Sources
	• Old Age/ Disabilities	• Age	• Psychological and physical impacts on young; elderly lack necessary physical, economic resources to respond, suffer health related repercussions, recover more slowly, reluctant to evacuate, physical difficulties, distress		
		• Disabilities	• Less able to respond effectively; require additional assistance		
LESS DEVELOPED COUNTIES (INDIA)					
Climate Change Studies					
O'Brien et al. 2004a and Leichenko et al. 2004 • Maps vulnerability to climate change and globalization in agricultural sector in India • Current and future climate conditions	• Human capital	• Adult literacy rate	• Decreased capability and access to information and less ability to cope	• n/a	• 1991 India Census of Population (district data) • CMIE Infrastructure Development Index
	• Social capital	• Female child mortality rate • Adult female literacy rate	• Disadvantaged • Female literacy affect child's survival		
	• Alternate economic activities	• District workforce employed in agriculture • Landless labourers	• Poorer, little income security • Inequality in landholdings		
	• Technological factors	• Irrigation rates • Infrastructure Development Index	• Lower rates than lower capacity to adapt to climatic and economic changes		
Aandahl and O'Brien 2001 • Initial selection of social vulnerability indicators to climate change and economic changes in agriculture sector in India • Current and future climate conditions	• Empowerment	• Sex ratio • Female literacy rate • Fertility level • Share of landholding by farm size • Ratio of agricultural labourers/cultivators	• More vulnerable since less capable of accessing resources (information, new employment) and exerting political rights	• Literature review; with plan to do statistical analyses in future	• 1991 India Census of Population (district data) • CMIE Infrastructure Development Index
	• Ecology	• Irrigation rate • Source of irrigation • Percent of villages with drinking water source • Fertilizer consumption	• More vulnerable and less likely to cope		
	• Poverty	• Percent of households below poverty line • Infant mortality rate • Percent of landless population • Housing – tenure status • Housing – standard	• More vulnerable since less resources to respond/adapt (risk of having to sell off productive resources)		

Age is an important determinant of vulnerability and young children and the elderly are particularly vulnerable to flooding. The elderly are more likely to have chronic illnesses and thus are more susceptible to infectious diseases, extreme health, and environmental conditions (Health Canada 2001). The elderly also may be less mobile or limited physically and more reluctant to leave their homes during an evacuation. Children are also particularly vulnerable because they are not able to act on their own. People of all ages with physical or mental disabilities may also have the same physical limitations or health-related concerns as the young and old. For example, people with compromised immune systems are more susceptible to infectious diseases and physical stress during floods, or are concerned about sanitation and safe drinking water (Health Canada 2001).

Gender studies of the 1997 Red River flood in Canada and the U.S. found that women were disproportionately impacted more than men (Enarson 1999; Enarson and Scanlon 1999; Rex 1999; Haque 2000). Enarson (1999) found elderly and disabled women were most vulnerable. Single mothers and women in violent relationships were also vulnerable because they needed more financial and emotional support. Low income women, the homeless, and the unemployed were also vulnerable because they had no place to go or had few financial resources to support their family. Many were unable to pay post-flood rent or find jobs. Women also had the additional burden of making household arrangements and duties, their home-based business were affected more because of earlier evacuations and more damage and reopened later, also there was an increased risk of domestic violence, and stereotypic gender patterns were more prominent (Enarson and Scanlon 1999; Rex 1999; Haque 2000).

Low income individuals or households lack financial resources to protect themselves and their assets; they then do not have insurance coverage and lack diverse income generating opportunities for recovery (Pilon 2004). Often people living in the lowest income bracket are less mobile and have fewer social and community contacts, limited resources for taking preparedness and response actions (Phillips et al. 2006), and less access to healthcare (Health Canada 2001).

Other indicators important in mapping vulnerability relate to housing: the type of structures that people live in and the period in which the homes were constructed. These factors indicate potential situational vulnerability of people who may be susceptible to hazards due to the structures they live in. For example, housing types, such as single-detached, semi-detached, row house, detached duplexes, and other single-detached homes are deemed less structurally sound and more vulnerable to hazards, such as flooding (Messner and Meyer 2005). Also homes built prior to floodplain regulation may be more vulnerable because they may have been built in areas susceptible to flooding. In 1975, the Flood Damage Reduction Program (FDRP) was introduced in Canada in response to extensive flood damage in the early 1970s. The objective of the Program was to identify, map, and designate flood risk areas and then prevent any future development in these areas. The Province of Ontario joined the program in 1978 and built upon previous mapping in Conservation Areas in the 1950s. In Ontario, the 100-year peak flow is typically used to mark the flood hazard limit while in some communities, a regional storm or highest observed flow is used (Environment Canada 2003). For London, the 250-year peak flow (regional storm) was adopted in 1973 for flood delineation and planning. Prior to this, a 1961 regulation used the high water mark (Helsten pers. comm. A). Before such regulations, homes could be built anywhere, including on the floodplains.

Geographic Information Systems

GIS is a key tool to map the spatial distribution of exposure and vulnerability. A GIS facilitates the input, storage, management, analysis, integration, and output of spatial data which can aid with real-time decision making and strategic planning for effective risk management and hazard preparedness

(Smith 2001). GIS can improve warning, evacuation, and emergency response systems by helping route emergency response vehicles and locating emergency response facilities (Lowry et al. 1995; Smith 2001). Hazard-related data such as soil and geology, urban infrastructure, and socio-economic data, can be input and stored in a GIS and then analysed to identify areas prone to hazards, identify vulnerable populations, monitor hazards and forecast disasters, and aid in land use zoning decisions to improve disaster mitigation and management (Roy et al. 2001; Smith 2001). Similarly in climate impact, adaptation, and vulnerability assessments, GIS allows for the monitoring of vulnerability over time and space, identifying 'hot spots' requiring adaptation policies, developing an understanding of the processes underlying vulnerability, developing and prioritizing adaptation strategies to reduce vulnerability, and determining the effectiveness of those strategies (Vogel and O'Brien 2004; Rygel et al. 2006). A GIS is ideal for hazards that can be mapped at a suitable scale, and "the greatest success has been achieved with the monitoring and forecasting of meteorological and flood hazards" (Smith 2001, p. 78).

4. VULNERABILITY ASSESSMENT METHODOLOGY

This section outlines the methods implemented to assess the vulnerability of the Forks of the Thames River in London, Ontario to floods due to a changing climate. It briefly describes the climate change flooding scenario development and provides details on the vulnerability assessment from data collection and development of the vulnerability indices to the flooding hazard and indices mapping.

Historic and Future Climate Change Flooding Scenarios

The historic or base case climate for this analysis was derived from meteorological station observations within and adjacent to the Upper Thames River watershed for the period from 1964 to 2001. Two Global Climate Model (GCM) simulations were selected as the climate change scenarios to explore the impacts of extremes – wetter conditions for more intense precipitation events (based on the CCSRNIES GCM and the B21 greenhouse gas emission scenario) for flood assessment, and warmer, drier conditions (based on the CSIROM2kb model and B11 greenhouse gas emission scenario) for drought analysis.

A modified *K*-nearest-neighbor (*K*-NN) non-parametric weather generator was developed and used to produce the two climate change scenarios (Sharif and Burn 2006, 2007). The method develops weather sequences by resampling historical data (daily maximum and minimum temperature, precipitation) in the watershed with perturbations from the GCM-based scenarios while preserving the prominent statistical characteristics. A key improvement in the scenario-generating technique is that the downscaled data produced for the watershed are spatially correlated as the same day's weather is adopted as the weather for all stations. Days with daily precipitation of 25 mm or more were disaggregated to hourly values for input to a hydrologic rainfall-runoff model (Wey 2006).

A semi-distributed event-based rainfall-runoff model (based on HEC-HMS) was developed for this project and is described by Cunderlik and Simonovic (2004, 2007). The drought modelling is described in Prodanovic and Simonovic (2006a). For the flooding assessment, precipitation events representing annual maximum daily rainfall were input in the hydrologic model to determine the corresponding peak flows (Prodanovic and Simonovic 2006b). A large number of event storms were run in the hydrologic model, so that a flow frequency analysis could be performed and return periods determined. A hydraulic model was used to convert flood flow into water elevation for floodplain mapping of the Forks of the Thames River area.

For each climate scenario, floodlines for the 1 in 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-year floods were generated by the UTRCA. The historical 1937 flood event in the Upper Thames River watershed was used as the standard to delineate the 1 in 250-year floodline; this event was estimated to be equivalent to the 250-year return period (Government of Ontario 2006). The 2-, 5-, 10-, 25-, 50-, and 100-year floodlines were generated from a hydraulic model (HEC-2) that calculated water surface elevations from basin characteristics and return period flows derived from a hydrologic model (HYMO) that incorporated rainfall-snowmelt events and climate data (Bevan 1986; Helsten pers. comm. B). The 500-year floodline was extrapolated from the 2-, 5-, 10-, 25-, 50-, 100-, and 250-year flows using a logarithmic scale (Helsten and Davidge 2005).

Floodlines for all eight return periods and three climate scenarios (historic, wet, dry) were provided by the UTRCA as shapefiles for use in this study. However, only the 1 in 100-, 250-, and 500-year floodlines were selected for further analysis because of their applications to planning in the region. The 100-year flood is used by the UTRCA to separate the flood fringe from the floodway and the 250-year flood is used to define the floodplain or hazard area (Helsten pers. comm. A). The 500-

year floodline coincided with flood damage estimation work completed by the UTRCA for this project (Helsten and Davidge 2005) and represents the most extreme condition used in disaster planning.

There was an error during the floodline generation process that is important to note. The 100-year floodline for the historic climate included a flooded area for the Cove, an area just south of the Thames River near the confluence of the north and south branches; the flooded Cove area represented a total area of 772,548 m^2. For some unexplained reason, floodlines for the Cove were not generated in any other floodline or climate scenario. Since the floodline generation process could not be rerun by the UTRCA, study proponents agreed to remove the floodlines for the Cove from the 100-year historic base case so that all flood coverages provided consistent areal coverage.

The shapefiles for the 1 in 100-, 250-, and 500-year floodlines were converted into ARC/INFO (ESRI 2006) coverages with the SHAPEARC command. The coverages were BUILT to restore polygon topology and edited in ARCEDIT to remove any erroneous lines. A code attribute was also added to the coverage to identify internal polygons in flooded areas; these internal polygons were excluded from future area calculations of the floodline because they were elevated areas that were not actually flooded.

Census Data Collection

Canada's census data "provide a statistical portrait" of the country and its population by assembling a collection of social, economic, and demographic information (Statistics Canada 2006). Census data are useful for identifying vulnerable populations and operationalizing the concept of vulnerability (Cutter et al. 2000). "Certain demographic and housing characteristics – age, race/ethnicity, income levels, gender, building quality, public infrastructure – are influential in amplifying or reducing overall vulnerability to hazards" (Blaikie et al. 1994, Hewitt 1997, and Tobin and Montz 1997 in Cutter et al. 2000, p. 726).

Census data provide a good means of obtaining consistently collected spatial attributes. In Canada, census data are "the only reliable source of detailed data for small groups (such as lone-parent families, ethnic groups … and immigrants) and for areas as small as a city neighbourhood or as large as the country itself" (Statistics Canada 2006). Statistics Canada 2001 Census data at the dissemination area level were used in the vulnerability assessment. Dissemination areas (DAs) are "small, relatively stable geographic unit[s] composed of one or more [neighbouring] blocks" with a population from 400 to 700 people, and are the "smallest standard geographic area for which all census data are disseminated" (Statistics Canada 2003, p. 251). Although hazards may vary at smaller geographic scales and at the household level, this scale of analysis is useful to and practical for local officials (Chakraborty et al. 2005, p. 26).

An ARC/INFO export interchange file (e00) was obtained of all DAs in Ontario (TDR 2007) and converted into a polygon coverage with IMPORT. To limit computing and display time in ArcMap, all DAs outside the City of London census subdivision boundary were deleted; the coverage was then projected into UTM NAD83.

In addition to the geographic boundary file, socio-economic data from the Census 2001 Profile Tables were also obtained at the DA level (TDR 2007). Variables related to population, age, sex, marital status, family status, dwellings, language, mobility, education, mode of transportation, and income were downloaded and became the factors of the vulnerability indicator development. The Profile Tables were joined together into one Excel (Microsoft 2001) spreadsheet for calculating the vulnerability indices (described below). The Excel spreadsheet containing the unique DA identifiers, indexed variables, and computed vulnerability scores was saved as a database file (dbf) and imported into ARC/INFO with the DBASEINFO command. The resulting INFO file was joined to the attribute table of the DA geographic boundary coverage, which also contained unique identifiers for every DA in the coverage; the unique identifier was used as the relate item between the two tables.

Natural Hazard Analysis

In the natural hazards approach to vulnerability assessment, exposure to the physical hazard is described as the distribution of the hazardous condition and the people and structures affected. The areas of the 1 in 100-, 250-, and 500-year floodlines for all climate scenarios were tabulated, and area and percentage changes in the floodlines between scenarios were calculated.

Buildings, dykes, bridges, roads, trails, and pit piles were provided by the UTRCA to determine vulnerable infrastructure and activities. The location of houses and parks were downloaded from the Ontario Basic Mapping web tool (MNR 2006). The City of London (Nyhout pers. comm.) provided the addresses of sewage treatment plans which there then mapped into the GIS using their street addresses. London's CityMap (City of London 2006) was also used to determine and map the location of emergency services, hospitals, historical landmarks and attractions, sports fields and/or facilities, and community centres within the study area.

The house and building layers were intersected with the floodlines to determine the number of structures affected within each floodzone. The floodlines were overlaid with the other data layers to determine vulnerable infrastructure (roads, bridges, water treatment plants, dykes), services (emergency and healthcare services), and economic and recreational activities (pit piles, trails, sports fields, tourist attractions, community centres). A map was constructed and output in the GIS to show the location of vulnerable structures and activities in the Forks of the Thames area.

The floodlines were also intersected with the Census data to identify the number of DAs flooded and to estimate the number of people and private dwellings affected under each scenario. In ArcMap (ESRI 2006), the 'Select by Location' tool was used to identify DA polygons that intersected with each floodline scenario coverage. The total number of people and private dwellings within each DA that was wholly or partially encompassed by the floodlines was used to provide a maximum estimate of the number of people affected. The total area and population and private dwellings counts for all selected DAs were summarised (summed) and output into a dbf file.

Next, the INTERSECT command was used to find the geometric intersection of the floodlines with the DA coverage. For each resulting intersected coverage, polygons with CODE = 1 were selected from the attribute table to identify all polygons within each DA that were flooded. The areas of all the selected records were then summarised based on their unique DA identifier and output as a dbf file. The resulting dbf file was joined to the dbf file containing the summarised total data for all DAs. The resulting dbf was opened in Excel. The proportion of area flooded within each DA was calculated by dividing the area of the DA that was flooded or intersected with the floodline by the total area of the DA. This proportion was then used to estimate the population and private dwellings located in the flooded area, assuming a constant or even population distribution across the DA. Exact counts could not be determined because there is no way of knowing where people actually live in each DA or the number of people living within each home or building. This method, however, did provide a closer approximation compared to the total counts for the entire DA.

Social Vulnerability Analysis

The natural hazard analysis describes the hazard exposure; however, it does not assess or differentiate the coping/adaptation capabilities of the population exposed to the flooding hazard. Therefore, vulnerability indicators were developed and mapped to allow for the analysis of the distribution of coping/adaptive capability within the community. Socio-economic attributes of the population and physical attributes of the place were selected that were likely to influence the capacity to cope or ability to adapt to flooding. Adaptation included proactive flood-proofing actions prior to an event, responding during the flooding emergency, and recovering after a flooding event.

Selecting Variables for the Social Vulnerability Indices

Three thematic areas relevant to coping capacity or adaptive capacity were defined for vulnerability indicator development and included in the analysis: ability to cope and respond, differential access to resources, and level of situational exposure. The attributes associated with these thematic areas would likely affect adaptation or undertaking proactive flood-proofing actions prior to an event, responding during the flooding emergency, and recovering after a flooding event in the context of the changing floodlines developed through the climate change scenario development and hydrologic modelling. Ten variables from the Canadian Census 2001 Profile Tables at the DA level were used (Statistics Canada 2003). The variables chosen were based on a review of existing literature assessing vulnerability to current hazards (Cutter et al. 2000; Montz and Evans 2001; Chakraborty et al. 2005; Phillips et al. 2005; Rygel et al. 2006) and a changing climate (Wu et al. 2002) as summarised in Table 3 presented earlier in the report. The contribution of each variable to vulnerability and the thematic categories are outlined in Table 4.

The first category consisted of variables that were combined for their potential to influence the population's ability to cope and respond to hazards. Factors, such as age, gender, and language are important physical or mental characteristics that affect a person's ability to cope and respond to floods. For example, the elderly are generally more vulnerable because they may be more reluctant to leave their homes during a flood, may have limited capacity to prepare for flooding, may require special evacuation needs or have physical difficulties during evacuation, may have more health-related problems related to hazards, or require more recovery time after being injured in a flood (Rygel et al. 2006). Other variables grouped in this category included people under the age of 19, people with no knowledge of the official languages, and females.

The second category of variables related to the population's differential access to resources and incorporated economic characteristics, such as income, family structure, available modes of transportation, and living situation that affect a person's access to resources in order to respond. These people or households may have less money for preventative measures, emergency supplies, or recovery efforts or have less access to lifelines such as communication and transportation (Rygel et al. 2006). Specific variables in this category included low income households, single parent families, people who rely on public transit, and renters.

The final category of variables related to an individual's situational vulnerability. Variables related to structural or physical vulnerability, such as housing type and age, are important to assess the likelihood of potential damage or failure. For example, single-storey structures are more vulnerable to flood damage or can completely be washed away in floods compared to multi-story structures. Similarly, structures built prior to the 1970s are more vulnerable because they may have been built on the floodplain before the regional floodline was regulated in the watershed.

Table 4 Vulnerability indicators selected for the Upper Thames vulnerability analysis.

Thematic Indicator Category and Associated Variables	Rational for Contribution to Vulnerability
Ability to Cope and Respond: ***characteristics that affect populations ability to cope and respond to flooding event***	
Over 65 years of age	• Limited mobility (physical difficulties in evacuation); reluctant to leave homes; health-related problems, longer recovery time (Health Canada 2001; Rygel et al. 2006)
Under 19 years of age	• Young children, in particular, physically weak; physical and mental health-related problems; less mobile (Health Canada 2001); legally dependent until age of 18
No Knowledge of Official Languages	• Language barrier; may not understand danger or respond appropriately; may not understand home preparedness preventative measures or emergency response
Females	• Physically disadvantaged in evacuation or home preparedness and repair; increased work, stress, physical domestic labour; slower to recover (Rex 1999)
Differential Access to Resources: ***economic characteristics that affect populations access to resources in order to respond to flooding***	
Low Income Households (spend more than 54% of their income on food, shelter and clothing)	• Limited resources to prepare or respond (i.e. lack communication devices to stay informed, have fewer social or community contacts; rely on public resources; lack resources to invest in post event activities) (Phillips et al. 2006)
Single Parent Families	• Limited resources to prepare or respond
Rely on Public Transit	• May lack mobility
Renters	• Landlords lax on disaster preparedness or cleanup (Rex 1999) • Limited resources and motivation to prepare or respond; less informed, fewer contacts
Level of Situational Exposure: ***structural integrity of homes; likelihood of potential damage or failure***	
Housing Type (single detached, semi-detached, row houses, detached duplexes, other single detached homes; mobile or moveable dwellings)	• Low structures (i.e. one or two storey homes) which are more vulnerable to damage from flooding since they are less structurally sound (Messner and Meyer 2005)
Period of Construction (pre 1970)	• Older homes may be constructed on floodplains; regulation not in affect until 1961 (high water mark) and 1973 (regional storm level i.e. 250-year flood line) (Helsten pers. comm. A) • Older neighbourhoods have ageing infrastructure which may be more susceptible to flooding (i.e. water and sewer systems; dykes, dams, etc.)

Calculating the Vulnerability Indices

A review of the literature identified several different methods for calculating vulnerability indices, but the approach used here was based on hazard analysis studies by Wu et al. (2002) and Chakraborty et al. (2005), which were modified versions of the approach used by Cutter et al. (2000). To produce the indicator scores, each of the ten variables were standardized to a value ranging from 0.0 to 1.0 using the following equation:

Equation 1
$$\text{Index Value} = \frac{\text{Actual Value for the Dissemination Area}}{\text{Maximum Value of all Dissemination Areas}}$$

Aggregating indicators into a single composite index is widely accepted. Vulnerability scores, one for each thematic category, were calculated by averaging the standardized vulnerability scores (Wu et al. 2002; Chakraborty et al. 2005) from the appropriate categories or groupings of individual indicators. For example, the indices scores for people over 65 years of age, people under 19 year of age, people with no knowledge of the official languages, and females were averaged together for a total vulnerability score that measures this group's ability to respond and cope. Similarly, the indicators that define one's differential access to resources and level of situational exposure were also averaged. Averaging the values makes is easy to compare vulnerability across space and time – but the importance of a single vulnerability factor is diminished when aggregated or averaged with others. A total overall vulnerability score was computed by summing the three vulnerability thematic indices to obtain a total score out of a maximum value of three.

When aggregating indicators of risk and coping ability together, it may be necessary to weight the indicators if some are more significant to vulnerability than others. Although weighting is subjective, weights are typically developed using local knowledge and experience from a larger group or expert panel (World Food Programme no date). A review of the literature has indicated that factors do not affect vulnerability equally, but availability of expert knowledge is limited in smaller communities and it is often difficult to reach a consensus on the weights amongst expert panel members (Lowry et al. 1995). Therefore, no weights were applied to the indicators in calculating the vulnerability index scores or total overall vulnerability scores for the Forks of the Thames area.

Mapping Social Vulnerability

In order to map the social vulnerability in the Forks of the Thames, the Excel spreadsheet containing DA identifiers, the indexed variables, and computed vulnerability scores was saved as a database file (dbf) and imported into ARC/INFO with the DBASEINFO command. The resulting INFO file was joined to the attribute table of the DA geographic boundary coverage, which contained unique identifiers for every DA in the coverage; the unique identifier was used as the relate item. The vulnerability scores for each individual thematic area were mapped, as well as the total vulnerability scores, into quintiles to classify low (≤ 20th percentile), medium-low (21-40th percentile), medium (41-60th percentile), medium-high (61-80th percentile) and high (81-100th percentile) vulnerability for the study area. The floodlines were superimposed on the social vulnerability maps to provide an indication of key vulnerable areas.

5. RESULTS

The results of the hazard analysis and social vulnerability assessment are discussed below. For this assessment, the climate change scenarios were specifically developed to explore the impacts of extremes – wetter conditions with more intense precipitation events, and warmer, drier conditions with more frequent drought. Since this report addresses flooding, most of the analysis focuses on the 100-, 250-, and 500-year return period floodlines for the wet climate scenario.

Natural Hazards Analysis

The areal extent of the floodlines for the historic and the two climate change scenarios increased as the probability or risk of occurrence decreased (i.e. more severe but less frequent in occurrence). For all scenarios, the 100-year floodline, which has the probability of occurring more frequently, affected the least amount of area compared to the 250- and 500-year floodlines, which did not occur as often but affected a wider extent. For each climate scenario, the change in area was greater between the 100- and 250-year floodlines than the change between the 250- and 500-year floodlines. The greatest increase in area (~30%) occurred between the 100- and 250-year floodlines for the dry climate scenario (when the dykes were breached near the confluence). The wet scenario had the smallest change in area between floodline scenarios compared to the dry or historic base scenarios (Figure 6).

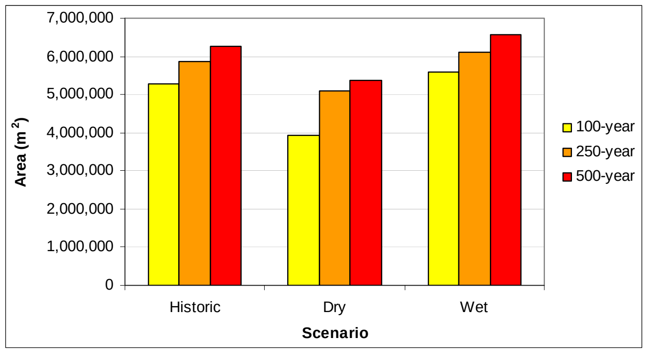

Figure 6 Total area of 100-, 250-, and 500-year floodlines under historic, dry, and wet climate scenarios.

In comparing the area and the number of people and homes flooded for each floodline scenario across the three climate scenarios, exposure to flooding hazard increased under the wet climate scenario. For each floodline scenario, the amount of area flooded increased slightly by 4 to 6% from the modelled historic area. There were also a greater number of homes and buildings flooded under the wet climate scenario when these data layers were overlaid with the floodline areas. The number affected ranged from 1,249 homes and 42 buildings for the 100-year floodline to 1,690 homes and 83 buildings for the 500-year floodline under the wet climate scenario (Table 5).

Exposed area decreased under the dry climate scenario, as much as 26% in the 100-year floodline from the historic modelled area. For the 250- and 500-year floodlines, the flooded area only decreased 13 to 15% in comparison. Under the dry scenario, the dykes near the confluence were not breached by the 100-year floodline and therefore a minimum of 68 homes and 18 buildings were flooded. This compares to 1,155 homes and 36 buildings for the 500-year scenario when the dykes were breached (Table 5).

Table 5 Modelled flooded area under historic conditions and two climate scenarios (wet for flooding and dry for drought conditions) and number of homes affected (all private homes/apartments, etc.) and buildings (commercial, institutional, industrial, etc.).

Floodline	Climate Scenario	Area (m^2)	Change in		No. Homes Flooded	No. Buildings Flooded
			Area	Percent		
100-year	Historic	5,291,440			1,141	34
	Dry	3,930,436	-1,361,004	-25.7%	68	18
	Wet	5,595,988	+ 304,548	+ 5.8%	1,249	42
250-year	Historic	5,858,976			1,376	58
	Dry	5,101,848	-757,128	-12.9%	1,059	33
	Wet	6,116,988	+258,012	+ 4.4%	1,486	59
500-year	Historic	6,268,729			1,560	71
	Dry	5,362,852	-905,877	-14.5%	1,155	36
	Wet	6,567,292	+298,563	+ 4.8%	1,690	83

The floodplain mapping for the wet climate change scenario in Figure 7 showed an increasing area exposed to flooding with higher return period floods. The north branch of the Thames River was the most flood-prone with the largest area flooded in the vicinity of the Forks of the Thames River on the western bank. The majority of homes exposed to flooding were located behind a series of dykes built along the Thames River which were breached for the 100-, 250-, and 500-year return period floods. The insert for Figure 7 provides greater detail on the homes and other buildings at flooding risk to the west of the centre of London. The majority of other buildings (industrial, commercial, institutional) exposed to flooding were located along the margins of the floodplain.

Other than the industrial, commercial, and institutional buildings located on the floodplain, the impact of flooding on other economic activities was low; pit piles were located outside the flooding risk area. However, some infrastructure (roads, railway lines, bridges, pollution control plants) and recreational resources (trails, sports facilities/fields) of London were at risk of flooding (Figure 8). Two of the three water treatment plants within the modelled area were located on or next to the floodplain. Transportation infrastructure was also at risk of flooding. There were numerous bridges crossing the Thames River including three rail crossings and 19 vehicle bridges. Roadways at risk of flooding were primarily in the residential area to the north and west of the confluence (Forks of the Thames).

In terms of emergency response and evacuation facilities, the City of London faired quite well. All 14 emergency services including fire, police, and ambulance stations were located outside the floodplain; although one fire station was located less than 250 m from the floodline. Of the eight hospitals within the study area, none were located within the floodplain, although three were located within 50 m of the 500-year floodline for the wet scenario. Finally, of all eight of the community centres located within the study area, two (including one senior centre) were located directly on the floodplain while another two were within 200 m of the 500-year floodline. The two centres located on the floodplain could not be used as evacuation centres during flooding events.

There were many recreational trails and wooded areas that would be impacted by flooding. There were also many parks located along the floodplain that have baseball diamonds, trails, swing sets, tennis courts, soccer fields, golf courses, trails, recreational bridges, etc. that would be flooded. Although flooding of these activities may not represent a significant economic impact, recreational use and enjoyment of these areas would be limited when flooded. There were also several sports facilities and tourist attractions located within or close to the floodplain (under all scenarios) that were in the area of flood risk: Labatt Park (baseball stadium) located right at the confluence; Thames Park along the South Thames River (with community pool and spray pad, tennis courts and baseball diamond); University of Western Ontario Tennis Centre along the North Thames river; and Storybook Gardens along the Thames west of the confluence.

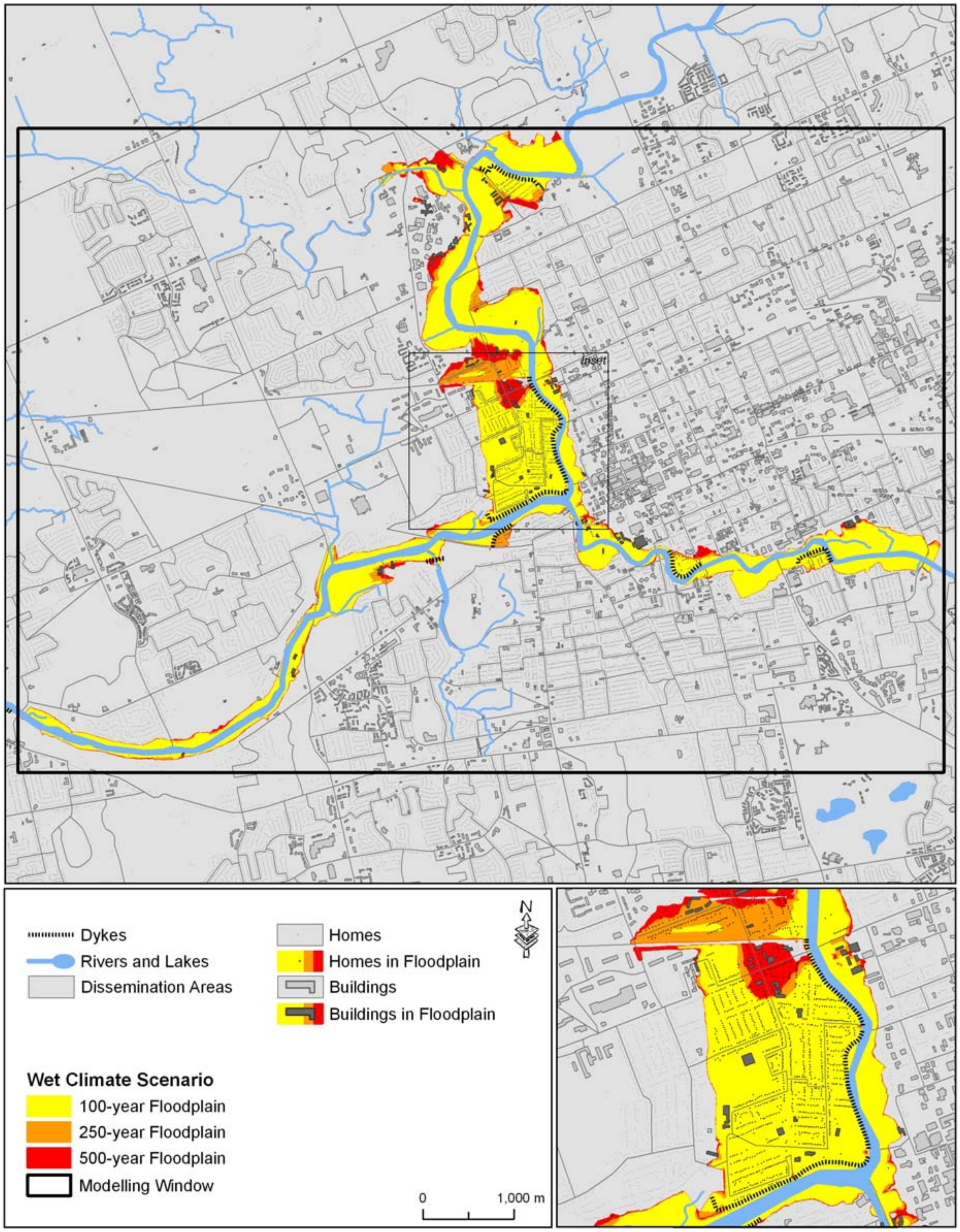

Figure 7 Homes and buildings flooded under the wet climate scenario in the Forks of the Thames.

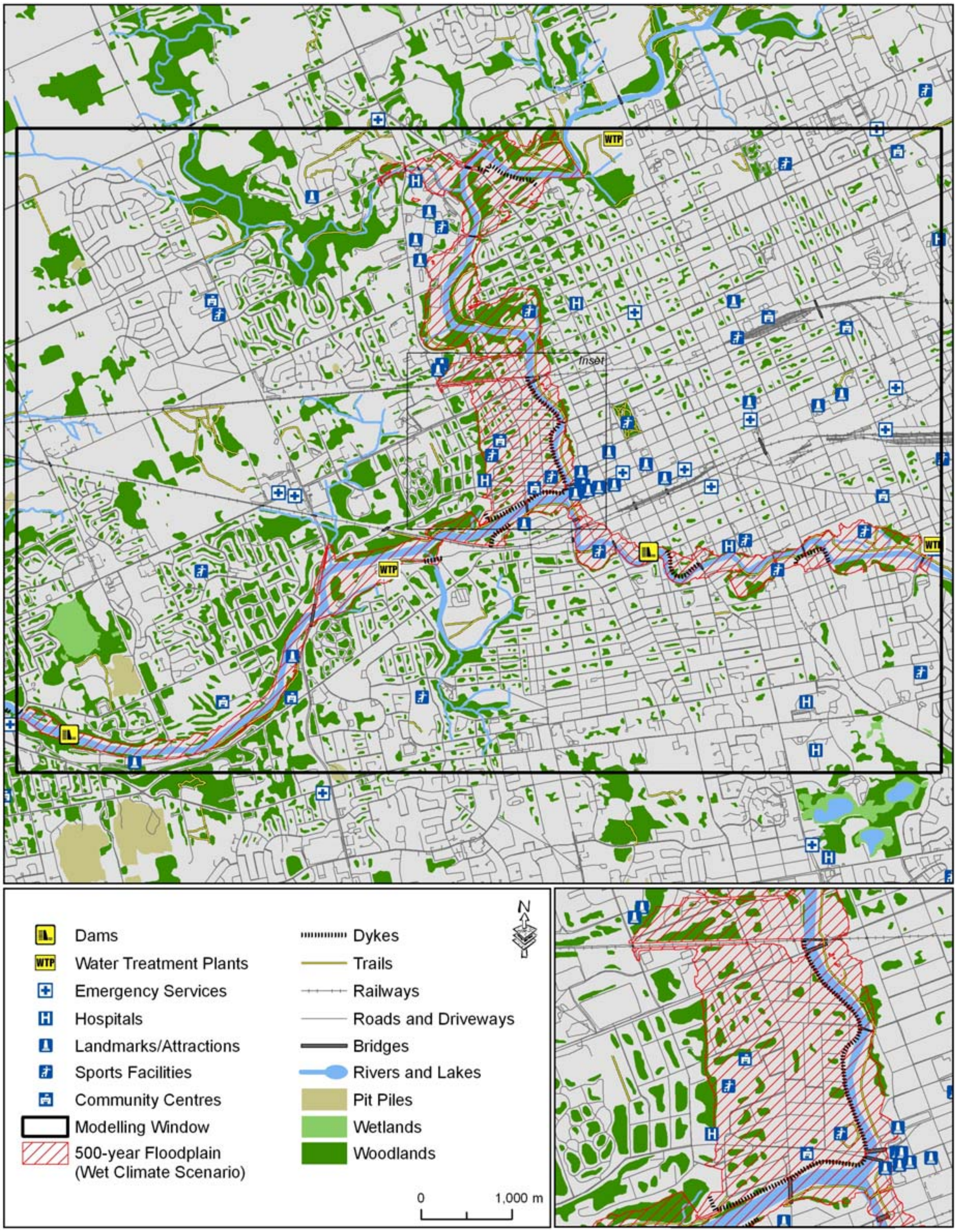

Figure 8 Impacted infrastructure and economic and recreational activities by the 500-year floodline under the wet climate scenario in the Forks of the Thames.

Overlaying the census data for the DAs with the floodlines allows for an estimation of the number of people and private dwellings affected by each return period floodline. More people and private household dwellings are exposed to flooding under the wet scenario compared to the historic and dry climate scenarios (Table 6). The proportion of population that could potentially be affected by flooding ranges from 4,881 people and 2,521 private dwellings under the 100-year dry scenario to 9,388 people and 4,886 private dwellings for the 500-year wet scenario.

Table 6 Total population and private dwellings per dissemination area (DA) affected by each floodline and climate scenario, the percentage of each DA flooded, and the estimated population and private dwelling counts based on percentage of area flooded assuming even population density within that DA based on Canada census data.

Climate Scenario	Floodline	Total Affected			Percent DA Area Flooded	Proportion Affected	
		No. DAs	Population	Dwellings		Population	Dwellings
Dry	100-year	41	20,206	9,715	10.0%	4,881	2,521
	250-year	45	22,430	10,905	14.5%	7,351	3,802
	500-year	45	22,430	10,905	17.4%	7,717	3,988
Historic	100-year	45	22,430	10,905	15.3%	7,701	3,969
	250-year	47	23,578	11,695	16.8%	8,474	4,381
	500-year	49	24,840	12,215	18.1%	9,119	4,740
Wet	100-year	45	22,430	10,905	15.7%	7,949	4,109
	250-year	47	23,442	11,325	17.4%	8,745	4,543
	500-year	48	24,201	11,910	18.6%	9,388	4,886

The historic climate scenario for the 1 in 250- and 500-year floodlines affects a greater number of DAs compared to the other scenarios, and thus a greater number of people and dwellings when considering the total population and dwelling counts for the entire DAs affected. But the wet scenario actually affects a greater number of people and dwellings based on the percentage or proportion of DAs flooded. All three floodlines under the wet scenario are larger in total extent than the historic floodlines, and thus affect a larger proportion of each DA in terms of area. The floodlines for the wet climate scenario should, theoretically, be larger in extent than the historic scenarios floodlines and thus affect a greater number of DAs as well. Visual comparisons of the floodlines indicate that in some locations of the floodlines, the historic scenario actually extends beyond the wet scenario limits. Therefore, there is a need to assess and improve the floodline generation process by examining the routing component and the digital elevation model; this was beyond the scope of this study however.

Social Vulnerability Analysis

The indicator scores representing the three thematic areas and the total vulnerability are shown in Figures 9 to 12. The DAs that are most vulnerable and located within the 100-, 250-, or 500-year floodlines of the wet climate scenario are circled on the vulnerability maps and indicate key vulnerable areas or “hot spots” within the Forks of the Thames study area.

The population’s ability to cope had the least impact on the total vulnerability score (Figure 9). There were only three DAs located wholly or partially on the floodplain that have low ability to cope and respond. The majority of DAs on the floodplain ranged from medium to high ability to cope, indicating less vulnerability to the flooding hazard. DAs with low ability to cope were generally distributed to the west of the north and south branches of the Thames and away from the floodplain. The area of high vulnerability, or low ability to cope, represents members of the community that are likely to have more challenges addressing pre-event vulnerability reduction, emergency response, and post-event recovery because of age, physical capabilities, language barriers, or time availability. During floods, the elderly and females contributed the most to the total vulnerability in terms of the population’s ability to cope. Those under the age of 19 years of age and people with no knowledge of the official languages were deemed less a factor in vulnerability since DAs with a high proportion of these communities were not located in the floodplain (Appendix A).

The population's differential access to resources was a contributor to the total vulnerability. DAs with low to medium access to resources were located in the east and central areas of the study area and in various locations along the floodplain (Figure 10). The area to the west of the Forks generally tended to have high access to resources. The indicator provides information on DAs with low income households that would not have the economic resources to invest in adaptation. For example, DAs with a high proportion of renters indicates areas where it is more likely that preventative measures would not be undertaken because renters and landlords are less likely to be motivated to invest in prevention and subsequent rebuilding and retrofitting as owner occupied areas. Other variables that contributed to low access to resources included households with low income and areas with people that rely on public transit. There were not a high proportion of single parent families located on the floodplain and thus this variable did not contribute greatly to the total vulnerability.

The level of situational exposure was most influential to total vulnerability. DAs with a high proportion of older homes were clearly identified along the Forks of the Thames floodplain, concentrated at the Forks and along the two branches of the Thames leading to the Forks. Many DAs here have medium-high to high levels of situational exposure (Figure 11). These are older areas of the community where houses were built before floodplain restrictions were implemented and thus more vulnerable to flooding. There was not a particularly high concentration of low storey homes in the floodplain area; most areas were classified as low to medium vulnerability.

The aggregated total vulnerability consisting of ability to cope and respond, differential access to resources, and level of situational exposures per DA is presented in Figure 12. Vulnerability to flooding was not evenly distributed throughout the Forks of the Thames River region. There were eight DAs identified as being highly vulnerable to flooding; one each on the northern and eastern extent of the modelling window, and the remaining centered in the middle of the Forks. These vulnerable areas or "hot spots" would benefit from additional planning and management attention in order to identify means of reducing flooding vulnerability.

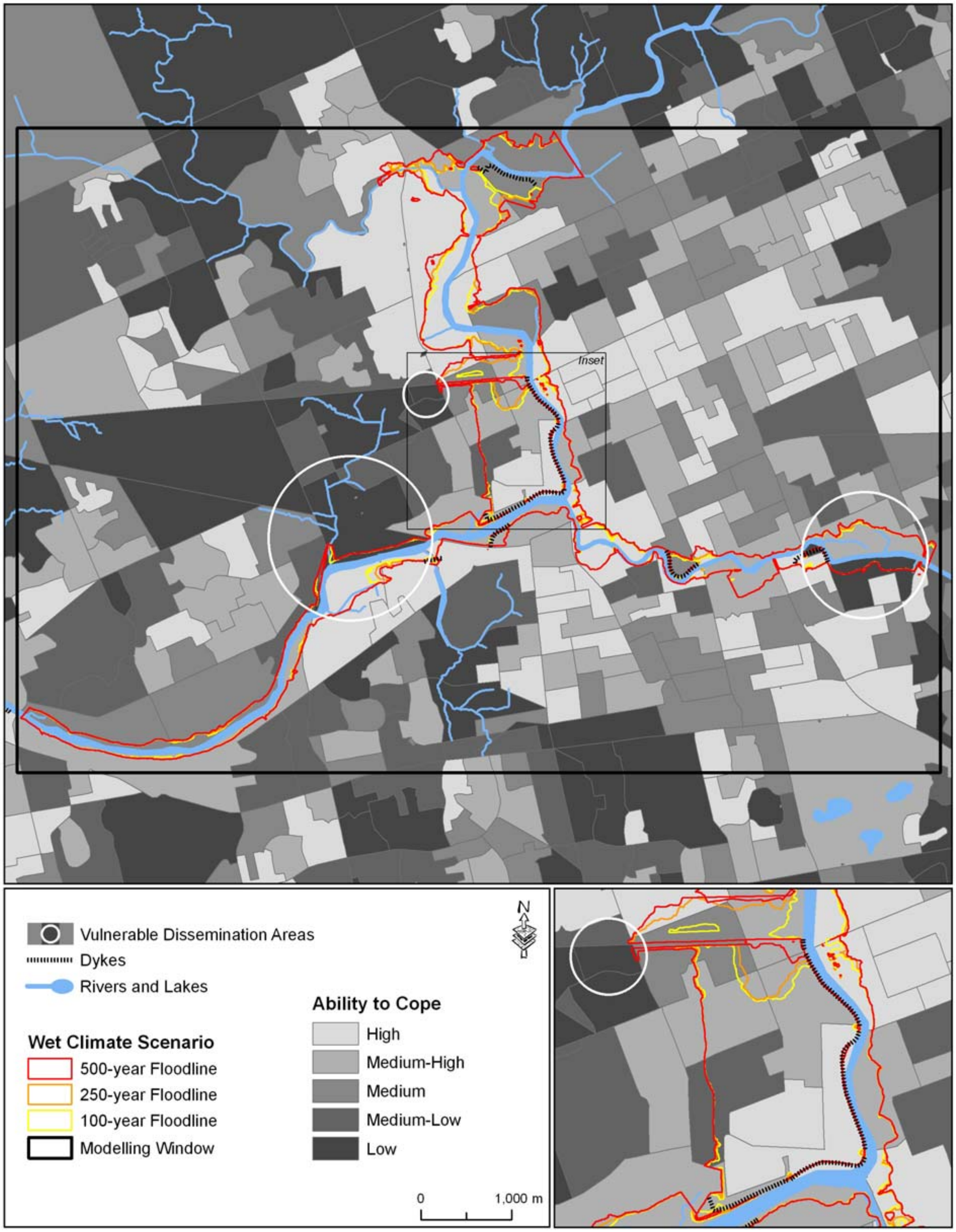

Figure 9 Ability to cope in the Forks of the Thames.

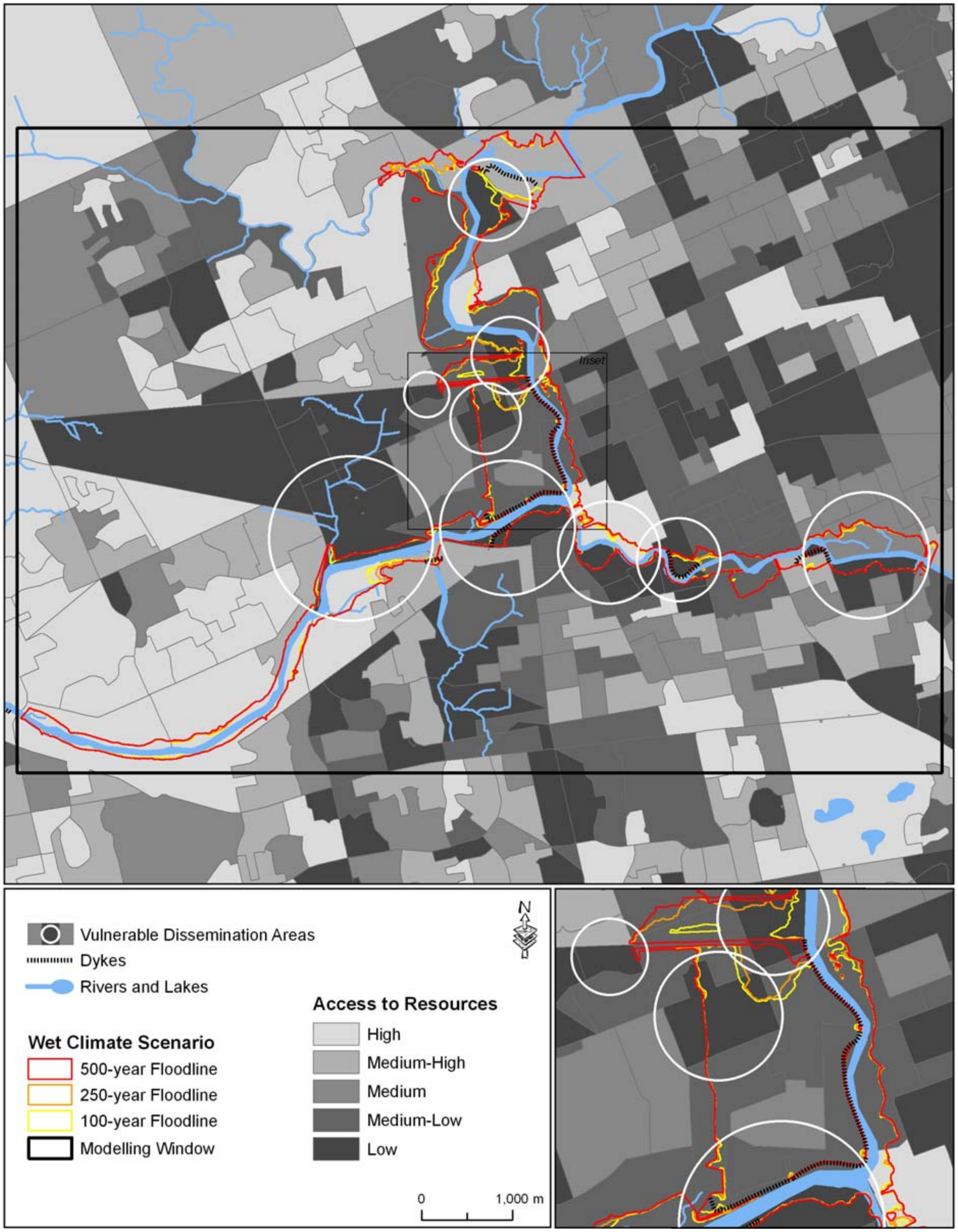

Figure 10 Differential access to resources in the Forks of the Thames.

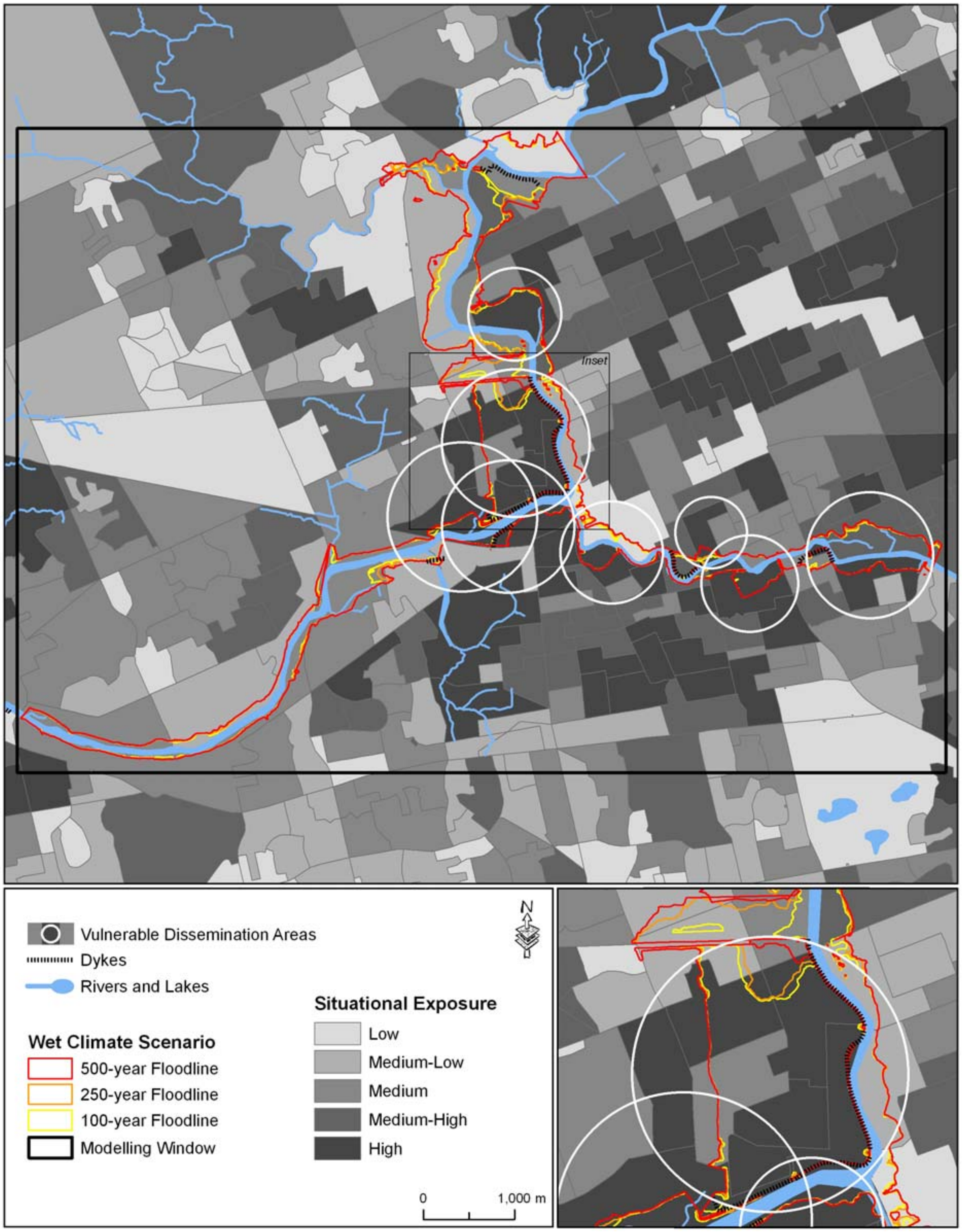

Figure 11 Level of situational exposure in the Forks of the Thames.

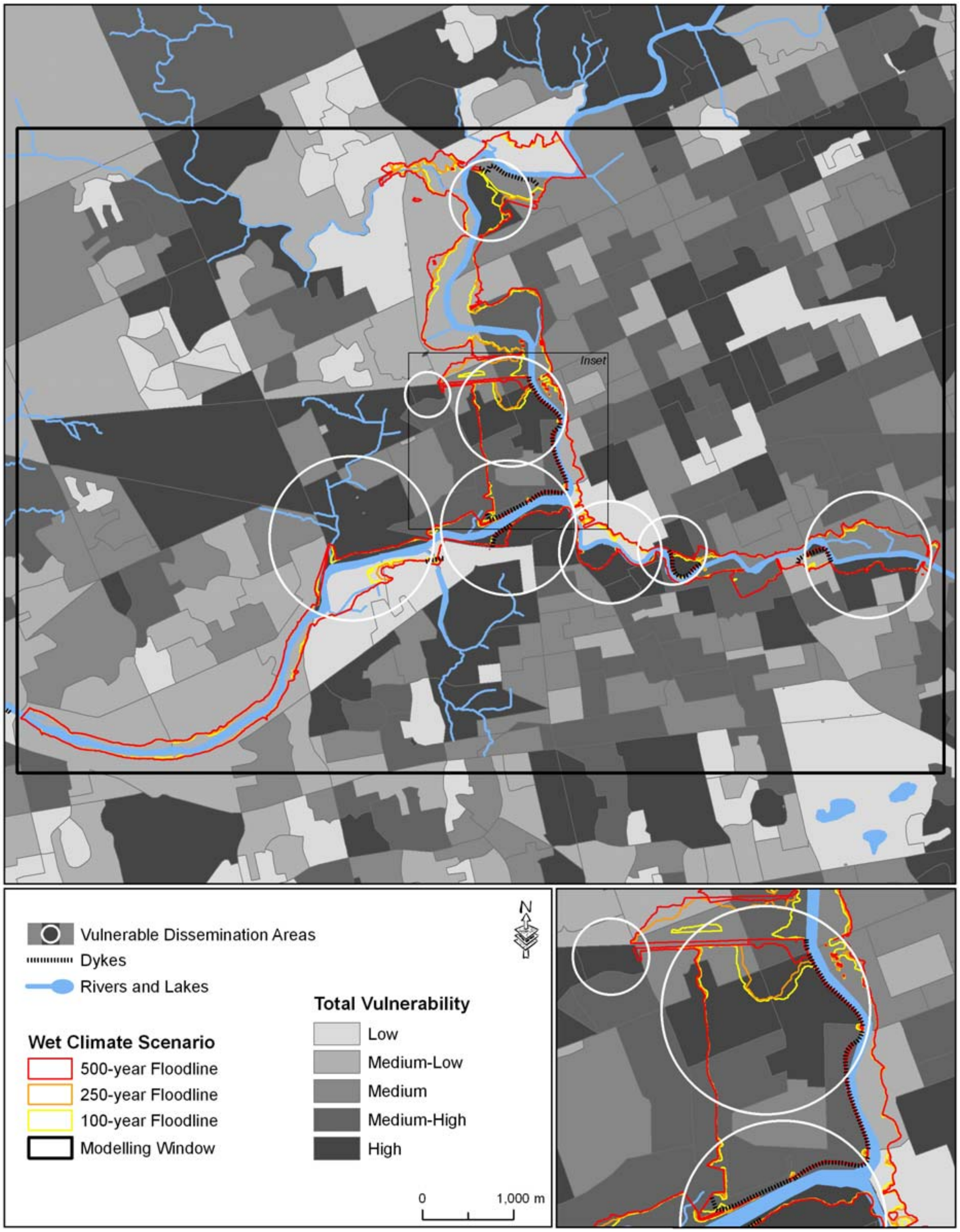

Figure 12 Total vulnerability in the Forks of the Thames.

6. DISCUSSION

The two goals of the project were to 1) explore the implications of a changing climate on extremes and assess vulnerability and 2) develop water resources risk and vulnerability assessment tools. A GIS was used as a tool to assess vulnerability in the Upper Thames watershed, specifically the Forks of the Thames, to flooding hazard in a changing climate. The natural hazard analysis component explored biophysical vulnerability under a changed climate, while the social vulnerability analysis developed indicators that identified potentially vulnerable areas due to socio-economic and physical attributes that influence the capacity to cope with the hazard.

The natural hazards analysis indicated that with more intense precipitation events projected under the wet climate change scenario, exposure to flooding hazard increased in the Forks of the Thames study area in London, Ontario. The areal extent of the 100-, 250-, and 500-year floodlines expanded and the number of people and structures exposed increased. The areas behind the dykes in the Forks of the Thames region will likely be breached in the 1 in 100-, 250-, and 500-year floods. In fact, the generated floodlines show that the dykes are breached by the 1 in 50-year flood (not shown) in both the historic and wet scenarios. In comparison, the dykes are only breached in the 1 in 250- and 500-year floodlines under the dry climate change scenario. The current dyking system, built in the late 1800s and early 1900s, was breached in 1937 when the worst flooding in the history of the City of London occurred. The dykes along with a series of dams constructed after 1947, the year of another major flood, have protected London during significant flooding events in 1977, 1986, 1997, and 2000. This preliminary analysis illustrates that increasing precipitation associated with climate change enhances the potential risk of flooding in the City of London and increases the likelihood of floodwaters overtopping the dykes.

The social vulnerability analysis developed indicators based on socio-economic and situational variables to explain some of the potential causes of vulnerability. The GIS facilitated assessment of the spatial distribution of vulnerability and differentiation of the adaptation capacities of the population exposed to the flooding hazard. “Situational exposure” – older pre-1970 neighbourhoods built before implementation of floodplain restrictions – contributed greatest to total vulnerability. The DAs with the high proportion of older homes were clearly identified along the Forks of the Thames floodplain, concentrated at the Forks and along the two branches of the Thames leading to the Forks. This illustrates the key influence land use policy can have on vulnerability. “Differential access to resources” identified those DAs with a high proportion of low income, renters, and single parent families whose vulnerability may be higher because they typically do not have as many economic resources to devote to adaptation. Similarly, the “ability to cope and respond” indicator identified those DAs in the community whose populations are likely to have more challenges addressing pre-event vulnerability reduction, emergency response, and post-event recovery because of age, physical capabilities, language barriers, or time availability.

Mapping the indices showed that vulnerability to flooding is not evenly distributed throughout the Forks of the Thames River study area. The analysis identified eight DAs that had high total vulnerability scores; one on the northern extent of the modelling window, another on the eastern extent, and the remaining centered in the Forks of the Thames region (see Figure 12). These “hot spots” are specific areas that might benefit from further assessment to identify policies that might assist vulnerable members of the community to implement preventative flood mitigation and emergency preparedness measures. The DAs include a high proportion of elderly or those relying on pubic transit that might require evacuation assistance or DAs with a high proportion of low income or single parent families that might require assistance to prepare for and cope with the flooding hazard. This approach moves the focus of the assessment beyond describing only the potential exposure and damages, and tries to understand the human aspects of the issue – those attributes of the DAs that might affect adaptive capacity and where policy and programs could specifically address issues associated with vulnerable populations.

This vulnerability assessment was based on only one climate change scenario developed by applying the *K*-NN downscaling technique with the CCSRNIES GCM and the B21 greenhouse gas emission scenario. The utility of the downscaling technique was demonstrated but more climate change scenarios based on a range of GCMs and emission scenarios should be used to inform watershed and municipal planning in the Upper Thames River watershed on future areas and communities of people at risk. Exploring a wide range of plausible future climate conditions that reflect an array of extreme wet conditions and assess the implications for flooding and vulnerability improves adaptation strategy development thereby increasing resilience of communities. Future work should also improve the modelling of floodline generation including, in particular, the floodwater routing and digital elevation model components (which was beyond the scope of this study). The Cove area requires particular attention as it is critical to defining the area flooded (as well as estimating dwellings and number of people exposed and DAs affected).

The climate change and flooding scenarios were based on projections for the 2050s but vulnerability of the Forks of the Thames community to these scenarios was assessed on the current socio-economic conditions based on the most recent Canadian Census data for 2001. The assessment provides a “snapshot” based on the current socio-economic conditions of how current vulnerability might be influenced by a changing climate as it did not incorporate projections of population growth, demographic change, land use change, and urban redevelopment that could influence vulnerability. Input from the Official Plan and Provincial population projections for the region, for example, could provide some socio-economic futures for the assessment.

The modelling for this study focused on the Forks of the Thames region. It would be of value to extend assessment of the impact of climate change on the floodlines beyond the Forks of the Thames to assess exposure and vulnerability throughout the City of London and the whole watershed with particular focus on other reaches of the river as well as towns such as Stratford that are currently susceptible to flooding. Extending the floodlines beyond the Forks of the Thames, would also allow for the examination of the impacts of flooding on other sectors of the economy. For example, there are a lot of flash floods in rural areas in the watershed. It would be interesting to see their impact on not only infrastructure (such as roads and bridges) but their impact on vegetation or agricultural crops, etc. Of course, this would require that additional data layers be obtained for such an analysis.

The GIS methodology developed for this study can be used by other resource management agencies as a vulnerability assessment tool for flooding and other potential hazards (e.g. coastal flooding) under current and future climates. The vulnerability approach used here, combined biophysical and social vulnerability, adding another dimension to the assessment process. It provided information on the changing exposure to hazards but also offered insights into what socio-economic attributes might help or hinder adaptation to the potential hazard. The GIS tool allowed investigation of the spatial nature of hazards and the populations that might be differentially affected; this can offer new insights for hazard/emergency preparedness, evacuation, and management as well as climate change risk and adaptation assessment.

7. CONCLUSIONS

The study shows that there is increasing risk from flooding events with the wet climate change scenario that needs to be considered in municipal and watershed planning in the Upper Thames River watershed. The vulnerability approach builds upon traditional natural hazards methods (e.g. describing how the flooding hazard changes) and enhances the information provided for planning and management by including socio-economic and physical factors that affect the community and the capacity to cope with or adapt to the hazard – flooding – in a proactive pre-event hazard/disaster prevention, emergency response, and subsequent cleanup. GIS was a useful tool to operationalize the vulnerability concept. Feedback is needed from the stakeholder community on the usefulness of the indicators and maps and will be solicited through a stakeholder meeting.

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APPENDIX A

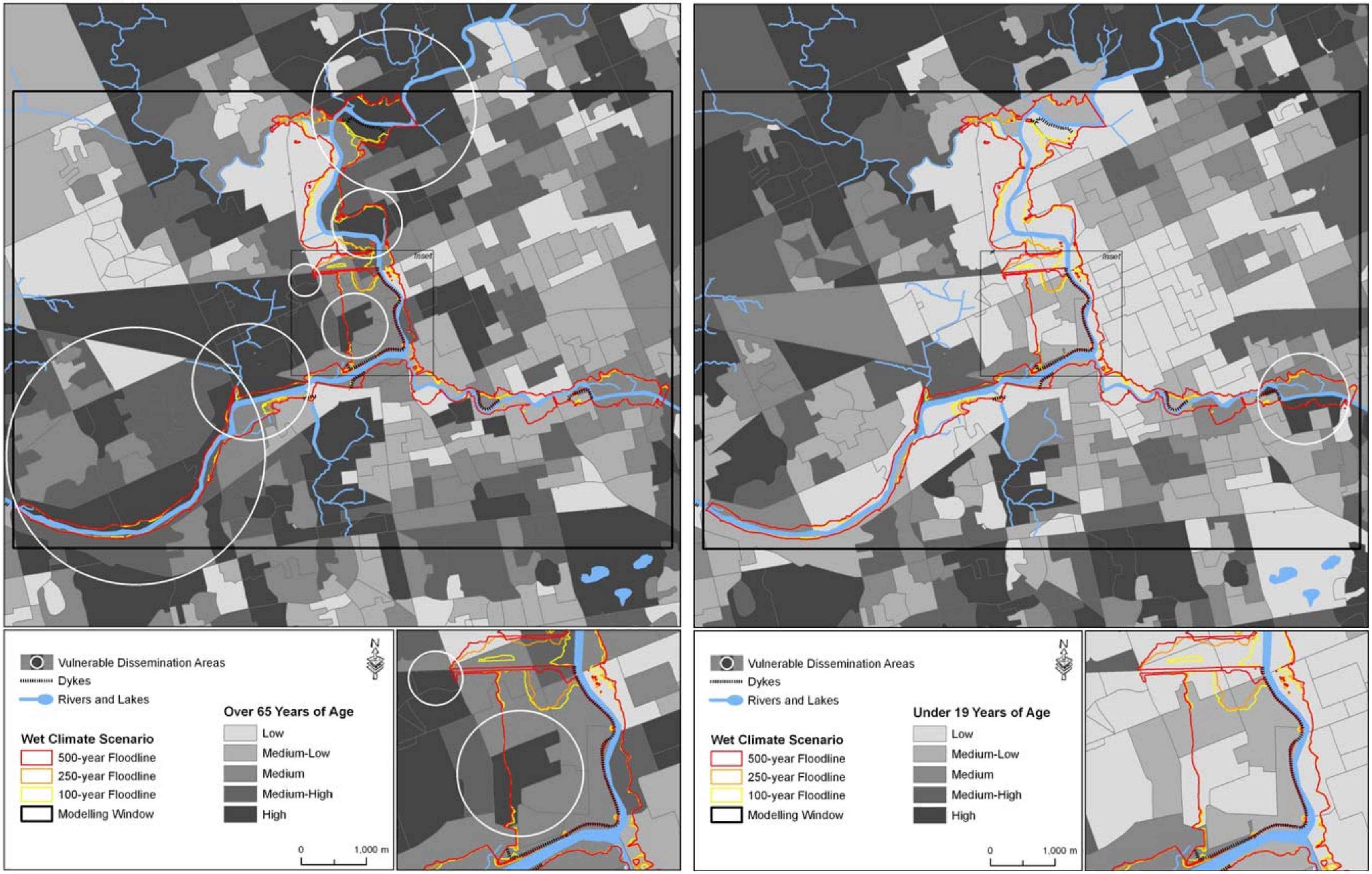

Figure A.1 Vulnerability scores for dissemination areas based on proportion of the population aged 65 years of age and older and the proportion under 19 years of age.

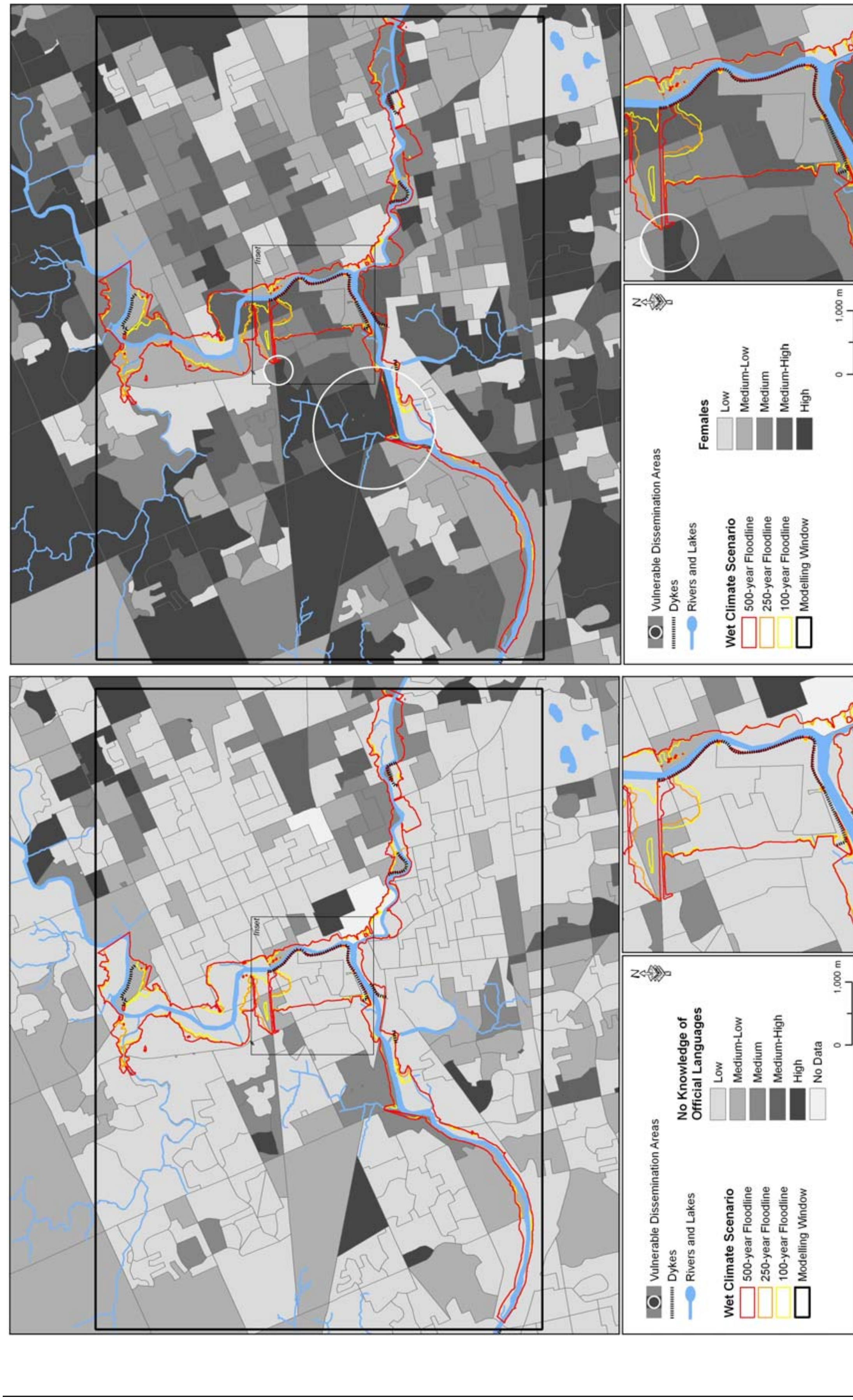

Figure A.2 Vulnerability scores for dissemination areas based on proportion of the population with no knowledge of the official languages and the proportion of females.

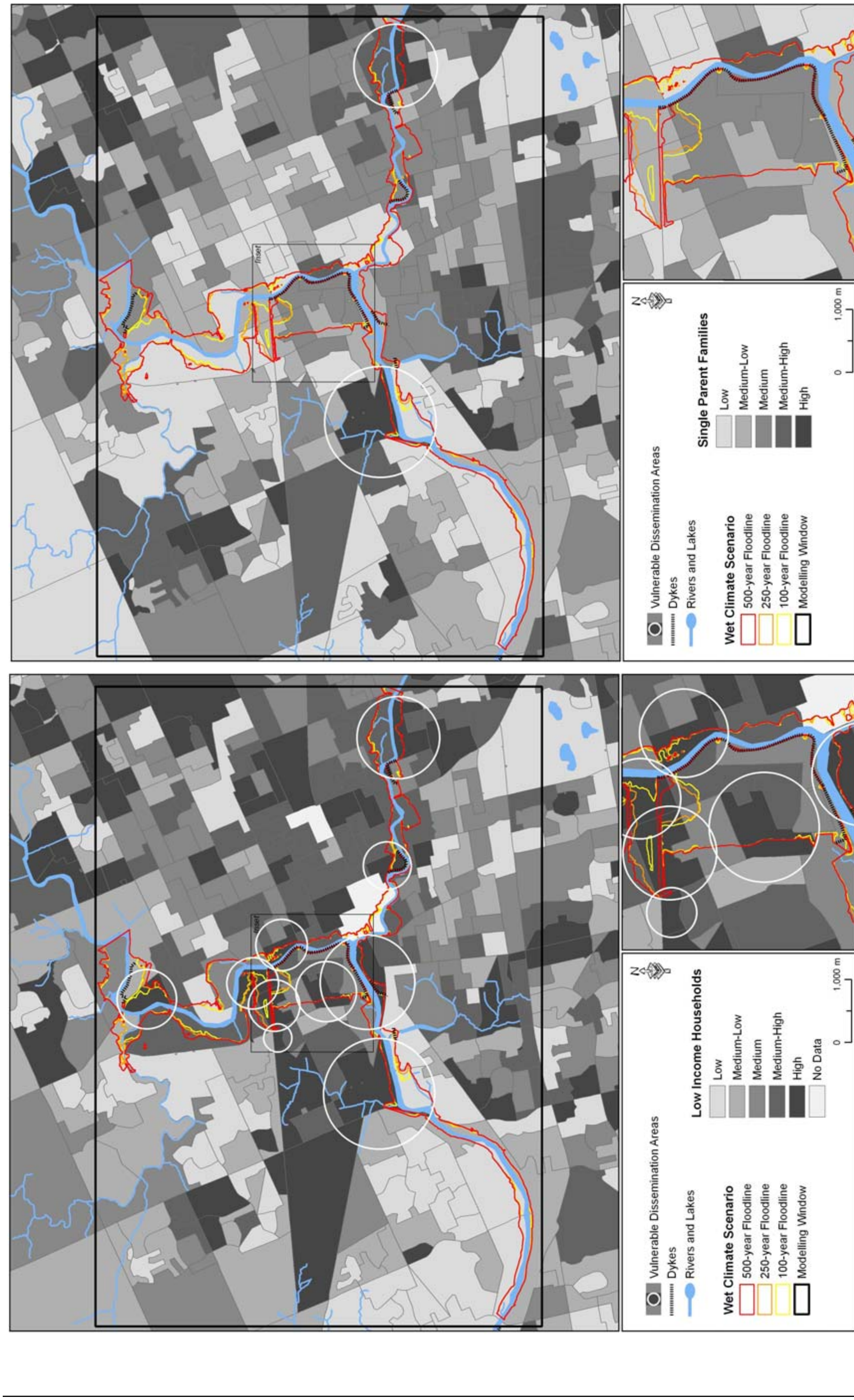

Figure A.3 Vulnerability scores for dissemination areas based on proportion of the low income households and proportion of single parent families.

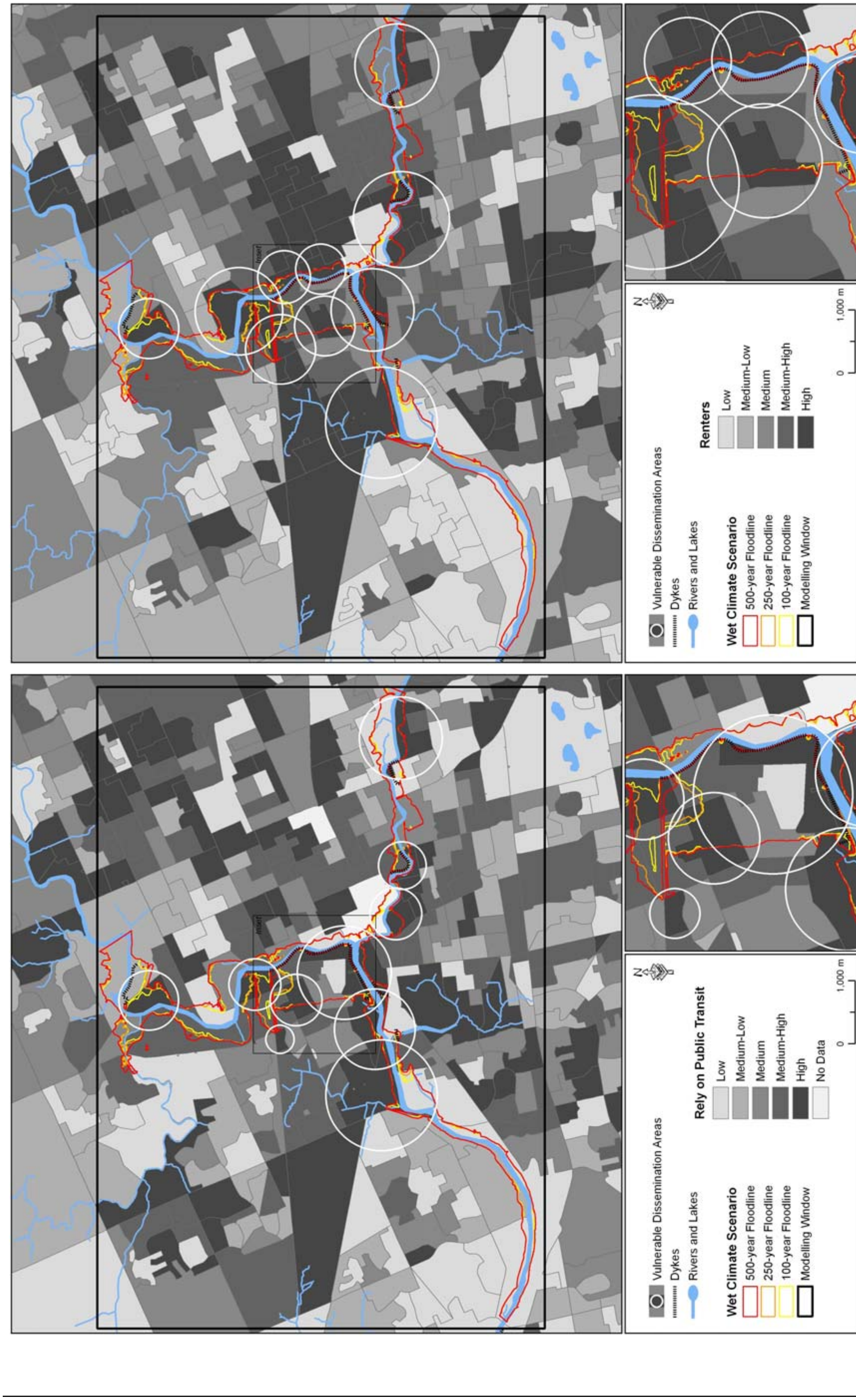

Figure A.4 Vulnerability scores for dissemination areas based on proportion of the population that rely on public transit and proportion who are renters.

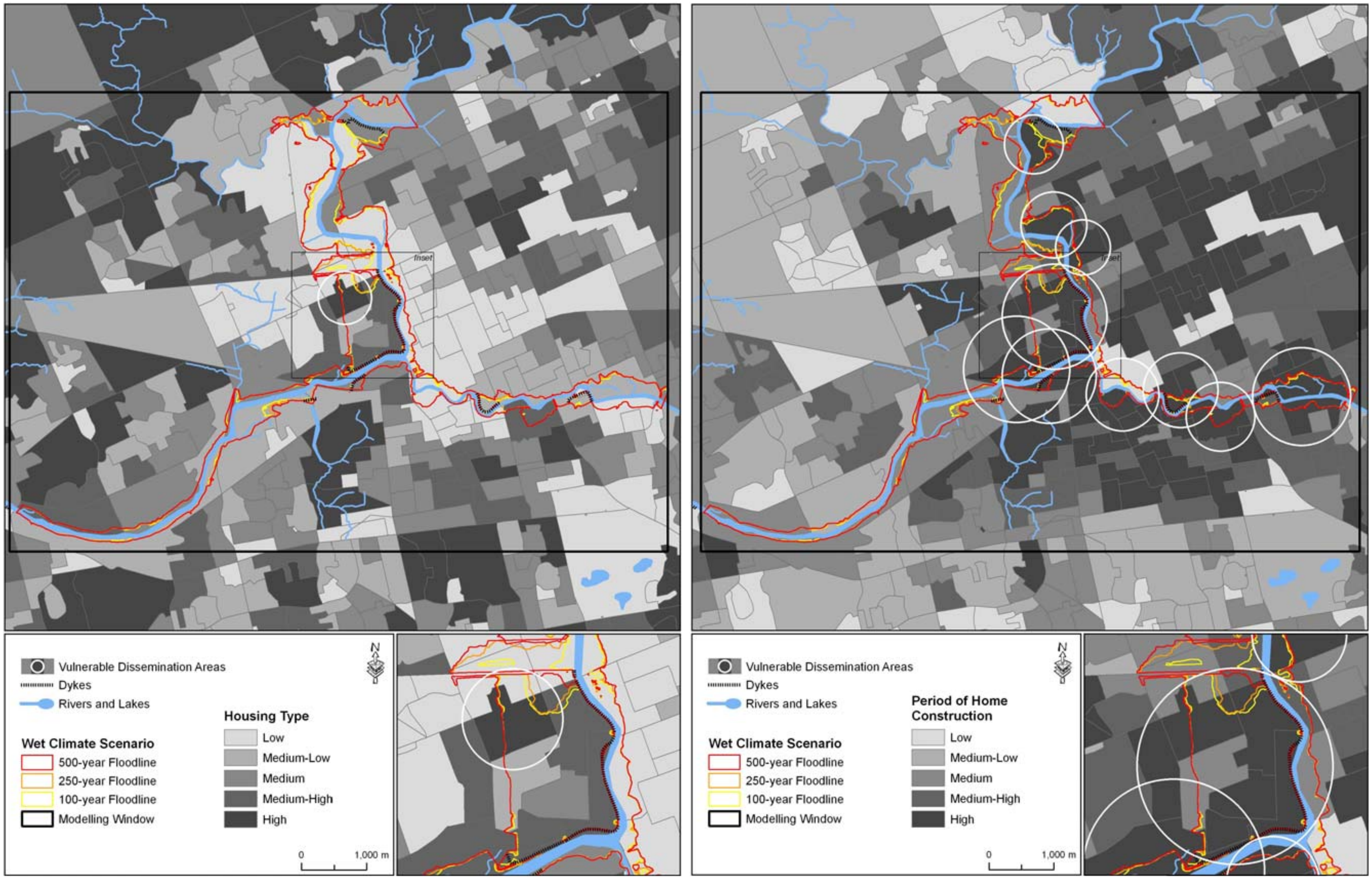

Figure A.5 Vulnerability scores for dissemination areas based on proportion of housing type (low level structures) and periods of construction (built before the 1970s).