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Physical, economical, infrastructural and social flood risk – vulnerability analyses in GIS

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List of Acronyms

CHRR	Center for Hazards and Risk Research
DI	Degree of Importance
DMF	Disaster Management Facilities
EP	Exceedance Probability
FSA	Forward Sortation Area
GDP	Gross Domestic Product
GIS	Geographic Information System
HMU	Hazard Management Unit
ICLR	International Catastrophic Loss Reduction
IDLS	Internet Data Library System
ODI	Overall Degree of Importance
PSEPC	Public Safety and Emergency Preparedness Canada
UTRCA	Upper Thames River Conservation Authority

Abstract

An exhaustive knowledge of flood risk, vulnerability and exposure in different spatial locations is essential for developing an effective flood mitigation strategy for a watershed. In the present study, a flood risk-vulnerability analysis is performed. All four components of flood vulnerability: (a) physical; (b) economic; (c) infrastructure and (d) social, are evaluated individually using a Geographic Information System (GIS) environment. The proposed methodology estimates the impact on infrastructure vulnerability due to inundation of critical facilities, emergency service stations, and road bridges. The components of vulnerability are combined to determine the overall vulnerability. The patterns of land use and soil type are considered as two major components of flood exposure. Flood hazard maps, overall vulnerability and exposure are used to finally compute the flood risk at different locations in the watershed. The proposed methodology is implemented to six major damage centers in the Upper Thames River watershed, located in south-western Ontario of Canada to assess the flood risk. A web-based information system is developed for systematic presentation of the flood risk, vulnerability and exposures by postal code regions or Forward Sortation Areas (FSAs). The system is designed to provide support for different users, i.e., general public, decision-makers and water management professionals. An interactive analysis tool is developed within the web-based information system to assist in evaluation of the flood risk in response to a change in land use pattern.

Keywords: vulnerability analysis, flood risk, web-based information system, flood management, GIS

I. INTRODUCTION

Flooding can have catastrophic impacts on the people, the economy, and the environment. The impacts of flooding are difficult to quantify due to, for example, situational dependence, such as a persons' previous exposure to flooding or other natural disasters. A person's ability to prepare and cope with a flooding event is highly individual, though there are demographic studies which suggest ways to identify a more vulnerable population. Demographic variables of a region are statistical characteristics which include age, gender, ethnicity, financial status, religion, marital status, language, and lifestyles. There are specific demographic characteristics which indicate a population is 'more at risk' or 'vulnerable to damages' in the occurrence of hazardous events. These characteristics are termed vulnerability indicators.

Historically, flooding has caused great damage to property, and physical infrastructure of many affected communities. However, damages that are caused by floods are not always external. The impacts of flooding on the lives of people and the inconveniences it causes to the population are also indices of flood damage. The population directly affected by the flood (in the form of direct damages to property or loss of life) generally suffers the largest impact (Hausmann and Perils, 1998). However, the population indirectly involved in flood events is also affected, and suffers damages. A flood can be caused by the overflow of rivers, tsunamis, hurricanes, storm surges, dam failures or flash flooding. This study will focus only on floods which are caused by the overflow of rivers that are characteristic for the region of interest – south-western Ontario.

The term flood hazard refers to the likelihood or probability of a particular flood event occurring. The exceedance probability represents the likelihood of a flood event, or the probability that during a particular time interval, river flow will exceed some specified or threshold value. The exceedance probability is representative of flood hazard, and is an integral component of flood risk.

Flood risk can be defined as total losses due to a flood event occurring in a specific area. Mathematically, risk is considered the product of a hazard and vulnerability of a region (UN, 1992). However, in this study flood risk is the product of vulnerability, hazard, and exposure components. The vulnerability of a particular region is characterized by physical, economic, infrastructure, and social susceptibility or sensitivity to damage from a flood event (Hebb and Mortsch, 2007). These categories of vulnerability are composed of a number of flood risk indicators that are grouped together in similar themes. Often, vulnerability is associated with existing social systems (Chakraborty et al., 2005). The 'exposure' is considered as a separate component of risk. It is affected by hydrologic conditions and flood response. In the present study, patterns of land use and soil type are considered as the exposure indices. Community leaders and decision-makers should be aware of the effects that changing land use has on precipitation and flood patterns (Sullivan et al., 2004). Due to high spatial variability of many variables considered in flood risk analysis, the Geographical Information Systems (GIS) appeared to be an effective tool for the flood risk computation and presentation. The combination of spatial data with various available statistical information in GIS, provides the support to decision-makers for improved planning of community growth.

Floods are naturally disruptive. They affect people's lives physically, mentally, and financially. Hausmann and Perils (1998) introduced description of direct, indirect, and intangible flood losses. Direct losses from flooding are those which cause structural damage to buildings, structures or infrastructure and include the financial consequences of cleaning up, mitigation and disposal. Indirect losses include damage due to business disruptions, power losses, travels and communication interruptions. Intangible losses include physical, financial or other damages which can not be quantified. They include damages such as traffic delays, psychological suffering, or loss of sense of security. All of these types of damages should be considered in flood assessment and mitigation schemes.

Flood risk analysis can provide insightful information to insurance companies in communities where flood insurance is offered as a nonstructural measure. Small scale flooding happens more frequently and it is easier to assess damages than a larger scale flood event (Hausmann and Perils, 1998). If flood insurance is offered, it is the responsibility of insurance companies to provide economic assistance to, and aid in the rapid recovery of flood victims. It is difficult to determine whether or not to invest in, or provide insurance opportunities to flood risk communities. Without detailed research and investigations, communities of people may be overlooked in flood risk insurance policy planning, or community members may not be aware of the potential flood risk they may face (Menzinger and Brauner, 2002). This demands an exhaustive flood risk-vulnerability analysis.

I.1 Flood risk-vulnerability analysis

Assessment of flood risk and dissemination of this information to all stakeholders (general public, decision-makers, and water managers) is very important in overall process of flood management. The general public may use the information in purchasing a house, or in selecting a site to start a business. Knowledge of flood risk could aid decision-makers in: developing land development plans and land use zoning; in planning emergency response strategies; in waste disposal site selections; in making infrastructure budgetary decisions; in developing guidelines for operation of existing infrastructure; in regional planning; and in general policy development at all levels. Water management and other professionals can utilize flood risk assessment information in planning, design, construction and maintenance of flood protection infrastructure (reservoirs, dikes, drainage pipes, etc). Flood risk information is used in research and education too. Each type of users' knowledge on flood risk analysis varies, and the way in which each would use the flood risk information also varies. In this project we see use of flood risk assessment as a tool for flood plain management.

The present research study is initiated with the concept of Hotspots project (Dilley et al., 2005; Arnold et al., 2006) completed by the Center for Hazards and Risk Research (CHRR) at Columbia University and the World Bank's Disaster Management Facility (DMF), now the Hazard Management Unit (HMU). In the Hotspots project, the risk levels are estimated by combining hazard exposure with historical vulnerability for two indicators of elements at risk - population and Gross Domestic Product (GDP) per unit area - for six major natural hazards: earthquakes, volcanoes, landslides, floods, drought, and cyclones. The relative risks for each grid cell rather than for countries as a whole is calculated at sub-national scales. Such information can inform a range of disaster prevention and preparedness measures, including prioritization of resources, targeting of more localized and detailed risk assessments, implementation of risk-based disaster management and emergency response strategies, and development of long-term land-use plans and multi-hazard risk management strategies. The Hotspots project mainly considers global risks of two disaster-related outcomes: mortality and economic losses, but the social impacts of natural hazards are not considered. Hotspots global analysis and case studies stimulate additional research, particularly at national and local levels, increasingly linked to disaster risk reduction policy-making and practice.

I.2 Objectives of the study

The main objectives of the present study are as follows:

(1) To develop a web-based tool for vulnerability mitigation assessment and facilitate vulnerability mitigation by providing various flood information.
(2) To develop a flood risk-vulnerability model for efficiently managing flood disasters.
(3) To find suitable vulnerability indicators and develop a scheme for their integration into an overall vulnerability index with high spatial density.
(4) To determine the spatial impact that the flooding of main communication routes and road bridges has on flood vulnerability.
(5) To determine the impact that the flooding of critical facilities (schools, hospitals, and fire stations) has on vulnerability.
(6) To implement the assessment of flood risk using postal codes or Forward Sortation Areas (FSA) for space discretization.
(7) To make the web-based tool accessible to all types of users providing selective access to information, this reduces the misuse of data and promotes data security.
(8) To develop an analysis tool for calculation of flood risk as a function of land use.

I.3 Literature review

The research study presented in this technical report deals with the development of a web-based flood information system, which provides risk information for different spatial locations, considering detailed information on flood hazard, exposure, and vulnerability. The extent of this literature review is therefore confined to provide a broad overview of methods used for vulnerability and hazard calculations to natural hazards with specific reference to flood disaster management. The available literature on the application of GIS and webpage development tools to flood management and mitigation is also reviewed here.

Shrubsole (2000) mentions government responsibilities in flood management. The Saguenay and Red River valley events are discussed and the preparedness, response and recovery from these events are described. It suggests that economic flood losses are at least partially dependent on current flood management strategies. This study provides alternative flood management strategies considering ecosystem management, partnerships and the role of science. It discusses the factors affecting flood damages and suggests that the best combination of structural and non-structural solutions can lead to sustainable settlement development.

Bender (2002) discusses the development and use of natural hazard vulnerability assessment techniques in the Americas. It emphasizes how and why a thorough flood vulnerability analysis is required for physical, economic, and social planning in a watershed.

Flax et al. (2002) developed a risk and vulnerability assessment methodology named as Community Vulnerability Assessment Tool (CVAT), which assists emergency managers and planners in their efforts to reduce hazard vulnerabilities through hazard mitigation, comprehensive land use, and development planning. The model considers a set of hazards, e.g., storm surge, wind, flood, tornado, etc. and gives a methodology to identify and prioritize the hazards. The model also identifies the critical facilities (e.g., police, fire, hospitals, shelters, utilities, etc.) and estimates how vulnerable they are to physical and operational impacts from hazards. A social vulnerability analysis is performed considering limited inputs, but the analysis is not extensive.

Menzinger et al. (2002) discusses flood risk from an insurance perspective. The elements and conditions of flood insurance are provided. The study suggests the availability of flood insurance protection if the risk collective is broad enough for it to be affordable to low and high risk areas, based on risk assessments using geo-information sciences.

Blong (2003) introduced a new damage index used in estimating the replacement costs of damaged buildings. The study presents the development and construction of the damage index in an Australian context. The results are values (ranging from 1-20) which can be compared on a time-independent scale to assess the impact of damages to buildings resulting from natural hazards.

Carter (2005) analyzed flood risk as a combination of threat, consequence, and vulnerability. The report also discusses the federal role in investment decisions of flood control structures like dams and levees. It is illustrated in the report that the federal policy focuses only on certain elements of risk, and it suggests alternative measures for incorporating other elements of flood risk into the decision making process. There is discussion of reducing property damage vulnerability and overall flood risk. Hurricanes, Katrina and Rita are used to illustrate flood disaster events, policies and decision making.

Chakraborty et al. (2005) developed two new quantitative indicators, i.e., a geophysical risk index, based on National Hurricane Center and National Flood Insurance Program data, and a social vulnerability index, based on census information. The study examines spatial variability in evacuation assistance needs as related to the hurricane hazard. The results indicate that geophysical risk and social vulnerability can produce different spatial patterns that complicate emergency management, which indicates the necessity of consideration of geophysical and social components of vulnerability for hazard management. It also discusses the importance of considering characteristics of local population in risk-vulnerability assessment.

Holz et al. (2006) discussed web-based information system for flood management in emergency flood situations by supplying in-time information for citizens in flood prone areas about flood development, as well as better coordination of resources and actions during pre-flood phases and its critical stage. The system has the capability of online forecast and flooding calculations but does not consider aspects other than hydrologic inputs. The study mainly served for illustrating Information and Communication Technology (ICT) based decision support solutions and testing new methods for flood forecasting by neural network methodology.

Rygel et al. (2006) focused in constructing a social vulnerability index and applied it to a case study of hurricane storm hazard. The purpose of the study was to demonstrate a method of aggregating vulnerability indicators using Pareto ranking that results in a composite index of vulnerability, but that avoids the problems associated with assigning weights.

Teng et al. (2006) provides risk assessment strategies in coping with environmental and social impacts of flooding in Taiwan. The study comments on improper urban development and climate changes and the potential each may bring to flood risk. Finally the study suggests flood mitigation schemes in emergency preparedness and response.

Werritty et al. (2007) discussed the social impacts of flood events in Scotland including attitude and behavior toward flooding events, warnings, evacuations and consequences. The study considered questionnaires, which were distributed to households in seven cities and a rural population in Scotland. From these questionnaires focus groups were conducted to provide insight into human behavioral responses to flood events. Impact assessment was performed by considering intangible or tangible and immediate or lasting impacts to assign impact values. The study suggests enhancing social resilience for sustainable flood management and provides further recommendations in flood emergency management for Scotland.

I.4 Outline of the report

The report is organized as follows. Section II provides detailed characteristics and geography of the study area – the Upper Thames River basin in southwestern Ontario, Canada. Section III contains important definitions pertaining to flood risk analysis and terms which will frequently appear in describing the present study. It also covers the primary tool used for analysis (GIS) and a basic description of the tool used in the web-based design and data organization. Included in Section IV are the components of risk; exposure, vulnerability and hazard. A description and details of each are provided, as well as why are they are significant in risk assessment and analysis. The methodologies for their assessments are explained with details. Section V discusses the representation of the data in a web-based information system. It also describes the organization of the website, and how is the data presented to three different types of users: general public, decision-makers and water management professionals. Representing flood information differently to each type of user provides a more effective support and more understandable environment. Finally, Section VI summarizes the results and conclusions from the study. It also presents limitations of the study, and the future work.

II. DETAILS OF THE STUDY AREA

II.1 General description

The Upper Thames River basin serves as the study area for this work. The 3,500 km^2 basin lies in southwestern Ontario nested between the Great Lakes Huron and Erie. The basin has a well documented history of flooding events dating back to the 1700s. It is comprised of the counties of Perth, Middlesex, Huron and Oxford. The location of the Upper Thames River watershed in Ontario, Canada is shown in Figure 1 and a more detailed map of the watershed is presented in Figure 2.

Two main tributaries of the Thames River, referred to as the North (1,750 km^2) and South (1,360 km^2) branches, intersect at a location in London known as 'The Forks', near the main core of the municipality of London. The South Thames meets Middle Thames just east of the city. The Forks region has served as a historical landmark for London, and the region is largely characterized by both commercial and residential structures. The Forks region has poor forest density, as a large portion of forest area has been isolated by urban constructions making it difficult to sustain plant and animal life. Many of the forested lots are found near the river or scattered throughout the city. The river flows are attenuated by 3 major flood control structures. Wildwood reservoir is located on the Trout Creek, a tributary of the North Thames branch, Fanshawe reservoir directly upstream of London and Pittock reservoir in Woodstock at the upper reach of the Thames River. Other than these three dams, there are also dykes in London and a flood wall in St. Marys. The river water quality is poor at the Forks, likely the result of fertilizers, eroding soils, spills and pollutants - consequence of development and rapid urban sprawl. Despite this, the Thames River is still considered rich in both cultural and natural heritage, housing various species of wildflowers, ferns and trees along its banks. It has a powerful history of post-glacial landscape, aboriginal occupancy, European settlement, military proceedings, and urban development. These are among many reasons that the Thames River was declared part of the Canadian Heritage River System in 2000.

Figure 1. Location of the Upper Thames river watershed in southern Ontario.

(Simonovic et al., 2007)

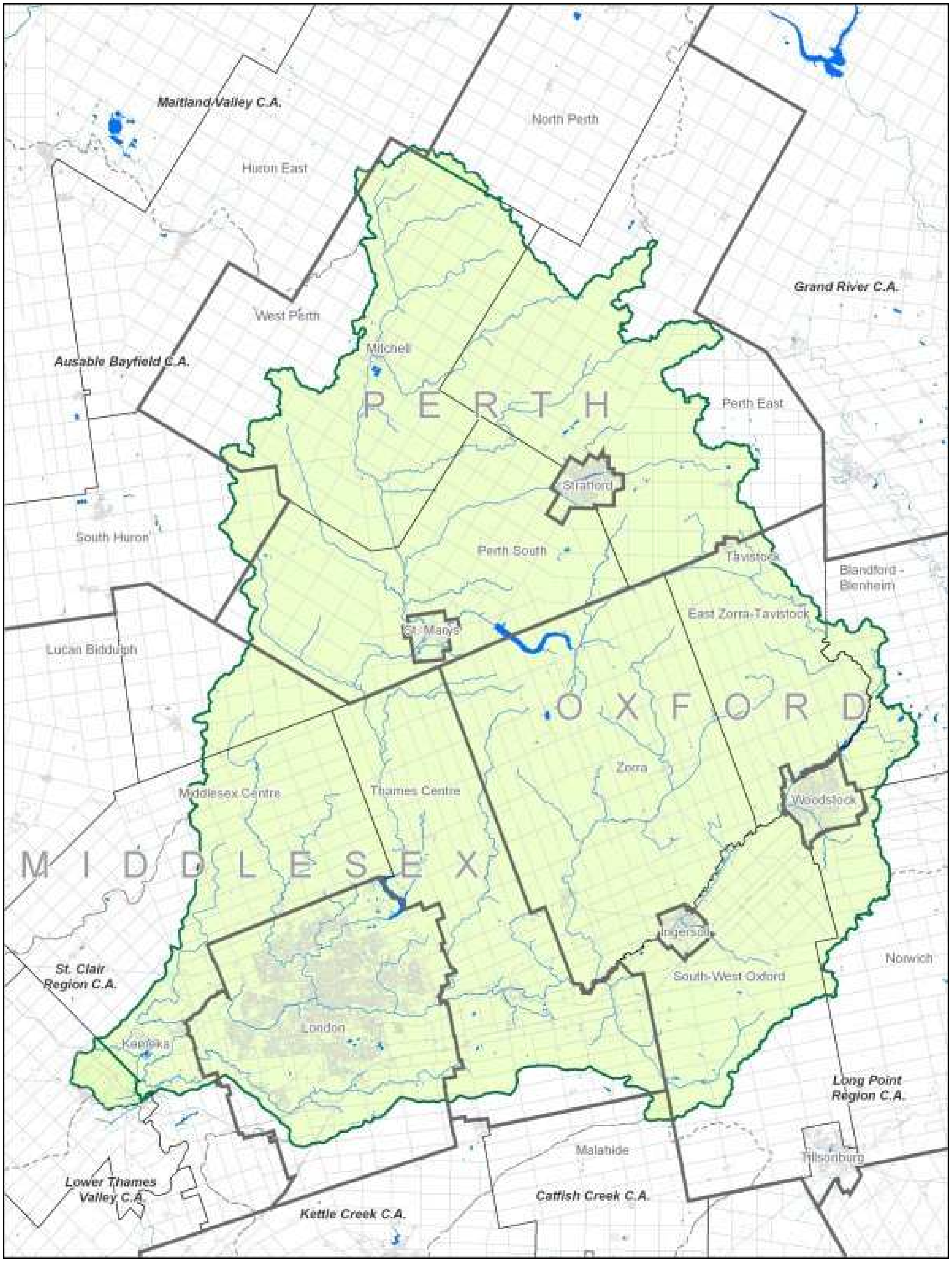


Figure 2. A detailed map of the Upper Thames river watershed.

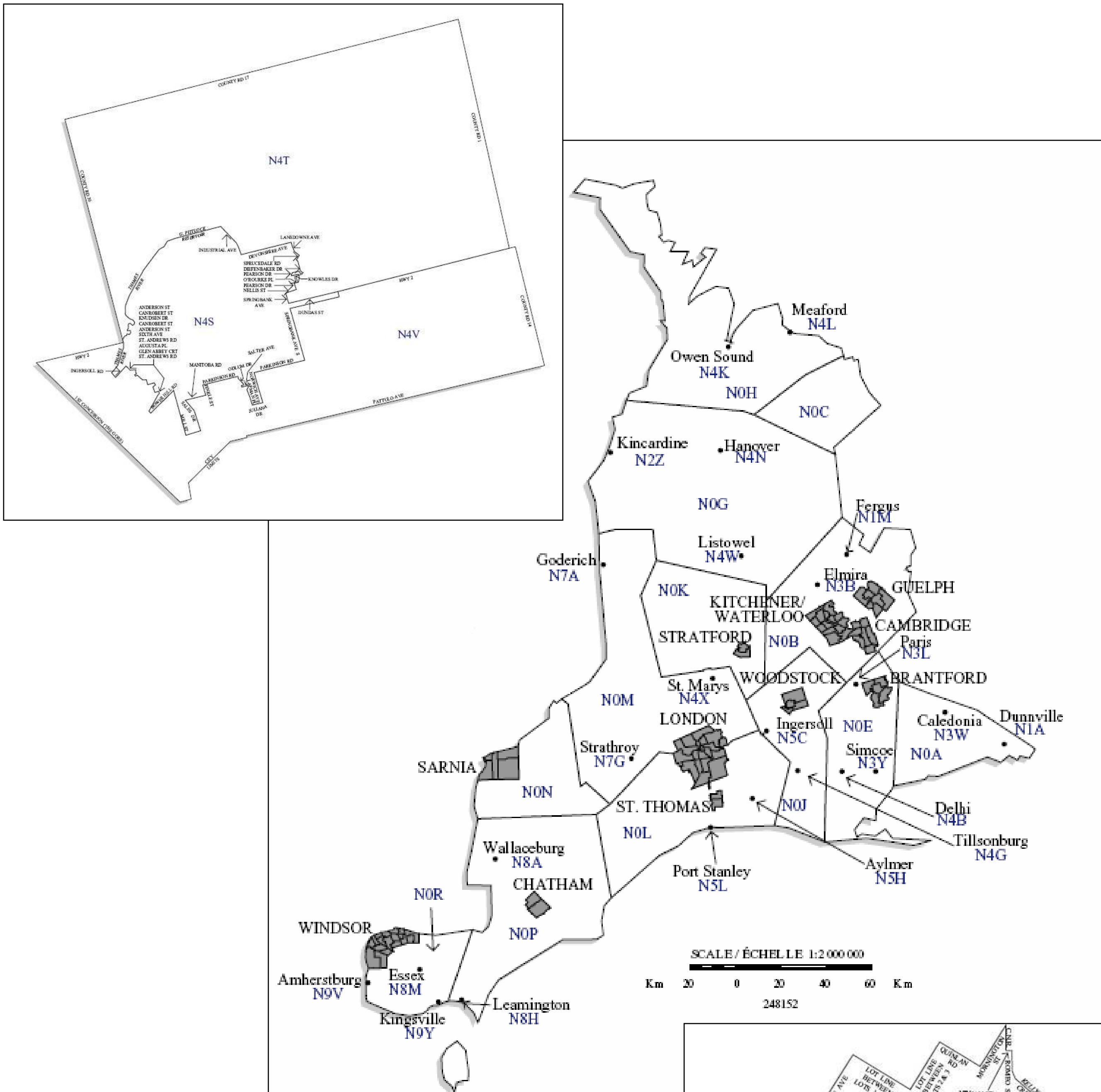
(Simonovic et al., 2007)

II.2 Forward Sortation Areas

This study area consists of major postal regions within the Upper Thames River watershed, some of which extend beyond the watershed boundaries. The regions are distinguished by the first three characters of its postal code designation, into regions known as Forward Sortation Areas (FSAs). The regions which historically experience more frequent flooding events were selected as areas of particular significance and the FSAs comprising these regions were selected for analysis. The cities of important FSAs include London, Woodstock, Mitchell, St. Marys, Ingersoll, and Stratford; with a particular emphasis on the city of London. A total of twenty-five FSAs from these cities have been considered in this study, provided in Table 1 and shown in Figures 3and 4. These FSAs are the smallest spatial geographic units considered in this study.

Table 1. A list of the FSAs considered and the municipalities to which they belong (PSEPC, 2005).

Damage Centre	FSAs
London	N5V N5W N5X N5Y N5Z N6A N6B N6C N6E N6G N6H N6J N6K N6L N6M N6N N6P
Mitchell	N0K
Woodstock	N4S N4T N4V
St. Marys	N4X
Stratford	N4Z N5A
Ingersoll	N5C



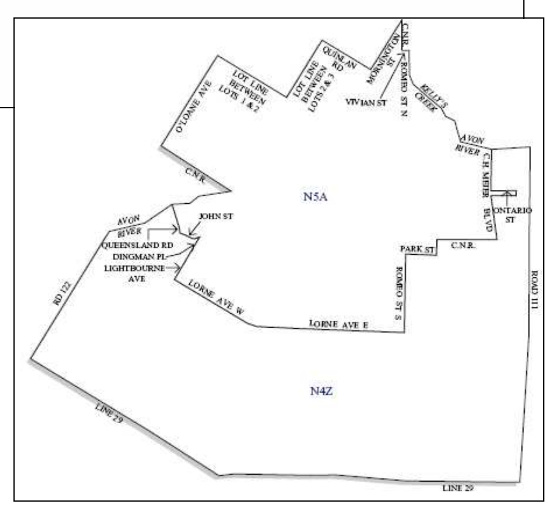


Figure 3. The orientation of FSAs in southwestern Ontario. (PSEPC, 2005)

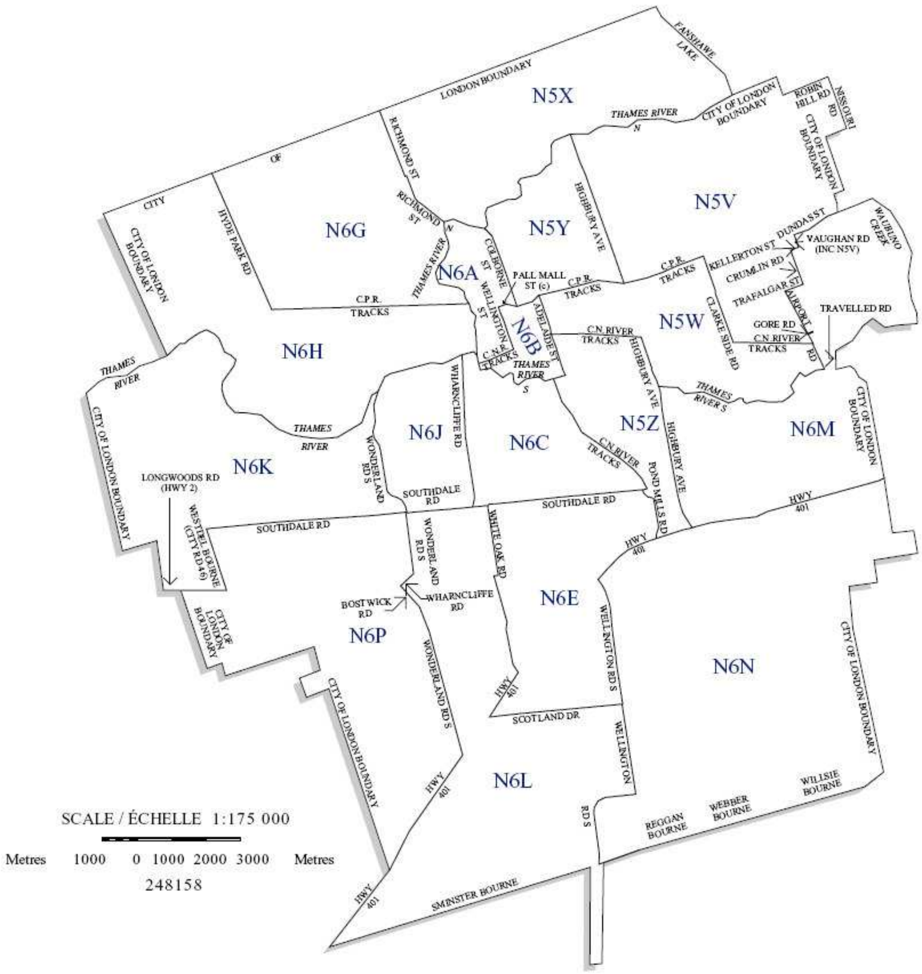


Figure 4. The orientation of FSAs in London, Ontario.

(PSEPC, 2005)

II.3 Data collection

Numerical data necessary for the development of a web-based flood information system has been collected from Statistics Canada, which is a reliable source of data and provides updated national statistics consistently every five years following a Census of the population. It includes a breakdown of data into areas of various sizes, including FSAs, and offers data for small census divisions which remain relatively stable over many years. This facilitates the process of updating the flood relevant data and flood risk calculations.

The GIS is a tool for effective presentation and processing of spatial information. It is possible to combine census data with other spatial information using GIS and obtain valuable information to use for processing. Spatial GIS datasets can include surficial geological characteristics of the region, land use, physical features, the location of structures, bridges, vegetation, quarries as well as critical facilities. The graphical data used in this project has been collected from a variety of sources, all compatible with the ArcGIS software. Spatial data can be provided in two different formats: vector (geometric shapes) or raster (grid-based). Vector data is used in the present study. Features of vector datasets are represented as points, lines, or polygons. Various layers and datasets were collected from Statistics Canada, The Ontario Fundamental Dataset, Upper Thames River Conservation Authority, Surficial Geology of Southern Ontario dataset, and Route Logistics. These datasets were available online or obtained from the Serge A. Sawyer map library and the IDLS library at the University of Western Ontario, London, Canada.

III. METHODOLOGY

III.1 Introduction

The present web-based flood information system provides extensive information on flood risk, vulnerability, hazard and exposure to different users, and it also contains all the raw data for further use in flood management (Black et al., 2007). Assessment of flood vulnerability has been done by combining existing methodologies and some innovative procedures. This section provides an (a) introduction of the methodologies used in this study, (b) basic discussion of GIS and (c) the webpage development tools used for information system development. As a prerequisite, some relevant technical definitions are provided for a better understanding of the flood related issues.

III.2 Some relevant definitions

III.2.1 Flood hazard

Flood hazard is a measure of the susceptibility/threat to a region due to its physical environment. It frequently encompasses hydrological analyses and the design and mapping of flood lines.

III.2.2 Flood vulnerability

Flood vulnerability is defined as a measure of a regions' or population susceptibility to damages (Hebb and Mortsch, 2007). Overall flood vulnerability, as considered in this study, is a combination of physical, economic, infrastructure, and social vulnerability. Each component is organized into themes which are further broken into specific flood risk-vulnerability indicators. The average value of these four vulnerability components is considered as the overall flood vulnerability.

III.2.3 Flood exposure

Similar to flood vulnerability, flood exposure also indicates susceptibility of a region to flood damages but has hydrological influences on flood flow and its responses. For example, soil permeability characteristic is a descriptor of flood exposure. Soil permeability has direct relationship with flood flow, as more permeable soil has less water holding capacity and can reduce surface runoff in floods, whereas less permeable soil has more water holding capacity and results an increased chance of water logging. In the present study, flood exposure is assessed from land use and soil permeability characteristics.

III.2.4 Flood risk

This study takes a different approach from most other works and defines flood risk as a combination of flood exposure, hazard and vulnerability. Mathematically this translates into the following expression:

$$Flood\ Risk = (Hazard) \times (Vulnerability) \times (Exposure) \tag{1}$$

III.3 Framework

The layout for collecting and integrating the data, along with the sequential procedural steps for data processing are outlined in Figure 5. After collecting and analyzing the data (using GIS tool), the data can be processed and information displayed online in a logical manner to various users.

III.3.1 Technical details of ArcGIS

ArcGIS is one of the useful tools for flood risk analyses and research. It is helpful for representing data spatially, and permits the overlay of many different features. It can combine all different features graphically into a map for simultaneous visual representation of data. It functions by utilizing data stored as layers in shape files (with extension .shp), which are positioned on top of each other. Figure 6 provides the concept of layering data using a Geographic Information System (GIS), as well as combining vulnerability components to assess overall flood vulnerability. Mapping is completed using the ArcMap routine of the ArcGIS software package. It functions as an interface where shape files are added, manipulated, and tabulated. ArcCatalog is another component of ArcGIS which facilitates the management and movement of files. To assist in manipulating and converting data, ArcToolbox provides basic tasks for data management. The fourth component in the ArcGIS software package is ArcScene, used in 3D modeling. Most of the GIS information analyzed in this study is in vector format.

GIS can perform area and perimeter computations using code stored in the 'calculations' feature of the program or it can 'count' the number of features on the map. This means additional data, not stored directly in shape files can be obtained from GIS data files by layering features and performing calculations.

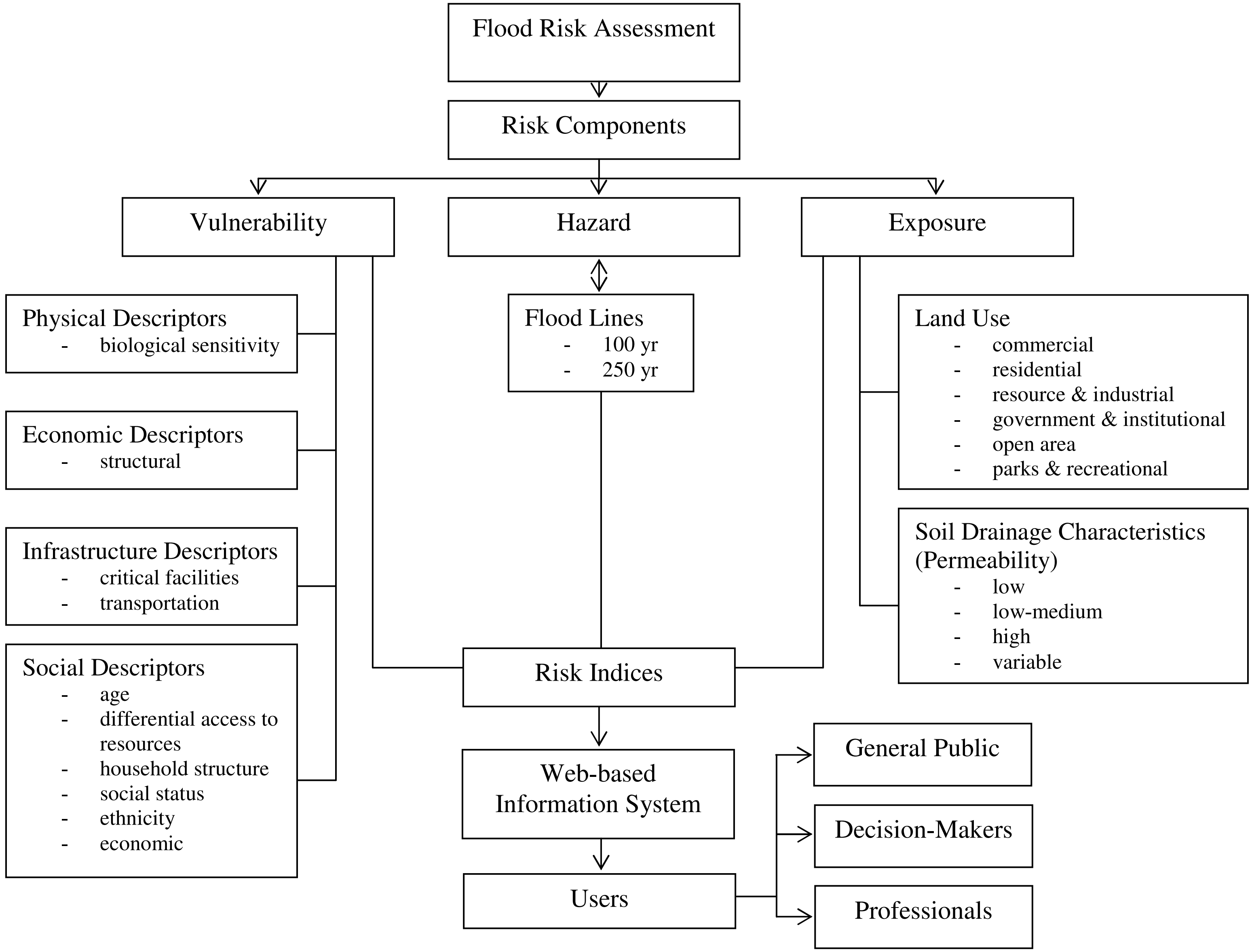


Figure 5. Flow chart of the procedure and data combination.

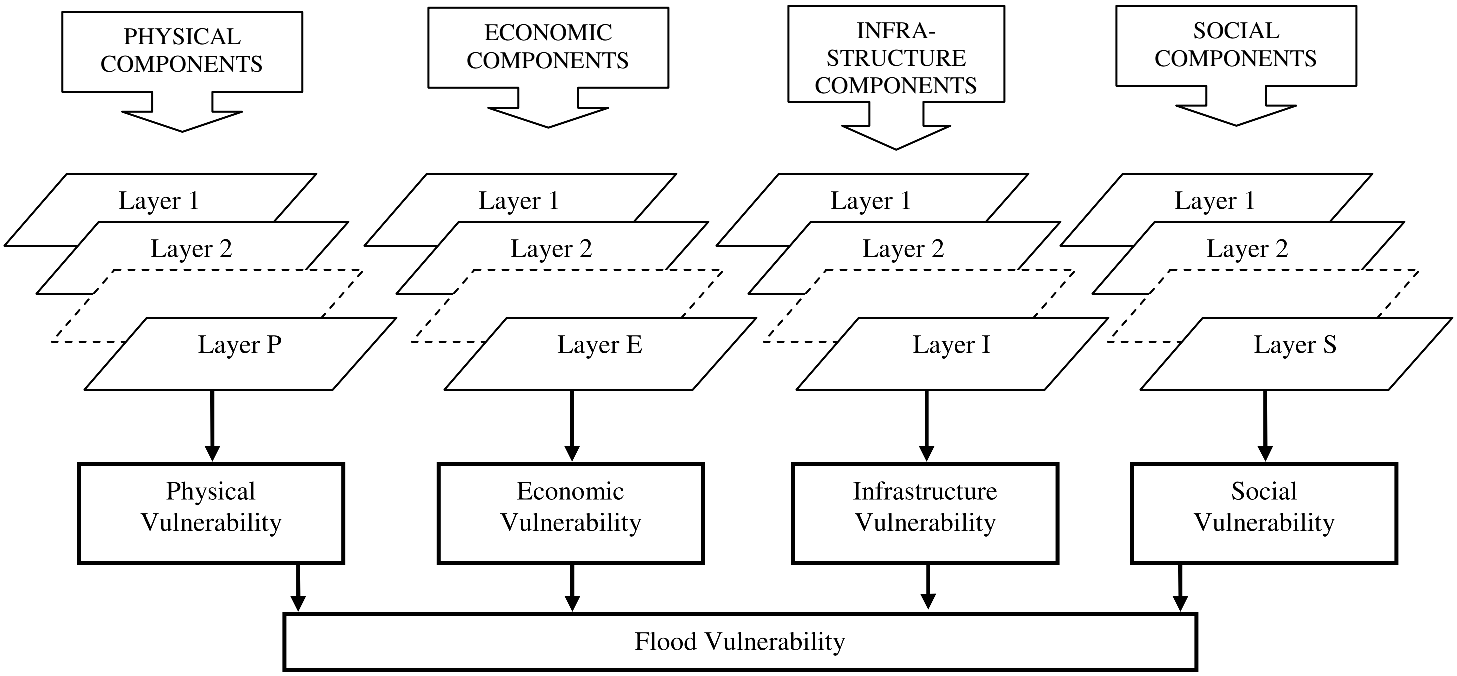


Figure 6. Process for deriving flood vulnerability using GIS.

The area calculation feature in GIS was used in calculating the area of each FSA. GIS maps provided spatial location for roads, railways, intersections, road bridges and other features of the FSAs. The 'length' and 'count' operations in GIS make it possible to calculate the length or number of features within each FSA (for example, the length of railway which falls within the boundaries of the forward sortation area N6A). Features could be layered on top of each other, making it possible to compile a computer grid/map graphic and perform vulnerability analyses.

III.3.2 Technical details of Adobe Dreamweaver CS3

Adobe Dreamweaver CS3 is a tool used in web design of flood information system. It can be used in the design, organization, and maintenance of a website. With assistance of this software it is easy to compile, edit, store, move, and format information used in the web-system design. It also permits a viewing feature which displays any changes in the design. Templates for web design are readily available and the program allows flash movie features to be easily incorporated into the webpage.

The flood information system webpage is organized in a fashion so that the flood information presented depends on the type of user. Initially, the user selects the postal code (the FSA) of interest and then selects the user category he/she is (general public, decision-maker or water management professional). This selection is integral in providing the proper and relevant flood information to each type of user.

IV. METHODOLOGY OF FLOOD RISK ASSESSMENT

In the present study, the descriptors of flood risk (hazard, exposure, and vulnerability) have been analyzed separately only to be combined in the final calculation of flood risk. Flood risk is the product of hazard, exposure, and vulnerability. The way each descriptor is assessed and represented in the information system is not the same. Each descriptor can be represented graphically, numerically, or using a combination of both. Similarly, the format in which the source data is available differs for each descriptor.

IV.1 Hazard analysis

Hazard describes a physical threat of a flood occurring and a region becoming inundated during a flooding event. The inclusion of hazard as a component of risk is essential since the vulnerability of the population is negligent if it is not directly exposed to the hazard (i.e., flood event). Hazard is a critical risk descriptor in flood analysis. In the present study however, the hazard calculation has not been performed. Already available 100-year and 250-year flood line data from the Upper Thames River Conservation Authority is used for risk calculation. The following section describes the flood line data.

IV.1.1 Flood lines

The probability or likelihood of flooding is described as the chance that a location will be flooded in any one year. For example, 1.3% chance of flooding each year implies 1 in 75 chance of flooding at that location in any year. Exceedance probability of a design flood x is represented as:

$$P[X \geq x] = 1 - F(x) \qquad (2)$$

where F(x) denotes the value of Cumulative Distribution Function (CDF) at x. The concept of exceedance probability is explained graphically in Figure 7. The return period (T_x) of design flood x is the reciprocal of exceedance probability, which is mathematically represented as:

$$T_x = 1/ P[X \geq x] = 1/[1 - F(x)] \quad (3)$$

A flood line of a particular return period is the line joining different points in space exposed to a flood of the same return period. It represents the spatial extent of threat from the flood of a particular return period. They are affected by the topography and river characteristics. The flood lines for a return period are evaluated by using physical, hydraulic and hydrologic characteristics of a particular location in the watershed. The present study utilizes 250-year flood line data for all FSAs being considered and 100-year flood line data for FSAs within the City of London, as per the availability.

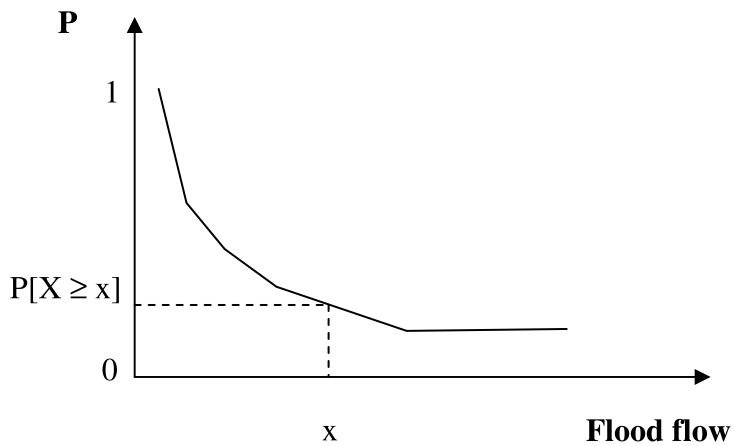


Figure 7. Graphical representation of flood exceedance probability

The one hundred year flood line shows the area which would be inundated by a 1 in 100 year flood event. The exceedance probability value or the likelihood of that flood event is 1/100 = 0.01 (or 1%).

A flood hazard map with 100 and 250-years flood lines is used as one of risk descriptors depicting spatial extent of floods with exceedance probability of 0.01 and 0.004, respectively. Most recent flood maps with 100 and 250-years flood lines for the study area are used in this work. Flood lines are calculated considering the present level of flood protection in the region.

The area between the 250-year flood lines is larger than the area between the 100-year flood lines because it represents spatial extent of the inundation caused by more severe and less frequent flood events. Combination of the information from the flood hazard map with the numerical data provides a hazard value to be used in flood risk estimation.

IV.2 Exposure analysis

Flood exposure is a different component of the flood risk. Patterns of land use and soil type are considered as the most important characteristics of flood exposure in the Upper Thames River watershed. Most commonly 'exposure' of a flooded area is considered either under the 'hazard' or the 'vulnerability' category of risk descriptors. However, in this study, exposure is considered as a separate component of risk and introduced as a weight in the flood risk assessment process. The indices of flood vulnerability, as discussed later, do not depend on physical characteristics of the watershed and river itself. The land use and soil permeability are two physical watershed characteristics which affect the flood flow (Sullivan et al., 2004). To differentiate these two characteristics from other flood vulnerability indices, they are introduced as flood exposures that describe the susceptibility of a region to flood damage and have physical impact on flood flows. This study only estimates a value of exposure for those FSAs within the municipality of London. The other FSAs considered in our work do not have available land use and soil data. An exposure value of 1 is assigned to the regions outside of the City of London.

IV.2.1 Impact of land use

The land use data includes seven different categories of use: open space, commercial, residential, parks and recreational, government and institutional, resource and industrial, and water body. Each of these land use categories has been assigned a 'Degree of Importance (DI)' value. These values, while estimated by the research team, can be changed by decision-makers with more extensive knowledge on how different land use influences runoff and flood response. Overdeveloped and highly commercialized areas include more pavement and asphalt covered impervious surfaces. They increase runoff (quantity and timing), whereas open land (including agricultural land) has larger areas exposed for direct infiltration of rainfall. With this knowledge, the DI values are assigned to each category of land use in the present study and tabulated in Table 2.

Table 2. DI values assigned to each category of land use

Type of land use	DI
Water Body	0.1
Parks & Recreational	0.2
Open Area	0.3
Government & Institutional	0.7
Commercial	0.8
Residential	0.8
Resource & Industrial	0.8

Area under each land use type is expressed as a fraction of the FSAs total area. Summation of the fraction of each type multiplied by its DI provided an exposure value representative of the land use for an FSA. Therefore, mathematically the flood exposure of land use for ith FSA is expressed as:

$$E_i^{Land} = \sum_{l=1}^{n} [DI_l \times (A_i^l / A_i)] \qquad (4)$$

where E_i^{Land} is the flood exposure of soil permeability, DI_l is the degree of importance of land use type 'l'. 'l' may be any of the land use types mentioned in Table 2. Area under each land use type (l) is expressed as A_i^l for ith FSA. Total area of the ith FSA is denoted as A_i .

IV.2.2 Soil permeability as an indicator of exposure

Soil permeability refers to the property of soil to allow water movement through its pores, which is inversely proportional to soil density. It is a hydrological drainage characteristic of soil. The more permeable the soil is the more water can be transmitted through it. A soil with low permeability, such as clay, doesn't permit much water flow. This could cause 'puddling' of water – the accumulation of water on the soil surface. Regions which are composed primarily of these types of soils are prone to a higher flood risk because the water requires a longer time to drain or infiltrate into the ground. Using a GIS dataset known as Surficial Geology of Southern Ontario, obtained from the Serge A. Sawyer Map Library at the University of Western Ontario, it was possible to spatially assess the soil permeability characteristics of the region. The data is available with different designations of permeability: low, medium-low, high or variable. A DI was assigned to each permeability category based on the soils ability to infiltrate water, facilitate its transmission, and decrease flooding. Table 3 lists the DI values used in the present study.

Table 3. DI values assigned to each category of soil permeability

Soil permeability	DI
Low	0.8
Low-medium	0.6
Variable	0.5
High	0.3

Area under each permeability category is expressed as a fraction of the FSAs total area. Summation of the fraction of each category multiplied by its DI provided an exposure value representative of soil permeability for an FSA. Therefore, mathematically the exposure of soil permeability for i^{th} FSA is expressed as:

$$E_i^{Soil} = \sum_{p=1}^{m} [DI_p \times (A_i^p / A_i)] \tag{5}$$

where E_i^{Soil} is the flood exposure of soil permeability, DI_p is the degree of importance of permeability category ‘p’. ‘p’ may be low, medium-low, variable and high. Area under each permeability category (p) is expressed as A_i^p for i^{th} FSA. Total area of the i^{th} FSA is denoted as A_i .

IV.3 Vulnerability analysis

Vulnerability is defined as measure of a region’s susceptibility to flood damage. It includes also population susceptibility to physical, mental, or emotional damage due to flooding. Vulnerability could be influenced by individual emotions, seriousness of the current situation, and previous experiences with natural disasters. Therefore, assessment of vulnerability is not an easy task. High level of vulnerability is often experienced by population with high level of poverty, minorities, and elderly. The main characteristics which predispose those individuals to a high level of vulnerability include limited mobility, communication barriers, and lack of resources. Hazards research has already recognized that these groups are exposed to more serious consequences and suffer more from a disastrous event. (Hebb and Mortsch, 2007)

Traditionally, vulnerability has considered biophysical factors. More recently social factors have also been incorporated into defining vulnerability to disasters (Chakraborty et al., 2005). The physical vulnerability generally incorporates the hazard and exposure of a population or structures to a flooding event. Social vulnerability focuses on the reaction, response, and resistance of a population to a disastrous event. Social vulnerability may exist even though a biophysical vulnerability may not. It is the combination of the two which creates a significant vulnerability consideration. Therefore, it is important to identify regions of social vulnerability, even if there is no biophysical vulnerability to flooding. These regions are likely to be more susceptible to any type of damage. Changing climatic patterns may change the biophysical vulnerability of a region over time, and a region may become physically vulnerable where it once was not. Vulnerable populations could have special needs in an evacuation situation, and it is important to identify these needs before an emergency, to aid in preparation and response to disasters. The estimation of vulnerability is challenging since the physical and demographic characteristics of a region are not static, and are always changing. By combining various spatial information and accurate, reliable sources of numerical data, it is possible to generate and readily update flood vulnerability estimations.

In this study, flood vulnerability has been defined as a combination of four types of distinctive vulnerabilities: physical, economic, infrastructure and social. Combined, these four types of vulnerability can provide a better estimation of the overall flood vulnerability. Each of these four types can further be broken down into vulnerability indicators which can be linked together by a common theme as shown in Table 4 [see Appendix A and Table (A) for the breakdown of vulnerability indicators].

Table 4. Flood risk vulnerabilities themes and indicators.

Category	Theme	Indicator
Physical	Biological Sensitivity	Wetlands
Economic	Structural	Period of Construction
		Structure Type
Infrastructure	Transport	Road
		Railway
		Unpaved Road
	Facilities	Critical Facilities
	Bridges	Road Bridges
Social	Age	Population Under 20 Years of Age
		Population 65+ Years
	Differential Access to Resources	Female Population
		Population of Female-Headed Single-Parent Households
		Population whose Main Mode of Transportation is Not Vehicle

Contd.

		Low Income Households
	Household Structure	Population Living Alone
		'Full Houses'
	Social Status	Population of Renters
		Mobility
		Population Who Have Not Graduated High School
		Regions of Low Community Participation
	Ethnicity	Population Whose Knowledge of Official Language is Neither English Nor French
		Population of Visible Minorities
	Economic	Employed Labour Force Working from Home
		Direct Workforce in Agriculture

Physical vulnerability has been defined separately from physical hazard. Physical vulnerability incorporates only those indicators of biological sensitivity. Physically vulnerable regions will experience higher flood damage and longer, slower recovery time. They include regions with high biodiversity and sensitive life. Wetlands are for example, considered regions of physical vulnerability in this study.

Economic vulnerability includes those indicators which are associated with monetary flood losses. Though all buildings directly affected by a flood may face damage, certain buildings and characteristics of a structure are susceptible to greater damage than others. Commercial structures (both temporary and permanent) have not been considered in this analysis due to a lack of available data. A more complete analysis would include vulnerable commercial structures and loss of revenue.

Social vulnerability has been explored in the literature earlier. Indicators similar to those used in this study have been used previously. However, the list of indicators used in this study has been significantly expanded. Many characteristics of a population could be used in a vulnerability analysis. Of these, a select group of indicators was selected based on relevance, available information, and specific characteristics of the region. Each indicator in the present study is considered independently, even though some may fall into more than one category (for example, female population or single-parent households).

Infrastructure vulnerability includes road networks, railways, and road bridges. Infrastructure components are important to the movement of a population, communication, and safety. If the infrastructure is affected by the flooding event then the population is affected too. Inundation that impedes traffic and hinders communications increases stress in the population exposed to the disaster. Inundation may also block important emergency routes and cause physical damage to roads. The material used in the road construction is also considered in the assessment of vulnerability. Unpaved roads, like gravel and dirt roads, would sustain more damage than a paved road when exposed to a flooding event. They may not maintain driving conditions and may need replacement after a flood occurrence. Infrastructure vulnerability considers these indicators but analysis may be expanded to include the impact of flooding on critical facilities and road bridges.

IV.3.1 Vulnerability due to flooding of critical facilities

Vulnerability of critical facilities is an indicator of infrastructure vulnerability. Critical facilities include institutions which play an integral role in public safety, health, and provision of aid. The critical facilities considered in this study include schools, fire stations, and hospitals.

Schools can be used for both education and as a place of refuge and a center of aid during a flood. If a school is inundated during flood, then the nearby schools will be affected in order to accept the student population from flood affected regions during the duration of the recovery process. Schools not directly affected by the flood could be converted into temporary housing/aid centers for those who are affected. Thus, if the schools are flooded, even those people who are not directly flooded will experience stress (a break in routine) inconvenience, and perhaps even health risks.

Fire stations respond to emergencies in the area near the station and aid in disaster relief. If a fire station is flooded, then the population in close proximity would be more vulnerable. The next fire station responsible for the area would be further away, and the response time will be longer.

Hospitals represent another type of critical facilities that require special attention during flooding. In hospitals there are patients who are immobile and may not be able to move even in the case of an emergency. People in hospitals are with health issues which could worsen because of the stressful nature of a flood disaster. In the case of hospital inundation there is a potential for water contamination. Inundated hospitals will not be able to provide the necessary emergency assistance for those in need.

The critical facilities are given special attention in vulnerability analysis in order to provide a more accurate estimate of flood risk. More vulnerable regions can be identified and proper preparation and response can be assigned accordingly.

Procedure for assessment of vulnerability due to inundation of critical facilities includes the use of GIS tools. A 6x6 grid layer was placed over the FSAs of London. These thirty-six cells lie over the entire city, breaking each FSA into smaller areas, as illustrated in Figure 8. The cell area of each FSA is calculated using an area calculation function provided by the ArcGIS tool. The fraction of an FSA under each cell was then calculated by dividing the individual area by the total area of the FSA region. Subsequently, the 'critical facilities' layer is placed onto the combination of grid cells and FSA layers to determine areas more susceptible to damage. The process used in assigning vulnerability values due to the impact on critical facilities is based on the assumption that the people closest to the facility will be its primary users. Thus, the spatial shape for calculation of vulnerability is square - vulnerability decreases equally in all directions with the distance from the inundated cell. This concept is illustrated in Figure 9. There are four different color designations of vulnerability (red, orange, yellow, and white) representing assigned vulnerability values. The number of schools/hospitals/fire stations in each cell is not considered. The presence of just one of these critical facilities is sufficient to classify the cell as important. All 'important' cells are equally important.

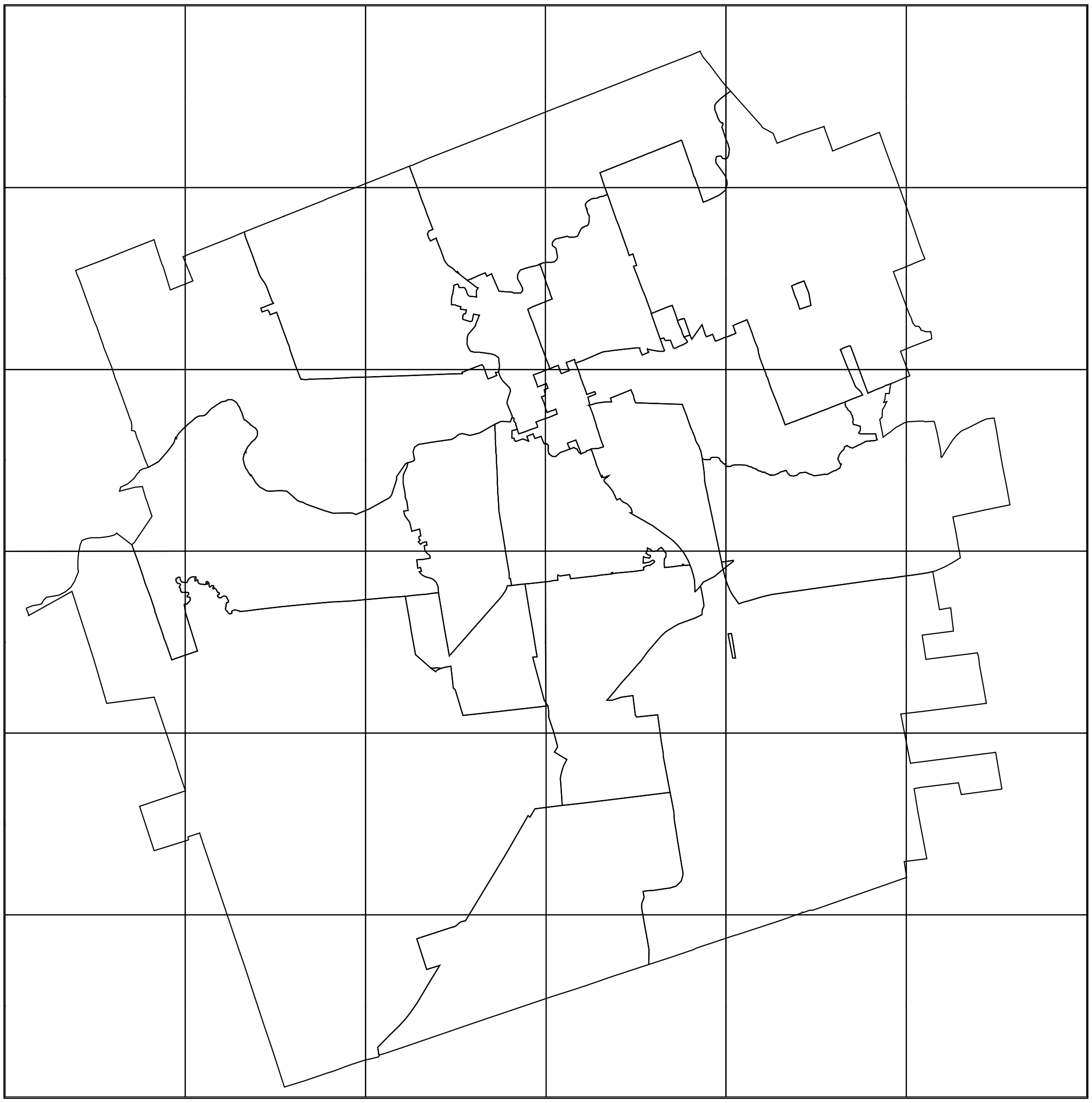


Figure 8. A 6x6 grid layered over the FSAs of London, Ontario (GIS generated image).

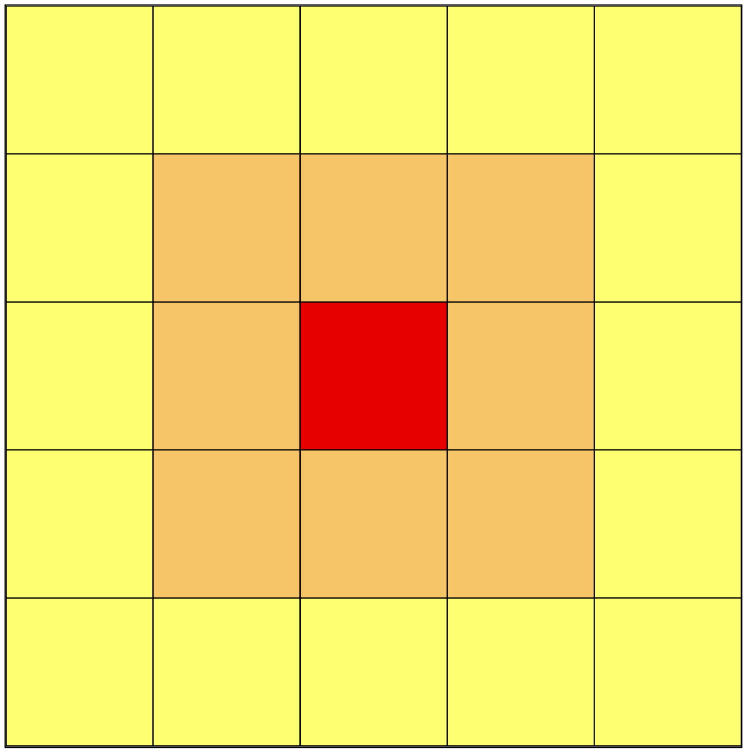


Figure 9. The square vulnerability shape and colors used in assigning vulnerability values for critical facilities (GIS generated image).

Procedure implemented using GIS tool is as follows:

1. Divide the designated watershed into grid – the grid should be regular in shape (in present analysis, a 6×6 square grid is used).

2. Degree of Importance (DI) is introduced to quantify the importance of a critical facility for the FSA where the facility is located or for other FSAs. Red, orange, yellow and white color codes correspond to 1.0, 0.75, 0.20 and 0.0 DI values, respectively. The colors are reflecting the vulnerability of each cell: red (high), orange (medium), yellow (low), white (no influence). The grid cells within an FSA that contain one or more critical facilities are identified. These grid cells are assigned red color, the highest 'degree of importance' of 1.0.

3. Assign orange color, a DI of 0.75 to the grid cells neighboring the red colored cells.

4. Assign yellow color, a DI of 0.25 to the grid cells neighboring orange cells (other than red cells).

5. Assign a white color, indicating 'zero' DI value to the remaining grid cells. The result is a square-shaped representation of vulnerability, which decreases with distance from the red (center) cell.

6. Following the previous five steps, assign DI values for all grid cells separately for each grid cell with red color. For example, if 10 grid cells contain critical facilities, the grids cells would be assigned appropriate DI values 10 times. Finally, the Overall DI (ODI) for a grid cell is calculated by simply averaging these 10 DI values.

7. The Vul_{e_i} for an FSA (area shown in bold solid line) is calculated as (see Figure 10):

$$Vul_{e_i} \text{ of i}^{\text{th}} \text{ FSA } = Vul_{e_i} = \sum_{j=1}^{k} (ODI_k \times A_k) \Big/ \sum_{j=1}^{k} A_k \tag{6}$$

where ODI_k is over all degree of importance for k^{th} grid cell, A_k is the area of i^{th} FSA with over all degree of importance ODI_k.

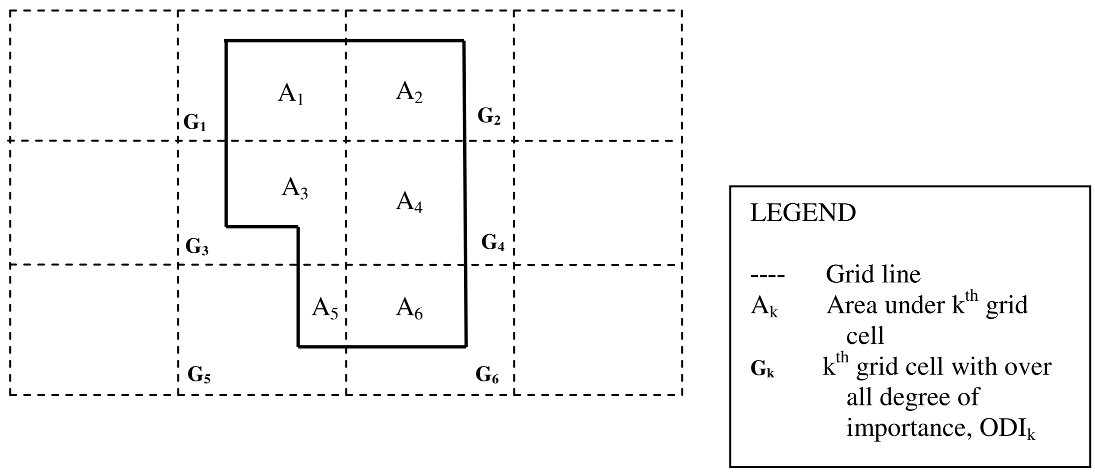


Figure 10. Example FSA region divided by grid cells.

8. Determine the standardized vulnerability value:

$$Vul_{e_i}^{std} = \frac{Vul_{e_i} - Vul_e^{\min}}{Vul_e^{\max} - Vul_e^{\min}} \tag{7}$$

where Vul_e^{max} and Vul_e^{min} are the maximum and minimum vulnerability values of critical facilities, Vul_{e_i} is the value of vulnerability for critical facilities pertaining to the i^{th} FSA.

This equation offers an improvement over the traditional standardization [i.e., diving all values by the maximum value, $Vul_{e_i}^{std} = (Vul_{e_i} / Vul_e^{\max})$] as it considers both the maximum and minimum value and ensures that the vulnerability values are within [0, 1] interval and always non-negative.

IV.3.2 Vulnerability due to inundation of road bridges

Overall infrastructure vulnerability is also affected by the inundation of road bridges. Vulnerability of an area due to the inundation of a bridge includes the interruption of traffic and communication barriers between different locations in the region. Inundation of, or damage to a particular bridge affects not only the FSA in which it is located, but also all other nearby FSAs. Bridges are used in travel by people all across the city. In this study, only bridges over the water bodies are considered significant. This is because these bridges have limited alternate routes associated with them, and are necessary for safe crossing of the water body. They are frequently used as means for transporting commercial goods, a route to and from the workplace, and as emergency routes in case of a disaster.

Procedure for assessment of vulnerability due to inundation of road bridges is based on the use of GIS tool too. The same 6×6 grid which was used in the calculation of the vulnerability due to inundation of critical facilities as shown in Figure 8 is used in the vulnerability assessment due to inundation of bridges. However, unlike in the case of critical facilities, the shape used in assessing this vulnerability is not a box, but rather cross-like in nature. The shape varies with the number of bridges in any particular grid cell. Figure 11 illustrates the shapes of vulnerability for cells containing 1-5 and 6-10 road bridges, respectively. The number of bridges over water that was contained in each cell, determines the shape that would be used in assessment of vulnerability. As the number of significant bridges increases in a cell, the more likely it is that inundation of bridges in that cell would affect more people. The vulnerability shape due to inundation of bridges is mainly based on a basic assumption: the need for crossing any given bridge decreases with distance from the bridge (i.e., the need for crossing the bridge is highest in areas that are closest to the bridge).

The proposed method assumes that the whole cell being considered is flooded, and that bridges in that cell are unavailable for use. Regions near the bridges that are flooded are inconvenienced and exposed to increased damage. It is assumed that the people in close proximity to the bridge over water use them more frequently then people who are not as close.

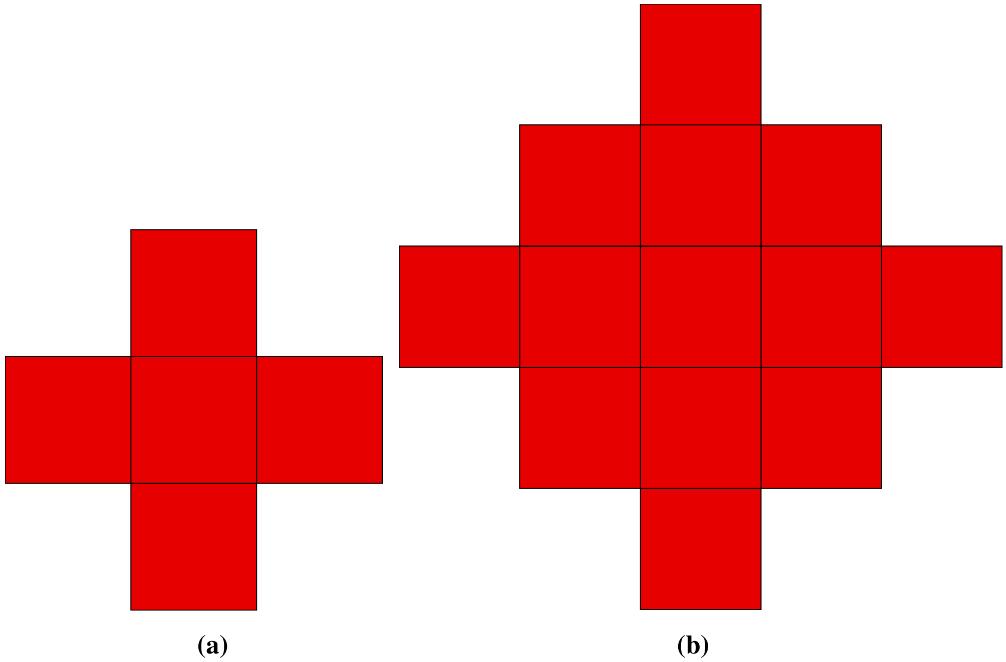


Figure 11. The vulnerability shapes assigned for cells with road bridges. Image (a) is the shape used for assigning vulnerability to cells where the presence of 1-5 bridges exists in the 'important' cell; and image (b) is the shape used for assigning vulnerability to cells where the 'important' cell contains 6-10 bridges (GIS generated image).

The cells are assigned a degree of importance based on the vulnerability mapping in proximity to the inundated cell. The degree of importance assignment is similar to the one used in assessing the infrastructure vulnerability due to inundation of critical facilities. However, the road bridges scenario designates a degree of importance as either red/high (1.00) or yellow/low (0.2). In both analyses it was assumed that the *whole* grid cell is equally affected by the flooding, thus damage is assumed to be uniform across the cell area. The population density within a portion of the FSA covered by a grid cell, is unknown. Therefore an equal distribution of population is assumed throughout each FSA.

The procedure for assessment of vulnerability due to inundation of road bridges also includes the use of GIS. The same procedure (steps 1 through 8) as described in section IV.3.1 are followed, with the use of the new vulnerability shapes as shown in Figure 11, to determine the infrastructure vulnerability due to road bridges.

IV.3.3 Calculation of the overall vulnerability index

The overall vulnerability index is obtained by integrating together the four different types of vulnerability (flood risk descriptors): physical, economic, infrastructure and social. The single value for vulnerability is used in flood risk assessment.

Each index is obtained by averaging the flood indicators within each descriptor. In the situation with no weights or equal significance of each vulnerability type, it is possible to determine an overall vulnerability value by averaging the four values (one for physical, economic, infrastructure and social vulnerability), for each FSA region as presented below:

$$Vul_i^O = (Vul_i^{Phy} + Vul_i^{Eco} + Vul_i^{Infra} + Vul_i^{Socl})/4 \qquad (8)$$

where Vul_i^{Phy}, Vul_i^{Eco}, Vul_i^{Infra} and Vul_i^{Socl} are the values of average physical, economic, infrastructure and social vulnerabilities respectively, for the i^{th} FSA.

This generates a single vulnerability value. These vulnerability values are comparable between different FSA regions, and provide insight into the spatial variability of flooding vulnerabilities.

IV.4 Results and discussion

The calculation of the vulnerability indices provides input for mapping each category of vulnerability using GIS. The darker color indicates an increase in vulnerability. Figure 12 shows the physical vulnerability map for each FSA. Figure 13 represents the economic vulnerability of individual FSAs. Infrastructure vulnerability is mapped in Figure 14, including the impact of inundation of 'critical facilities' and 'road bridges'. Finally, Figure 15 maps the social vulnerability of the FSAs. Various vulnerability indices are averaged to determine an overall vulnerability value. GIS is used to map the overall vulnerability of individual FSAs and the final map is shown in Figure 16. These maps give a general description of region's vulnerability, and can provide for emergency flood management, disaster mitigation activities and planning of disaster protection infrastructure.

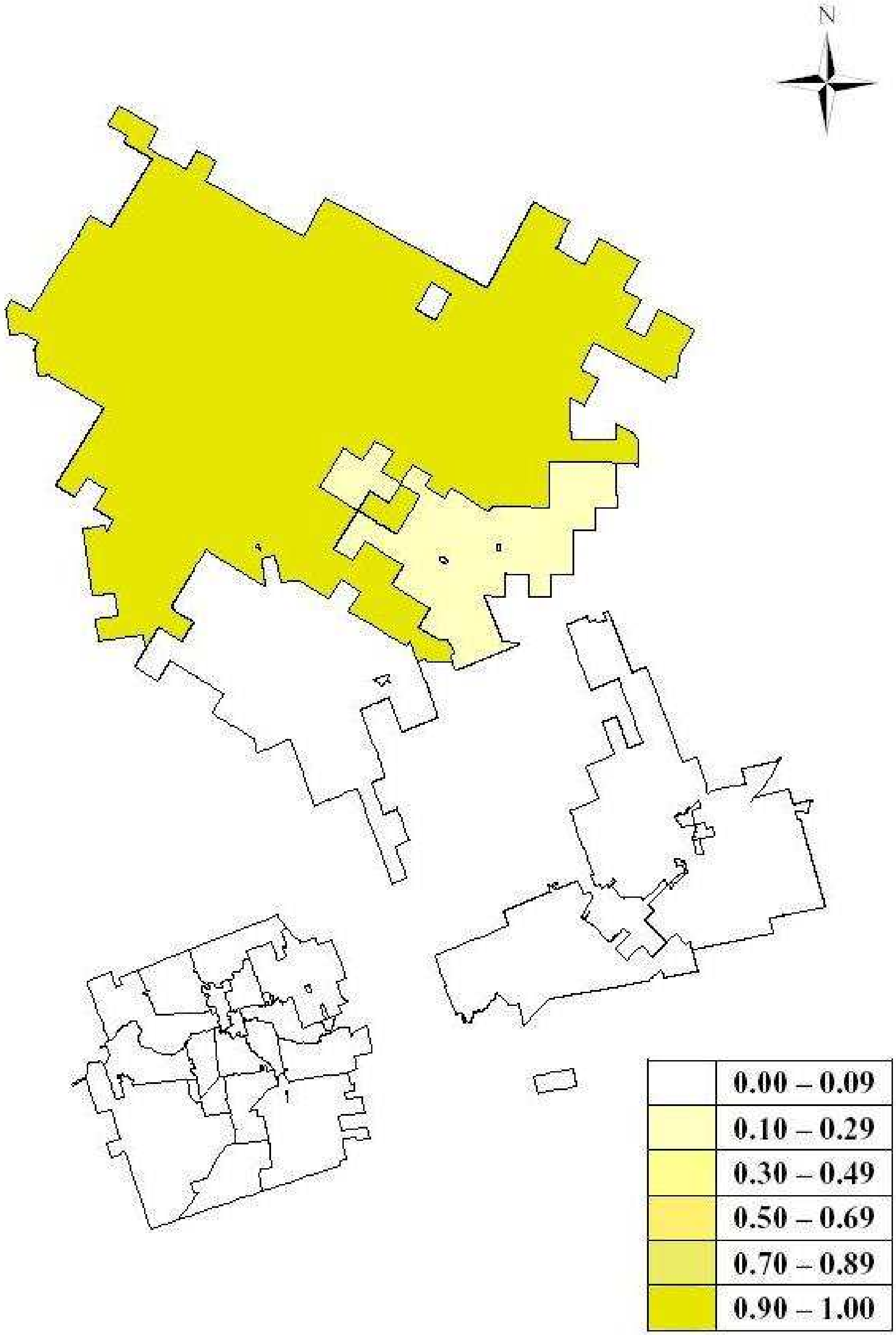


Figure 12. GIS generated map of standardized average physical vulnerability.

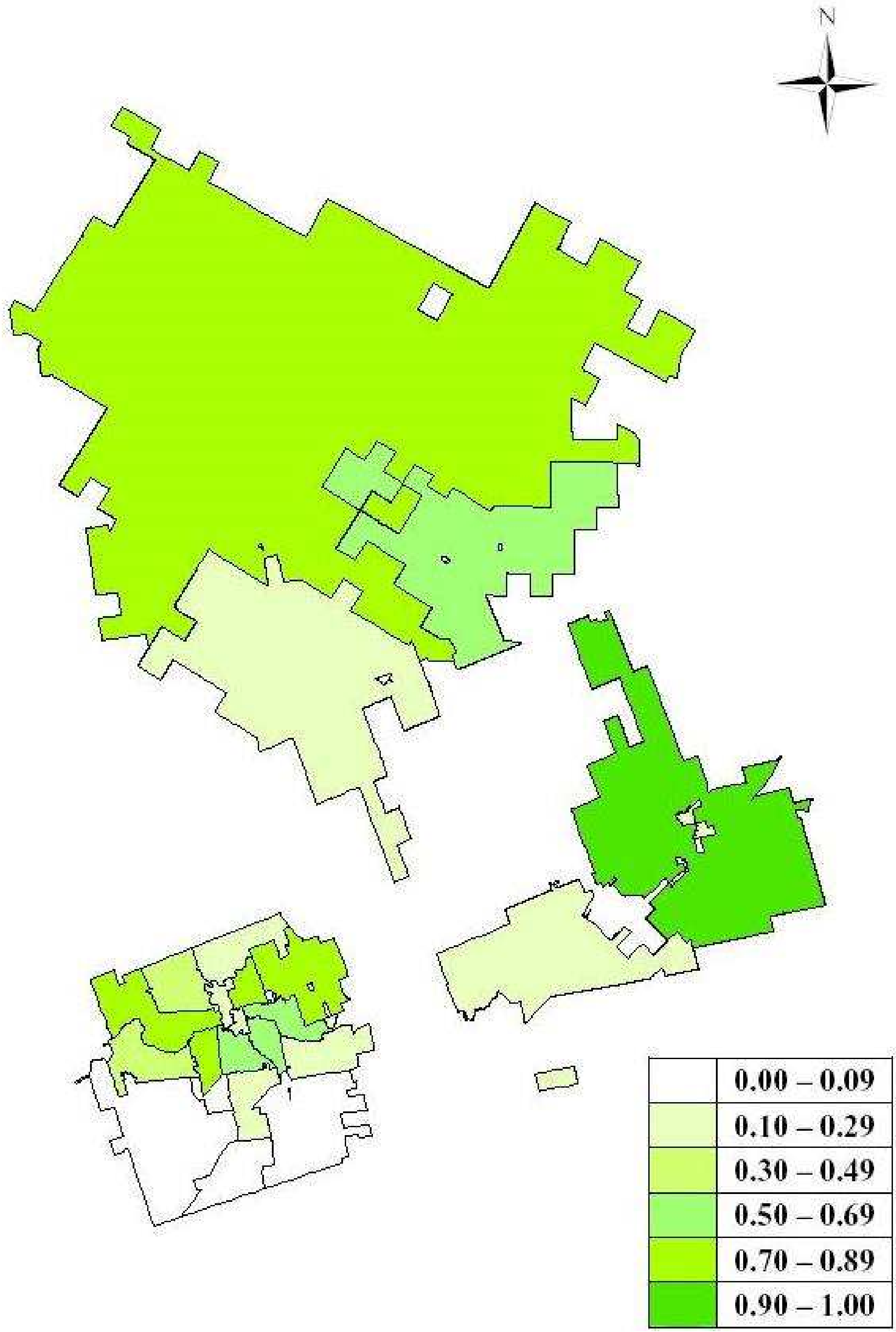


Figure 13. GIS generated map of standardized average economic vulnerability.

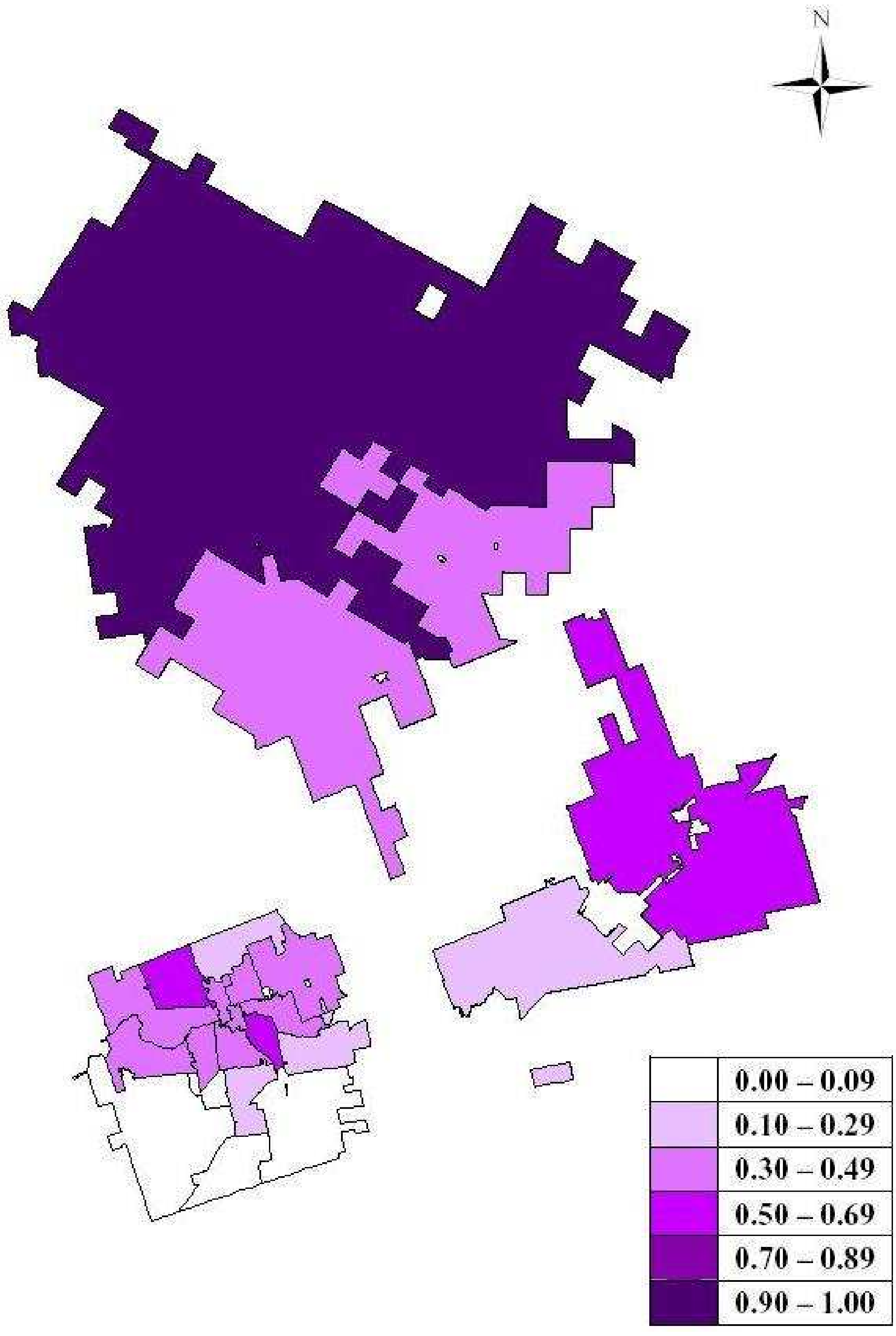


Figure 14. GIS generated map of standardized average infrastructure vulnerability.

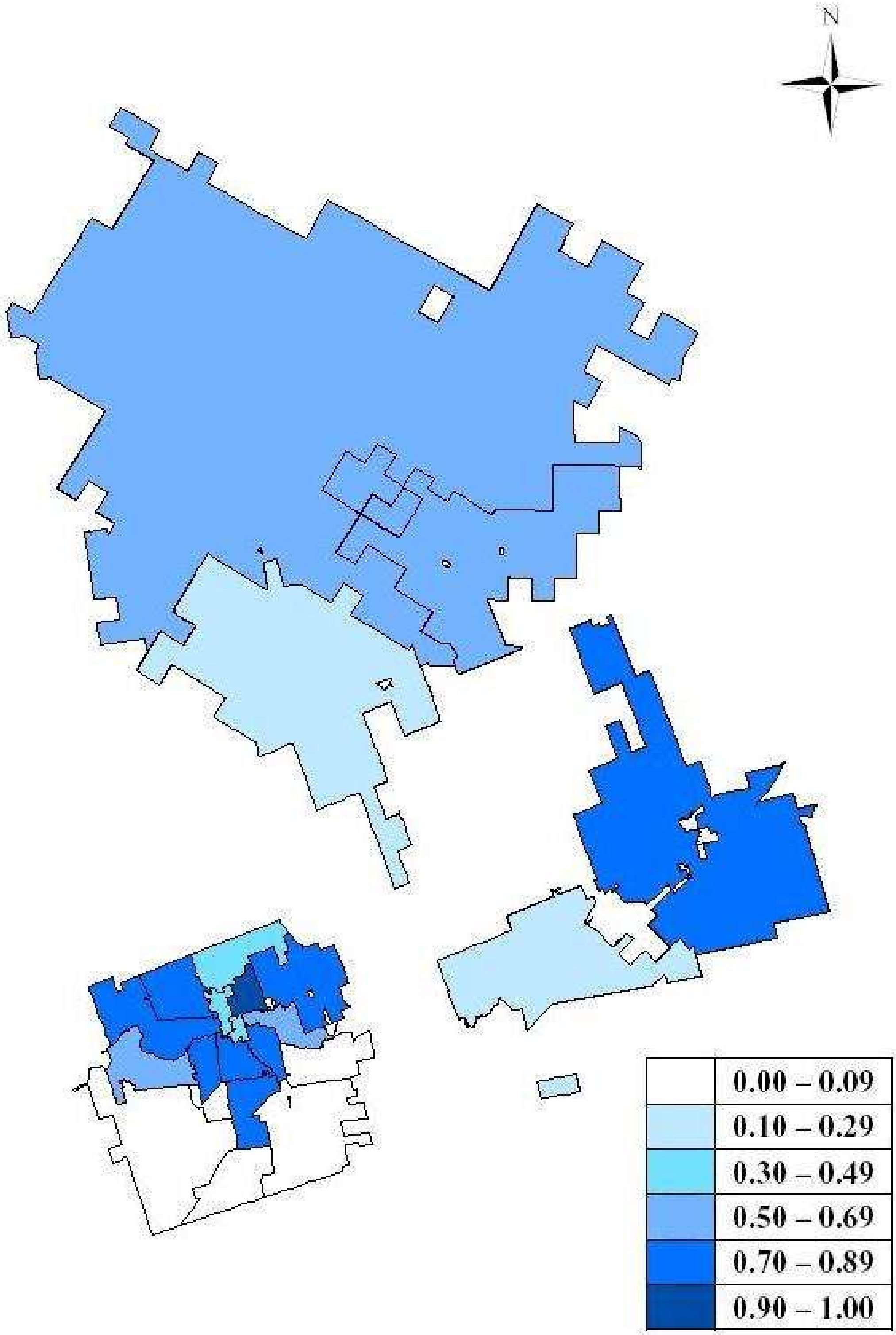


Figure 15. GIS generated map of standardized average social vulnerability.

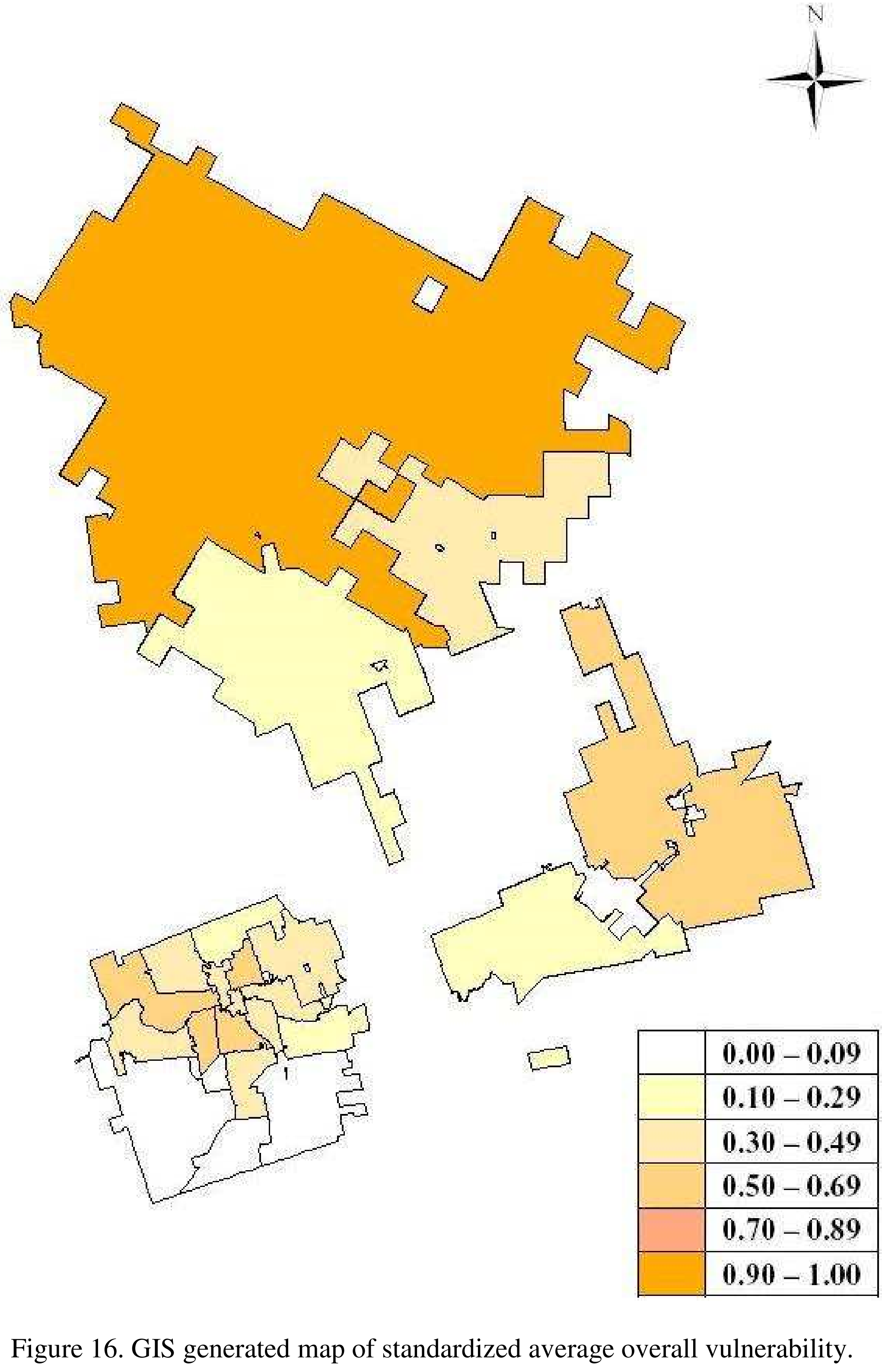
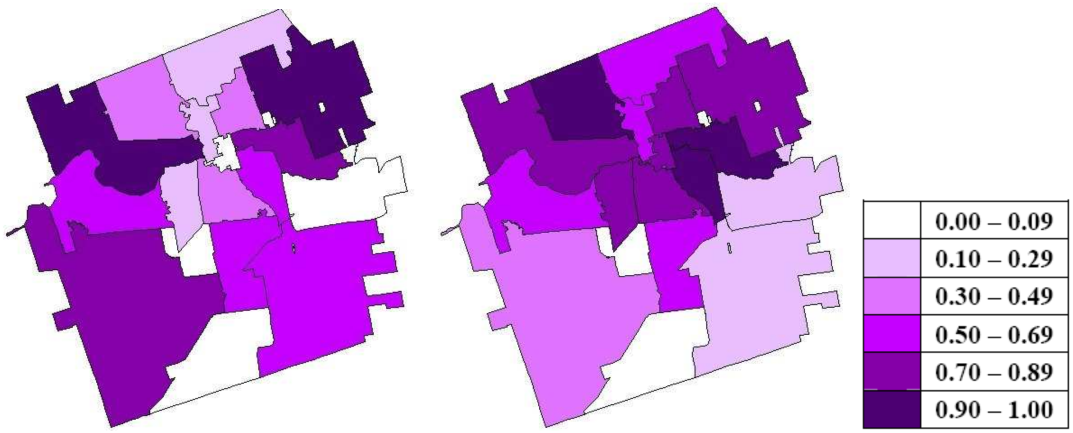


Figure 16. GIS generated map of standardized average overall vulnerability.

The present study incorporates a unique consideration of inundation of road bridges and critical facilities in assessing infrastructure vulnerability. Figure 17 displays the difference in infrastructure vulnerability due to consideration of critical facilities and road bridges.



(a) (b)

Figure 17. GIS generated map of average infrastructure vulnerability for the FSAs of London. Image (a) represents the infrastructure vulnerability not considering the impact of road bridges and critical facilities in vulnerability assessments; whereas Image (b) is a representation of infrastructure vulnerability including the road bridges and critical facilities analyses. Both sets of values of vulnerability are standardized. (GIS generated image).

In most cases, the infrastructure vulnerability of the FSA increases with the addition of impacts due to inundation of road bridges and critical facilities. The processed data and results obtained from the present risk-vulnerability analysis are presented in Tables (B) and (C) of Appendix A.

V. PRESENTATION OF THE FLOOD RISK INFORMATION

V.1 Development of a user interface

V.1.1 Introduction to website

The World Wide Web has become an integral part of today's communications and a prevailing source of information. It is widely used by all types of people. Providing a website for people to access flood risk information is an effective way of informing the public about the susceptibility to flooding that they may otherwise not be aware of. A website can serve as an information center and may provide analysis tools for interactive processing of available flood information. The web also provides the opportunity to tailor the presentation of the same information to different types of users.

V.1.2 User relevant information

Gearing the information to different users provides for more efficient use of the information system. The amount of information provided to each user differs according to their needs and anticipated use of information. The prototype web based Information System created for this flood risk analysis targets three different user categories: general public, decision-makers, and water management professionals. Each category of user is provided flood risk analysis and data in a different way which is designed to meet the anticipated needs of each user group.

The general public has access to a simple explanation of flood risk terminology, tables providing values of vulnerability and a description of what they mean, GIS screenshots of 100-year and 250-year flood lines, as well as a simple analysis tool for flood risk calculation.

Decision-makers are provided with a more detailed description of flood risk terminology and the implications of flooding. They have access to the same hazard flood line maps as the general public. Decision-makers are provided a more detailed and flexible analysis tool which allows the user to change the percentage of each land use category and compare the present level of flood exposure and flood risk to those obtained under changed land use scenarios. This may assist in the analyses of different land development initiatives and their consequences.

Professionals are presented the most detailed descriptions and the most technical flood related information. They are provided a very detailed numerical breakdown of vulnerability and exposure, including a list of all indicators used in the analyses. They also have access to the hazard flood line maps similar to those provided to the general public and the decision-makers. The analysis tool available to water management professionals is the same as one provided to the decision-makers. The professionals are the only user with access to a ‘raw data’ containing all of the unanalyzed numerical data used for the flood risk analyses.

V.2 Results and discussion

The web-based flood information system can be used as an efficient, convenient way to present information to different types of users. The layout of the website provides accessibility to flood risk assessment for the general public, decision-makers, and water management professionals. The homepage of the website is shown in Figure 18. Initially the user is asked to provide its location, followed by selection of its FSA region and identification (user type). The website is user-friendly and the details can be found in the report by Black et al. (2007).

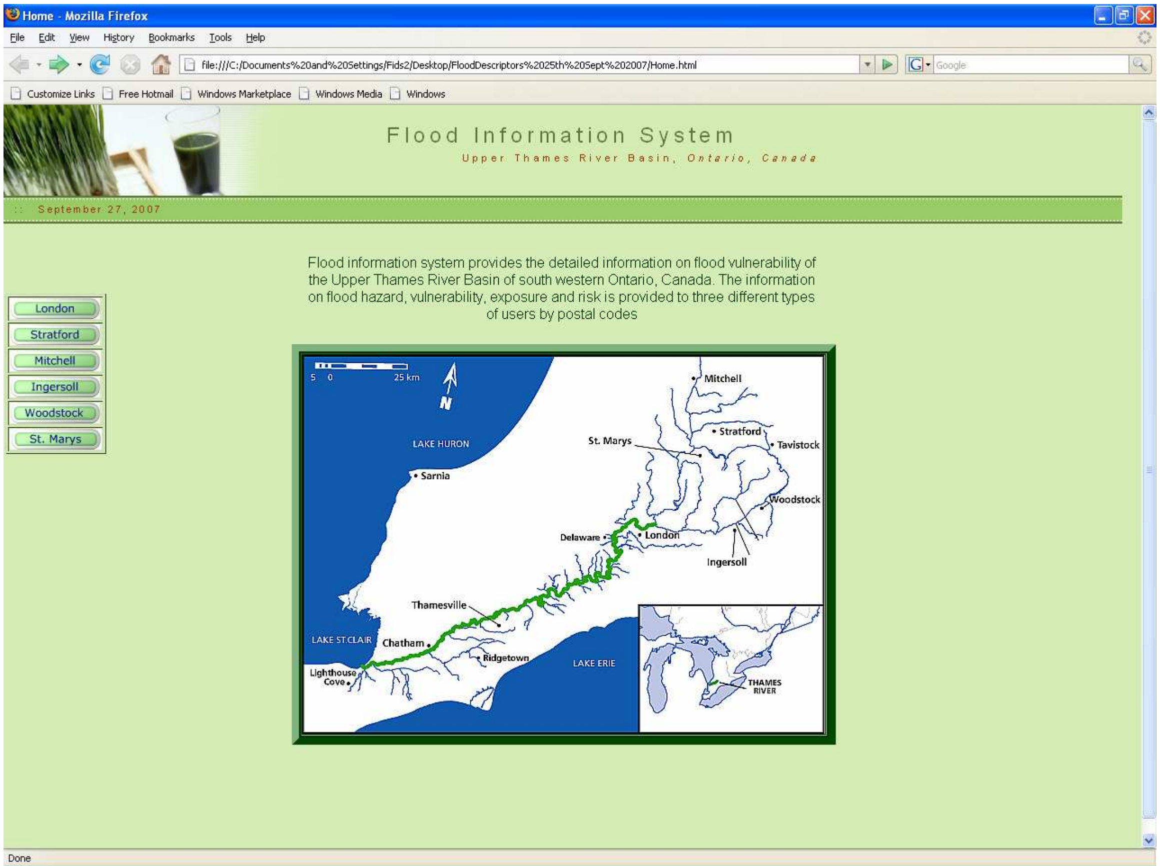


Figure 18. A screenshot of the home page of the web-based flood information system.

VI. SUMMARY AND CONCLUSIONS

The present study analyzes flood risk and vulnerability in the Upper Thames River basin. Though there are well developed flood risk analyses methodologies in the literature, this study provides some new ideas and different approaches for flood risk-vulnerability analyses. The present study considers a large region as a case study with six major damage centers in Upper Thames River watershed. The impact of inundation of critical facilities and road bridges on 'vulnerability' is analyzed. New indices are introduced in the infrastructure flood vulnerability analysis, for example – length of railway, length of road, number of major intersections. Typically, 'exposure' has been included as a component of flood vulnerability. The present study considers 'exposure' separately from 'vulnerability analysis' and uses it as a weight in the calculation of risk, which is obtained as the product of vulnerability, exposure and hazard values. The minimum and maximum values of vulnerability were considered in this study's standardizing methods instead of using the conventional formula for standardizing vulnerability. The study provides an 'analysis tool' for estimation of flood risk as a consequence of changes in land use patterns. This flood risk information is provided uniquely to different users: general public, decision-makers, and water management professionals. A user-friendly web based information system is designed to systematically present all flood information. This system uses differential access to flood information based on the anticipated needs of each user category.

There are some limitations in the analysis performed in this study. In the present flood information system all the components of exposure and vulnerability are not considered due to unavailability of data. The assignment of Degree of Importance (DI) for the calculation of impacts due to inundation of critical facilities, emergency service stations and road bridges across the river on vulnerability is dependent on preferences of decision-makers or flood planners. The same limitation is present in the calculation of flood exposure. In the present case study only two flood lines are available, e.g., 100- and 250-years flood lines, which restrict the calculation of flood risk. The system does not provide any representative value of flood hazard or the value of exceedance probability for an FSA.

The present study could be extended to address other important flood management considerations such as, for example, climate change (Prodanovic and Simonovic, 2006). The values of flood risk for different FSAs may be calculated considering the impact of climate change. No hydrologic calculation is performed in the present study for finding out present position of the flood lines in the watershed. The uncertainty due to imprecision in the assignment of Degree of Importance (DI) for calculation of impact of critical facilities and road bridges across the river on vulnerability may be addressed in the flood risk calculation by the introduction of fuzzy set theory (Zadeh, 1965). The impact of critical facilities and road bridges across the river on infrastructure vulnerability is calculated only for the City of London. The same analysis may be performed for other damage centers in the watershed. Different shapes can be used in the road bridges and critical facilities' analyses. More details about the population distribution and behaviours in close proximity to road bridges could justify considering different vulnerability shapes. The present system considers mainly 2001 statistical data. The results may be updated with more recent data. The proposed methodologies of flood risk-vulnerability analyses are not limited to the present case study in any way. They may be easily applied to any other watershed.

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APPENDIX A

Table A. Flood risk descriptors, vulnerability and indicators.

<table>
<tr><td colspan="7">Table of Vulnerability and Exposure Indicators
Risk = Hazard * Exposure * Vulnerability</td></tr>
<tr><th>Category</th><th>Descriptor</th><th>Theme</th><th>Indicators</th><th>Description</th><th>Justification</th><th>Source</th></tr>
<tr><td rowspan="4">Physical</td><td>Hazard</td><td>Hydrologic Information</td><td>250-yr Floodplain
100-yr Floodplain</td><td>Maps of 250-yr and 100-yr flood lines</td><td rowspan="2">Usually flood lines are based on the design flood. It identifies the flood surface profiles and derives the regulatory lines. In the present study, the design floods are designated as 100 and 250-year flood. Larger flood events will put a larger area at flood risk.</td><td>Upper Thames River Conservation Authority</td></tr>
<tr><td rowspan="2">Exposure</td><td>Land</td><td>Land use</td><td>Map of ‘blocks’ of land and their major land use (residential, commercial, open, industrial, agricultural, & woodland)</td><td>GIS Map</td></tr>
<tr><td>Soils</td><td>Permeability</td><td>Surface and subsurface soils which exhibit poor water drainage</td><td>Location more susceptible to flooding and ‘pooling’ of water</td><td>GIS</td></tr>
<tr><td>Vulnerability</td><td>Biological Sensitivity</td><td>Wetlands</td><td>Presence/absence of wetlands</td><td>Wetland areas are more prone to flooding; environmentally sensitive (biodiversity)</td><td>GIS</td></tr>
</table>

(Contd.)

Category	Descriptor	Theme	Indicators	Description	Justification	Source
Economic	*Vulnerability*	Structural	Period of construction	The time period in which each dwelling was constructed	Older houses have sustained more weathering and are more susceptible to damage and may have insufficient storm water drainage, or in need of maintenance/repair (aging infrastructures)	Census 2001
			Structural type	# of each type of house built	Low level dwellings (and mobile homes) and dwellings with basements are more susceptible to flood damage, and incur a higher % home damage	Census 2001

(Contd.)

Category	Descriptor	Theme	Indicators	Description	Justification	Source
Infrastructure	*Vulnerability*	Transport	Road	Length of road	Importance should be given to those particular postal code areas with high values of length of road, railways, water structures and water & waste water conveyance systems. Unpaved roads will sustain more damage. The postal codes can be ranked as per these characteristics.	Ontario Fundamental Dataset (GIS)
			Railway	Length of railway		Ontario Fundamental Dataset (GIS)
			Unpaved roads	Length of roads which are not paved		GIS
		Facilities	Critical facilities	Facilities of particular community importance (schools, hospitals, fire stations, airports, museums, landfills, hazardous waste sites, utilities etc)	Damage to these facilities inconvenience a collectively large proportion of the population; some damage may be irreversible; some damage hazardous to health and sanitation; closures cause additional stress	London Example Dataset (GIS)
		Bridges	Road bridges	Bridges which are depended upon to cross bodies of water.	Damage to these bridges could cause inconveniences in travel, work and emergency situations. Could also be dangerous and costly to repair.	GIS

(Contd.)

Category	Descriptor	Theme	Indicators	Description	Justification	Source
Social	*Vulnerability*	Age	Population under 20yrs of age	# of people under 20yrs	Physically weak; young are susceptible to health related problems; limited mobility; incapable/difficulties in decision making and disaster response	Census 2001
			Population 65+ yrs of age: - population - living alone	# of all people over 65yrs and number of people over 65yrs & living alone	Limited mobility; more reluctant to leave home; less informed; no one to aid them; suffer more health related issues; physically weaker	Census 2001
		Differential access to resources	Female population	# of females in area	Physically disadvantaged; slower recovery; higher domestic labour; increased stress and emotion; more likely to be poor	Census 2001
			Population of female-headed single-parent households	# of single moms	Differential access to resources; longer recovery; high stress	Census 2001
			Population whose main mode of transportation is not by vehicle	# of people who rely on transportation other than a car to get to work	May lack transportation during an evacuation	Census 2001
			Low income households	# of houses who are considered low income	Differential access to resources; damages cause higher financial instabilities;	Census 2001

(Contd.)

					difficulties in recovering	
		Household structure	Population living alone	# of people residing by themselves	Less informed; less support	Census 2001
			'Full houses'	# of households with more than 6 persons residing	More likely poor; limited resources; disadvantaged	Census 2001
		Social status	Population of Renters	# of people renting a house	Less informed; less disaster preparedness; less cleanup after a disaster	Census 2001
			Mobility status	# of people who have frequently changed location	Less familiar with area and potential flood risks; less familiar with emergency responses of area; less prepared for disaster; less contacts	Census 2001
			Population who have not graduated from high school	# of people without a high school graduation certificate	Communication problems; difficulties in assessing and responding/recovering to disasters	Census 2001
			Regions of low community participation	# of people involved in unpaid community activities	Areas with low community participation will have higher stress; slower recovery time; less willing to help each other	City of London & Census 2001
		Ethnicity	Population official lang. neither English nor French	# of people who do not have a sound understanding of Canada's official	Language and communication barriers may prevent them from responding or reacting appropriately	Census 2001

(Contd.)

				languages		
			Population of visible minorities	# of people who are visibly a minority	Communication barriers; slower recovery time	Census 2001

		Economic	Employed labour force working from home	# of people who regularly work from home	When home is damaged their career is also damaged; added stress; greater losses; find jobs during the flooding	Census 2001
			Direct workforce in agriculture	# of people directly involved in agricultural activities	Usually poorer; direct affect on personal and career life; find jobs during the flooding	Census 2001

Table B. Calculation of vulnerability taking into consideration impact of inundation of critical facilities and road bridges

			London						
			N6A	**N6B**	**N6C**	**N6E**	**N6G**	**N6H**	**N6J**
Physical	*Bio. Sensitivity*	Wetlands	0.0000	0.0000	0.0142	0.0001	0.0000	0.0145	0.0000
Economic	*Structural*	Period of Construction	0.43	0.41	0.95	0.17	0.27	0.66	0.60
			0.11	0.13	0.25	0.10	0.69	1.00	0.16
		Type of Dwelling	0.00	0.04	0.04	0.00	0.04	0.00	1.00
		SUM	0.54	0.58	1.23	0.27	1.00	1.66	1.76
		AVG	0.1802	0.1922	0.4111	0.0906	0.3332	0.5535	0.5855
		STAND	0.2636	0.2818	0.6127	0.1282	0.4949	0.8280	0.8763
Infrastructure	*Critical Facilities*	Bridges Over Water	0.75	0.73	0.62	0.22	1.00	0.51	0.52
		Fire Stations	0.63	0.95	0.90	0.59	1.00	0.45	0.85
		Schools	0.84	1.00	0.95	0.48	0.93	0.51	0.97
		Hospitals	0.97	0.84	0.79	0.29	1.00	0.56	0.84
	Transportation	Unpaved Roads	0.01	0.00	0.01	0.05	0.02	0.03	0.02
		Railway	0.03	0.06	0.03	0.01	0.00	0.21	0.01
		Road	0.02	0.01	0.04	0.05	0.05	0.06	0.03
		Intersections	0.21	0.14	0.48	0.36	0.44	0.52	0.34
		SUM	3.46	3.74	3.82	2.05	4.45	2.85	3.58
		AVG	0.4321	0.4670	0.4770	0.2558	0.5563	0.3558	0.4469
		STAND	0.4321	0.4670	0.4770	0.2558	0.5563	0.3558	0.4469

(Contd.)

				London									
				N6K	**N6L**	**N6M**	**N6N**	**N6P**	**N5V**	**N5W**	**N5X**	**N5Y**	**N5Z**
Physical	*Bio. Sensitivity*	Wetlands		0.0040	0.0000	0.0085	0.0437	0.0046	0.0017	0.0000	0.0344	0.0013	0.0054
Economic	*Structural*	Period of Construction		0.31	0.01	0.01	0.03	0.12	0.48	0.90	0.22	1.00	0.68
				0.62	0.01	0.47	0.00	0.06	0.98	0.14	0.33	0.38	0.41
		Type of Dwelling		0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.04	0.04	0.00
			SUM	0.92	0.02	0.48	0.03	0.18	1.63	1.04	0.59	1.42	1.09
			AVG	0.3079	0.0058	0.1607	0.0085	0.0616	0.5447	0.3468	0.1966	0.4736	0.3621
			STAND	0.4567	0.0000	0.2341	0.0039	0.0843	0.8147	0.5154	0.2883	0.7071	0.5386
Infrastructure	*Critical Facilities*	Bridges Over Water		0.54	0.00	0.50	0.05	0.21	0.46	0.73	0.65	0.91	0.70
		Fire Stations		0.28	0.06	0.20	0.03	0.00	0.31	0.63	0.33	0.68	0.95
		Schools		0.53	0.00	0.38	0.02	0.04	0.49	0.75	0.41	0.81	0.97
		Hospitals		0.49	0.00	0.19	0.02	0.05	0.41	0.57	0.60	0.83	0.79
	Transportation	Unpaved Roads		0.04	0.03	0.02	0.06	0.10	0.05	0.01	0.03	0.01	0.01
		Railway		0.00	0.00	0.01	0.14	0.00	0.18	0.22	0.00	0.02	0.15
		Road Intersections		0.05	0.04	0.03	0.06	0.12	0.06	0.05	0.04	0.04	0.03
				0.46	0.04	0.06	0.07	0.19	0.49	0.40	0.29	0.38	0.41
			SUM	2.39	0.18	1.38	0.44	0.71	2.44	3.37	2.35	3.69	4.01
			AVG	0.2990	0.0224	0.1723	0.0548	0.0887	0.3054	0.4207	0.2934	0.4610	0.5016
			STAND	0.2990	0.0224	0.1723	0.0548	0.0887	0.3054	0.4207	0.2934	0.4610	0.5016

(Contd.)

				Mitchell N0K	N4S	Woodstock N4T	N4V	St. Marys N4X	Stratford N4Z	N5A	Ingersoll N5C
Physical	*Bio. Sensitivity*	Wetlands		1.0000	0.0000	0.0000	0.0042	0.0017	0.0000	0.1339	0.0924
Economic	*Structural*	Period of Construction		0.60	0.90	0.00	0.00	0.22	0.00	0.83	0.31
				0.40	0.31	0.23	0.07	0.21	0.11	0.49	0.25
		Type of Dwelling		0.50	0.79	0.00	0.00	0.11	0.00	0.04	0.04
			SUM	1.50	2.00	0.24	0.07	0.55	0.11	1.35	0.60
			AVG	0.5013	0.6673	0.0785	0.0237	0.1817	0.0375	0.4509	0.1996
			STAND	0.7491	1.0000	0.1098	0.0270	0.2658	0.0479	0.6729	0.2929
Infrastructure	*Critical Facilities*	Bridges Over Water		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Fire Stations		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Schools		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Hospitals		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Transportation	Unpaved Roads		1.00	0.24	0.00	0.00	0.28	0.00	0.23	0.14
		Railway		1.00	0.56	0.00	0.01	0.32	0.00	0.41	0.38
		Road		1.00	0.31	0.00	0.00	0.26	0.00	0.24	0.17
		Intersections		1.00	0.93	0.03	0.02	0.33	0.00	0.65	0.41
			SUM	4.00	2.04	0.04	0.03	1.19	0.00	1.53	1.10
			AVG	1.0000	0.5100	0.0105	0.0080	0.2985	0.0000	0.3835	0.2747
			STAND	1.0000	0.5100	0.0105	0.0080	0.2985	0.0000	0.3835	0.2747

(Contd.)

			London						
			N6A	N6B	N6C	N6E	N6G	N6H	N6J
Social	*Age*	Pop. under 20	0.13	0.12	0.74	0.91	0.87	0.58	0.65
		Pop. 65+	0.32	0.17	0.58	0.30	0.40	1.00	0.57
	Differential	Female Pop.	0.34	0.27	1.00	0.88	0.90	0.96	0.84
	Access to	Lone Parents	0.13	0.19	0.73	0.73	0.61	0.50	0.72
	Resources	Mode of Transport	0.77	0.66	0.92	0.53	0.62	0.54	0.55
		Low Income	0.69	1.00	0.25	0.43	0.33	0.29	0.43
	Household	Living Alone	0.54	0.60	0.88	0.32	0.40	1.00	0.69
	Structure	Full House	0.08	0.06	0.40	0.78	0.63	0.35	0.40
	Social Status	Rented Dwellings	0.48	0.60	0.83	0.40	0.38	0.98	0.79
		Mobility	0.39	0.41	0.71	0.68	0.66	0.69	0.67
		Less than High School	0.13	0.21	0.61	0.63	0.36	0.62	0.63
		Hrs Unpaid Work	0.40	0.36	0.99	0.80	0.84	1.00	0.84
	Ethnicity	Official Languages	0.14	0.17	0.37	0.87	0.43	0.35	0.46
		Minority Groups	0.15	0.15	0.41	1.00	0.89	0.40	0.54
	Economic	Work From Home	0.14	0.07	0.33	0.18	0.35	0.35	0.22
		Agricultural Labour	0.04	0.03	0.05	0.04	0.05	0.07	0.05
		SUM	4.88	5.07	9.79	9.47	8.71	9.68	9.05
		AVG	0.3051	0.3167	0.6120	0.5918	0.5443	0.6050	0.5656
		STAND	0.3834	0.3989	0.7935	0.7666	0.7031	0.7842	0.7315
AVG OVERALL VULNERABILITY			0.2293	0.2440	0.3786	0.2346	0.3584	0.3822	0.3995
STAND AVG OVERALL VULNERABILITY			0.2957	0.3155	0.4983	0.3028	0.4710	0.5032	0.2957
Exposure		Land Use	0.63951407	0.759887	0.648629	0.500264	0.484006	0.416794	0.626034
		Soils	0.40828518	0.31805	0.714768	0.718733	0.564256	0.535076	0.683771
		Stand. Land Use	0.7362	1.0000	0.7562	0.4311	0.3954	0.2481	0.7067
		Stand. Soil	0.2139	0.0000	0.9403	0.9497	0.5836	0.5144	0.8668

(Contd.)

				London									
				N6K	N6L	N6M	N6N	N6P	N5V	N5W	N5X	N5Y	N5Z
Social	*Age*	Pop. under 20		0.69	0.00	0.05	0.01	0.14	1.00	0.53	0.50	0.80	0.72
		Pop. 65+		0.55	0.00	0.02	0.01	0.11	0.38	0.49	0.33	0.52	0.38
	Differential	Female Pop.		0.81	0.00	0.06	0.01	0.15	0.96	0.68	0.57	0.97	0.77
	Access to	Lone Parents		0.51	0.00	0.02	0.00	0.06	0.90	0.60	0.30	1.00	0.88
	Resources	Mode of Transport		0.40	0.00	0.00	0.00	0.04	0.52	0.61	0.27	1.00	0.53
		Low Income		0.23	0.27	0.00	0.34	0.00	0.42	0.49	0.10	0.78	0.59
	Household	Living Alone		0.44	0.00	0.01	0.01	0.04	0.37	0.60	0.26	0.81	0.49
	Structure	Full House		0.48	0.00	0.01	0.02	0.08	0.73	0.31	0.37	0.52	0.47
	Social Status	Rented Dwellings		0.49	0.00	0.00	0.00	0.02	0.48	0.48	0.23	1.00	0.49
		Mobility		0.55	0.00	0.05	0.01	0.06	0.78	0.56	0.35	1.00	0.61
		Less than High School		0.45	0.00	0.04	0.02	0.10	0.82	0.77	0.25	0.78	0.74
		Hrs Unpaid Work		0.81	0.00	0.05	0.02	0.14	0.89	0.73	0.57	1.00	0.76
	Ethnicity	Official Languages		0.31	0.00	0.07	0.02	0.02	0.83	0.29	0.23	1.00	0.93
		Minority Groups		0.48	0.00	0.03	0.01	0.02	0.69	0.22	0.37	0.83	0.57
	Economic	Work From Home		0.35	0.01	0.03	0.03	0.12	0.21	0.15	0.23	0.19	0.12
		Agricultural Labour		0.04	0.01	0.00	0.02	0.05	0.06	0.06	0.02	0.08	0.05
			SUM	7.62	0.29	0.44	0.52	1.15	10.03	7.57	4.96	12.26	9.10
			AVG	0.4765	0.0182	0.0272	0.0327	0.0719	0.6267	0.4731	0.3101	0.7665	0.5686
			STAND	0.6125	0.0000	0.0121	0.0195	0.0718	0.8131	0.6079	0.3901	1.0000	0.7355
AVG OVERALL VULNERABILITY				0.2718	0.0116	0.0922	0.0349	0.0567	0.3696	0.3101	0.2086	0.4256	0.3594
STAND AVG OVERALL VULNERABILITY				0.5267	0.3534	0.0000	0.1095	0.0317	0.0612	0.4862	0.4054	0.2675	0.5621
Exposure		Land Use		0.455924	0.303563	0.321194	0.309284	0.309122	0.442713	0.642486	0.411115	0.680053	0.665778
		Soils		0.513952	0.739951	0.623453	0.704035	0.654827	0.482851	0.375931	0.455895	0.434502	0.499026
		Stand. Land Use		0.3339	0.0000	0.0386	0.0125	0.0122	0.3049	0.7427	0.2357	0.8250	0.7938
		Stand. Soil		0.4643	1.0000	0.7239	0.9149	0.7982	0.3906	0.1372	0.3267	0.2760	0.4290

(Contd.)

				Mitchell		Woodstock		St. Marys	Stratford		Ingersoll
				N0K	N4S	N4T	N4V	N4X	N4Z	N5A	N5C
Social	*Age*	Pop. under 20		0.77	0.83	0.16	0.03	0.26	0.06	0.74	0.36
		Pop. 65+		0.45	0.73	0.07	0.00	0.20	0.02	0.68	0.24
	Differential	Female Pop.		0.71	0.97	0.16	0.02	0.27	0.06	0.92	0.38
	Access to	Lone Parents		0.22	0.47	0.05	0.00	0.09	0.02	0.38	0.20
	Resources	Mode of Transport		0.38	0.47	0.04	0.01	0.17	0.04	0.81	0.17
		Low Income		0.08	0.23	0.05	0.47	0.08	0.10	0.14	0.12
	Household	Living Alone		0.29	0.60	0.06	0.01	0.13	0.02	0.68	0.20
	Structure	Full House		1.00	0.52	0.06	0.02	0.24	0.02	0.45	0.24
	Social Status	Rented Dwellings		0.20	0.55	0.08	0.01	0.08	0.02	0.57	0.15
		Mobility		0.29	0.56	0.14	0.02	0.11	0.02	0.55	0.28
		Less than High School		0.66	1.00	0.11	0.02	0.23	0.05	0.84	0.37
		Hrs Unpaid Work		0.62	0.95	0.14	0.02	0.24	0.05	0.89	0.36
	Ethnicity	Official Languages		0.14	0.17	0.03	0.00	0.00	0.02	0.08	0.03
		Minority Groups		0.05	0.16	0.06	0.01	0.02	0.04	0.19	0.04
	Economic	Work From Home		1.00	0.37	0.04	0.00	0.19	0.01	0.41	0.15
		Agricultural Labour		1.00	0.27	0.01	0.00	0.15	0.00	0.22	0.13
			SUM	7.85	8.85	1.27	0.64	2.45	0.54	8.55	3.41
			AVG	0.4907	0.5532	0.0794	0.0403	0.1532	0.0339	0.5343	0.2134
			STAND	0.6315	0.7150	0.0818	0.0296	0.1805	0.0210	0.6897	0.2609
AVG OVERALL VULNERABILITY				0.7480	0.4326	0.0421	0.0191	0.1588	0.0179	0.3757	0.1950
STAND AVG OVERALL VULNERABILITY				1.0000	0.5717	0.0414	0.0101	0.1999	0.0085	0.4944	0.2491
Exposure		Land Use		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Soils		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C. Calculation of vulnerability with and without consideration of inundation of road bridges and critical facilities.

		London																
		N6A	**N6B**	**N6C**	**N6E**	**N6G**	**N6H**	**N6J**	**N6K**	**N6L**	**N6M**	**N6N**	**N6P**	**N5V**	**N5W**	**N5X**	**N5Y**	**N5Z**
Infrastructural																		
Unpaved Roads	Total Road	70216	46687	121976	153987	138784	168868	99474	154340	119719	82759	182904	349985	188003	140788	113360	112126	101556
	Paved Road	56095	44491	105848	94967	108185	127752	72832	109672	76591	59057	112819	223738	131985	124090	72620	93637	88441
	Unpaved Road	14121	2196	16128	59020	30599	41116	26642	44668	43128	23702	70085	126247	56018	16698	40740	18489	13115
	Standardized	0.01	0.00	0.01	0.05	0.02	0.03	0.02	0.04	0.03	0.02	0.06	0.10	0.05	0.01	0.03	0.01	0.01
	Relative #	0.20	0.05	0.13	0.38	0.22	0.24	0.27	0.29	0.36	0.29	0.38	0.36	0.30	0.12	0.36	0.16	0.13
	Standardized	0.38	0.00	0.21	0.83	0.43	0.49	0.55	0.60	0.78	0.59	0.83	0.78	0.62	0.18	0.77	0.29	0.20
Railway	Total Railway	3303	7267	3520	1356	406	25185	1047	0	0	971	16321	0	21733	26871	0	2726	18333
	Standardized	0.03	0.06	0.03	0.01	0.00	0.21	0.01	0.00	0.00	0.01	0.14	0.00	0.18	0.22	0.00	0.02	0.15
Road	Total Road	70216	46687	121976	153987	138784	168868	99474	154340	119719	82759	182904	349985	188003	140788	113360	112126	101556
	Standardized	0.02	0.01	0.04	0.05	0.05	0.06	0.03	0.05	0.04	0.03	0.06	0.12	0.06	0.05	0.04	0.04	0.03
Intersections	Total Major	261	180	540	416	505	592	394	528	81	103	107	242	551	465	343	436	469
	Standardized	0.21	0.14	0.48	0.36	0.44	0.52	0.34	0.46	0.04	0.06	0.07	0.19	0.49	0.40	0.29	0.38	0.41

		Mitchell	Woodstock			St. Marys	Stratford		Ingersoll
		N0K	**N4S**	**N4T**	**N4V**	**N4X**	**N4Z**	**N5A**	**N5C**
Infrastructural									
Unpaved Roads	Total Road	2908825	899927	16607	18457	751525	5762	689270	486543
	Paved Road	1705258	604157	9668	15455	413055	4110	408733	321200
	Unpaved Road	1203567	295770	6939	3002	338470	1652	280537	165343
	Standardized	1.00	0.24	0.00	0.00	0.28	0.00	0.23	0.14
	Relative #	0.41	0.33	0.42	0.16	0.45	0.29	0.41	0.34
	Standardized	0.91	0.70	0.92	0.29	1.00	0.59	0.89	0.73
Railway	Total Railway	120775	67825	0	1172	38986	0	49862	46378
	Standardized	1.00	0.56	0.00	0.01	0.32	0.00	0.41	0.38
Road	Total Road	2908825	899927	16607	18457	751525	5762	689270	486543
	Standardized	1.00	0.31	0.00	0.00	0.26	0.00	0.24	0.17
Intersections	Total Major	1098	1019	71	53	390	35	730	474
	Standardized	1.00	0.93	0.03	0.02	0.33	0.00	0.65	0.41

(Contd.)

London ONLY		N6A	N6B	N6C	N6E	N6G	N6H	N6J	N6K	N6L	N6M	N6N	N6P	N5V	N5W	N5X	N5Y	N5Z
Critical Facilities	Bridges Over Water	0.75	0.73	0.62	0.22	1.00	0.51	0.52	0.54	0.00	0.50	0.05	0.21	0.46	0.73	0.65	0.91	0.70
	Fire Stations	0.63	0.95	0.90	0.59	1.00	0.45	0.85	0.28	0.06	0.20	0.03	0.00	0.31	0.63	0.33	0.68	0.95
	Schools	0.84	1.00	0.95	0.48	0.93	0.51	0.97	0.53	0.00	0.38	0.02	0.04	0.49	0.75	0.41	0.81	0.97
	Hospitals	0.97	0.84	0.79	0.29	1.00	0.56	0.84	0.49	0.00	0.19	0.02	0.05	0.41	0.57	0.60	0.83	0.79
Unpaved Roads	Total Road	70216	46687	121976	153987	138784	168868	99474	154340	119719	82759	182904	349985	188003	140788	113360	112126	101556
	Paved Road	56095	44491	105848	94967	108185	127752	72832	109672	76591	59057	112819	223738	131985	124090	72620	93637	88441
	Unpaved Road	14121	2196	16128	59020	30599	41116	26642	44668	43128	23702	70085	126247	56018	16698	40740	18489	13115
	Standardized	0.10	0.00	0.11	0.46	0.23	0.31	0.20	0.34	0.33	0.17	0.55	1.00	0.43	0.12	0.31	0.13	0.09
Railway	Total Railway	3303	7267	3520	1356	406	25185	1047	0	0	971	16321	0	21733	26871	0	2726	18333
	Standardized	0.12	0.27	0.13	0.05	0.02	0.94	0.04	0.00	0.00	0.04	0.61	0.00	0.81	1.00	0.00	0.10	0.68
Road	Total Road	70216	46687	121976	153987	138784	168868	99474	154340	119719	82759	182904	349985	188003	140788	113360	112126	101556
	Standardized	0.08	0.00	0.25	0.35	0.30	0.40	0.17	0.35	0.24	0.12	0.45	1.00	0.47	0.31	0.22	0.22	0.18
Intersections	Total Major	261	180	540	416	505	592	394	528	81	103	107	242	551	465	343	436	469
	Standardized	0.35	0.19	0.90	0.66	0.83	1.00	0.61	0.87	0.00	0.04	0.05	0.32	0.92	0.75	0.51	0.69	0.76
Unpaved Roads		0.10	0.00	0.11	0.46	0.23	0.31	0.20	0.34	0.33	0.17	0.55	1.00	0.43	0.12	0.31	0.13	0.09
Railway		0.12	0.27	0.13	0.05	0.02	0.94	0.04	0.00	0.00	0.04	0.61	0.00	0.81	1.00	0.00	0.10	0.68
Road		0.08	0.00	0.25	0.35	0.30	0.40	0.17	0.35	0.24	0.12	0.45	1.00	0.47	0.31	0.22	0.22	0.18
Intersections		0.35	0.19	0.90	0.66	0.83	1.00	0.61	0.87	0.00	0.04	0.05	0.32	0.92	0.75	0.51	0.69	0.76
AVG (Without)		0.1622	0.1160	0.3474	0.3795	0.3444	0.6635	0.2556	0.3930	0.1427	0.0929	0.4137	0.5788	0.6571	0.5447	0.2608	0.2858	0.4276
Standardized		0.1215	0.0406	0.4462	0.5023	0.4408	1.0000	0.2853	0.5260	0.0873	0.0000	0.5622	0.8516	0.9888	0.7918	0.2943	0.3381	0.5867
AVG (With)		0.4792	0.4987	0.5812	0.3870	0.6640	0.5848	0.5248	0.4266	0.0791	0.2042	0.2215	0.3260	0.5373	0.6073	0.3789	0.5476	0.6400
Standardized		0.6839	0.7173	0.8584	0.5264	1.0000	0.8646	0.7619	0.5941	0.0000	0.2138	0.2434	0.4221	0.7833	0.9029	0.5125	0.8009	0.9590

APPENDIX B. PREVIOUS REPORTS IN THE SERIES

ISSN: (print) 1913-3200; (online) 1913-3219

[1] Slobodan P. Simonovic (2001). Assessment of the impact of climate variability and change on the reliability, resiliency and vulnerability of complex flood protection systems, Water Resources Research Report no. 038, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 91 pages. ISBN: (print) 978-0-7714-2606-3; (online) 978-0-7714-2607-0.

[2] Predrag Prodanovic (2001). Fuzzy set ranking methods and multiple expert decision making, Water Resources Research Report no. 039, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 68 pages. ISBN: (print) 978-0-7714-2608-7; (online) 978-0-7714-2609-4.

[3] Nirupama and Slobodan P. Simonovic (2002). Role of remote sensing in disaster management, Water Resources Research Report no. 040, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 107 pages. ISBN: (print) 978-0-7714-2610-0; (online) 978-0-7714-2611-7.

[4] Taslima Akter and Slobodan P. Simonovic (2002). A general overview of multi-objective multiple-participant decision making for flood management, Water Resources Research Report no. 041, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 65 pages. ISBN: (print) 978-0-7714-2612-4; (online) 978-0-7714-2613-1.

[5] Nirupama and Slobodan P. Simonovic (2002). A spatial fuzzy compromise approach for flood disaster management, Water Resources Research Report no. 042, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 138 pages. ISBN: (print) 978-0-7714-2614-8; (online) 978-0-7714-2615-5.

[6] K. D. W. Nandalal and Slobodan P. Simonovic (2002). State-of-the-Art Report on Systems Analysis Methods for Resolution of Conflicts in Water Resources

Management, Water Resources Research Report no. 043, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 216 pages. ISBN: (print) 978-0-7714-2616-2; (online) 978-0-7714-2617-9.

[7] K. D. W. Nandalal and Slobodan P. Simonovic (2003). Conflict Resolution Support System - A Software for the Resolution of Conflicts in Water Resource Management, Water Resources Research Report no. 044, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 144 pages. ISBN: (print) 978-0-7714-2618-6; (online) 978-0-7714-2619-3.

[8] Ibrahim El-Baroudy and Slobodan P. Simonovic (2003). New Fuzzy Performance Indices for Reliability Analysis of Water Supply Systems, Water Resources Research Report no. 045, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 90 pages. ISBN: (print) 978-0-7714-2620-9; (online) 978-0-7714-2621-6.

[9] Juraj Cunderlik (2003). Hydrologic Model Selection for the CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions. Water Resources Research Report no. 046, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 40 pages. ISBN: (print) 978-0-7714-2622-3; (online) 978-0-7714-2623-0.

[10] Juraj Cunderlik and Slobodan P. Simonovic (2004). Selection of Calibration and Verification Data for the HEC-HMS Hydrologic Model. Water Resources Research Report no. 047, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 29 pages. ISBN: (print) 978-0-7714-2624-7; (online) 978-0-7714-2625-4.

[11] Juraj Cunderlik and Slobodan P. Simonovic (2004). Calibration, verification and sensitivity analysis of the HEC-HMS hydrologic model. Water Resources Research Report no. 048, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 113 pages. ISBN: (print) 978-0-7714-2626-1; (online) 978-0-7714-2627-8.

[12] Predrag Prodanovic and Slobodan P. Simonovic (2004). Generation of synthetic design storms for the Upper Thames River basin. Water Resources Research Report no. 049, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 20 pages. ISBN: (print) 978-0-7714-2628-5; (online) 978-0-7714-2629-2.

[13] Ibrahim El-Baroudy and Slobodan P. Simonovic (2005). Application of the Fuzzy Performance Indices to the City of London Water Supply system, Water Resources Research Report no. 050, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 137 pages. ISBN: (print) 978-0-7714-2630-8; (online) 978-0-7714-2631-5.

[14] Ibrahim El-Baroudy and Slobodan P. Simonovic (2006). A Decision Support System for Integrated Risk Management, Water Resources Research Report no. 051, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 146 pages. ISBN: (print) 978-0-7714-2632-2; (online) 978-0-7714-2633-9.

[15] Predrag Prodanovic and Slobodan P. Simonovic (2006). Inverse Flood Risk Modelling of The Upper Thames River Basin. Water Resources Research Report no. 052, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 163 pages. ISBN: (print) 978-0-7714-2634-6; (online) 978-0-7714-2635-3.

[16] Predrag Prodanovic and Slobodan P. Simonovic (2006). Inverse Drought Risk Modelling of The Upper Thames River Basin. Water Resources Research Report no. 053, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 252 pages. ISBN: (print) 978-0-7714-2636-0; (online) 978-0-7714-2637-7.

[17] Predrag Prodanovic and Slobodan P. Simonovic (2007). Dynamic Feedback Coupling of Continuous Hydrologic and Socio-Economic Model Components of the Upper Thames River Basin. Water Resources Research Report no. 054, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 437 pages. ISBN: (print) 978-0-7714-2638-4; (online) 978-0-7714-2639-1.

[18] Subhankar Karmakar and Slobodan P. Simonovic (2007). Flood frequency analysis using copula with mixed marginal distributions. Water Resources Research Report no. 055, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 144 pages. ISBN: (print) 978-0-7714-2658-2; (online) 978-0-7714-2659-9.

[19] Jordan Black, Subhankar Karmakar and Slobodan P. Simonovic (2007). A web-based flood information system. Water Resources Research Report no. 056, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 133 pages. ISBN: (print) 978-0-7714-2660-5; (online) 978-0-7714-2661-2.