Vulnerability Measures for Flood and Drought and the Application in Hydrometric Network Design

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Climatic variability and change can have profound impacts on human societies and wildlife habitats. Extreme events and natural hazards such as floods, droughts, and windstorms, can lead to loss of lives, economic damages, and disruption in livelihoods, infrastructure, and ecosystems. These impacts depend on the intensity and the magnitude of the hazard and the characteristics of the society hit by the disaster. Investigating and predicting adverse effects of frequent climatic hazards are essential for policy makers and resource managers to plan for the future and be prepared for the consequences of these types of natural disasters. Vulnerability assessments provide a framework to detect the potential threats by exploring the nature of the hazard as well as the political, economic, and social conditions that are expected to affect the capacity of communities to cope with or adapt to that hazard.

This research involves the development of a framework for vulnerability assessment of flood and drought at the river basin, sub-catchment, and community scale. The vulnerability assessment method is composed of three major components of exposure, sensitivity, and adaptive capacity. Several indicators are identified to represent these major components of the vulnerability structure. The developed vulnerability assessment has then been implemented on the Upper Ottawa River Basin, Canada. A Geographic Information System-based methodology is used to manage a wide variety of data, to aggregate and integrate several indicators including socio-economic and biophysical indicators, and to visualize the final vulnerability map. The studied areas are categorized in three levels of the vulnerability, high, moderate, and low. North Bay is identified as highly vulnerable to both flood and drought risk. Noranda is also classified as a highly flood-vulnerable area.

The vulnerability assessment will provide a valuable insight for mitigation planning as well as prioritizing resource allocation for decision makers. In this research, the location and adequacy of the hydrometric monitoring stations in the Upper Ottawa River Basin are evaluated using the vulnerability map for optimum design of monitoring network.

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CCME	Canadian Council of Ministers of the Environment
CEC	Commission for Environmental Cooperation
CEGEP	Collège d'enseignement général et professionnel
CSD	Census subdivision
DEM	Digital Elevation Model
DFI	Drought Frequency Index
EVI	Environmental Vulnerability Index
FDC	Flow Duration Curve
FVI	Flood Vulnerability Index
GDP	Gross Domestic Product
HDI	Human Development Index
HYDAT	Hydrometric Database
IPCC	Intergovernmental Panel on Climate Change
NFIP	National Flood Insurance Program
PHDI	Palmer Hydrological Drought Index
RHBN	Reference Hydrometric Basin Network
RDI	Reconnaissance Drought Index
SOPAC	South Pacific Applied Geosciences Commission
SPI	Standardized Precipitation Index
SWSI	Surface Water Supply Index
UNDP	United Nations Development Programs
WPI	Water Poverty Index
WQI	Water Quality Index

CHAPTER ONE

INTRODUCTION

Hazardous events such as drought and flood disrupt normal activities in human societies and natural habitats and cause several damages to both of them. The essential elements for studying negative impacts and evaluating their possible consequences are hydrometric data. Hydrometric data are collected by analogue or digital gauging stations to document hydrologic characteristics and are used for a wide range of purposes.

1.1 Importance of Hydrometric Monitoring Network

There is no doubt about the importance of streamflow data collection in management and planning of water systems. Data which are collected by means of monitoring networks are essential for almost all activities in the design, management, and continuing operation of many water resources systems. Human livelihood depends on the water resources systems such as reservoirs, water distribution systems, irrigation networks, and flood warning systems. As well, these data are input data for predicting and forecasting many climatic events as well as for studying hydrological impacts of climate change. Therefore, an efficient data collection system is a high priority for water sector decision makers (Burn and Goulter, 1991). Unfortunately, in recent decades, due to financial restraints, a considerable number of these data collecting stations have been shut down in many parts of the world. This decline in the number of monitoring stations is exacerbated by global warming, which can cause an increase in the magnitude and likelihood of extreme events, and shortage of fresh water resources. Apart from the lack of financial support, lack of appreciation of the value of long term data, inappropriate institutional framework, and exposure to natural disasters can be considered as the reasons of the decline in the density of networks (Mishra and Coulibaly, 2009). A resolution is the design of a monitoring network in a manner to maximize total information collected with optimum numbers of monitoring stations under the constraint of budget limitations. Several attempts have been made on designing water monitoring network to maximize collected information and minimize the redundancy (Rodríguez-Iturbe and Mejía, 1974; Moss and Tasker, 1979; Husain, 1987; Burn and Goulter, 1991; Krstanovic and Singh, 1992; Yang and Burn, 1994; Li et al., 2012).

1.2 Application of Vulnerability Assessment in Hydrometric Network Design

One aspect of designing monitoring network is space design, which is to select the optimum number of monitoring stations in the best locations to collect the maximum information with minimum cost and redundancy. Flood and drought data are important information on which a wide range of users in various sectors such as agronomists, hydrologists, climatologist, water resource managers and planners, researchers, urban managers, and decision makers in government and private sectors depend. Therefore, areas that are more frequently exposed to these natural threats, can be considered as good candidates in the list of possible best locations for monitoring network stations. More importantly, if these areas are detected as vulnerable areas in terms of drought and flood, it means that the magnitude and likelihood of the threat, as well as its socio-economic consequences, are significant. Then, detecting flood and drought prone areas and also vulnerable people helps to narrow down the process of optimizing locations and number of monitoring stations. Therefore, the vulnerability assessment can be applied as an additional constraint in monitoring network design to detect optimum locations for new stations. Also, due to budgetary cutbacks in recent years, one common approach in many states is to decrease the number of locations at which data are collected. Detecting the vulnerable areas to flood and drought can help to preserve the valuable information in crucial areas particularly in a situation which, for instance, there is only one active station in the proximity of the area.

1.3 Vulnerability

The negative consequences of the hazard depend on its intensity as well as the socio-economic characteristics of the society. In other words, both climate and human systems contribute to the adverse consequences of extreme climate events. However, there is not a universally accepted way to formulate the complicated relationship of human and climate systems. The vulnerability framework is a powerful analytical tool to assist decision makers considering more integrated aspects of a hazard's consequences.

The word "vulnerability" in a climatic hazard context can have different meanings and components despite of its unsophisticated general meaning. Traditionally, climate scientists have measured vulnerability by calculating the magnitude and likelihood of the occurrence of the extreme climate events. In this approach, the role of human, which is an important factor affecting the level of the damages, is neglected. On the other hand, social scientists look at vulnerability as a response of a system to a radical change and the ability of a system to adjust to stressors or to cope with the adverse impacts of extreme events. They calculate vulnerability exclusively by a set of socio-economic factors such as poverty, inequality, access to resources, ethnicity, language barrier, etc. In their point of view, the principal element of the vulnerability is the socio-economic and internal characteristics of the system rather than external characteristics of natural extreme events.

Based on these two approaches, vulnerability assessment has been categorized into biophysical and social. Hazard-impact method, which is a conventional approach to evaluate physical hazards associated with climatic variables, is considered as biophysical vulnerability (Adger et al., 2004). The integrated vulnerability assessment consists of both aspects of vulnerability and needs to evaluate the physical characteristics of a hazard as well as social characteristics of a society that is subjected to that hazard. Hence, to assess vulnerability, it is required to develop an appropriate framework with adequate components to recognize all aspects that might contribute to the vulnerability of a system. Due to high level of complexity associated with the structure of the vulnerability as well as unclear relationship among its components, a wide variety of indicators should be recognized and applied to reflect the main characteristics of its social and physical components. This challenging process needs to understand the nature of hazardous events such as flood and drought and their consequences to society by a wide range of demographical, hydrological, and census data.

1.4 Importance of Vulnerability Studies

Flood and drought are natural threats that frequently affect lives and assets of many communities across the world. Despite all progress that has been made in science and technology, human beings are still susceptible to climate hazards. Human societies understand that the first step to mitigate the consequences of the extreme events is to recognize the potential areas where damage might occur. Several attempts have been made to develop a tool to determine vulnerable stakeholders. Since the vulnerability assessment examines physical factors as well as socioeconomic, institutional, cultural, and political factors, it is a powerful tool to detect risky areas and susceptibility of people. Therefore, by determining the vulnerable areas and people in a system, decision makers will be able to develop hazard-control management programs and planning for individuals and communities. Thus, the vulnerability assessment can be considered as a detective tool for climate hazard(s) in different scales.

The vulnerability framework is also a powerful predictive tool to understand the complicated behaviour of individuals and communities in different climate scenarios. Since climate change is one of the most serious issues that influences all communities across the world regardless of their geographical locations or economical situations, decision makers at various scales need to evaluate the level of vulnerability of their communities to the impacts of climate variability and for preparedness planning to adopt to and to deal with them.

Hence, the vulnerability assessment is essential in all level of decision making as well as policy making to support and to improve the process of enhancing the adaptive capacity in a society and to strategically plan for the future with rational resource allocation and to reduce the risk of economic and human losses.

1.5 Objectives of this Study

This research is conducted as a part of broader strategic project to develop a "*decision support tool for integrated water monitoring networks design and evaluation*", which is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC). Two groups from McMaster University and University of Waterloo are involved in this project. The researchers from McMaster University have focused on developing the multi-objective optimization system based on dual entropy-multi objective optimization and ε-hBOA approach. The task that was defined as a contribution of the University of Waterloo is to determine water vulnerability indicators and define appropriate indicators for both human and ecosystem vulnerability to be used as additional constraints in multi-objective optimization system for integrated water monitoring network design.

Over the last decade, the majority of vulnerability studies have been conducted in the context of climate change at a national scale. However, since vulnerability is spatially differentiated from one place to another, even within a single country, determining appropriate indicators and measures on a local scale is equally, if not more, important. It is additionally of interest to consider future climate hazards and variability when assessing the vulnerability of a system. The major objective of this thesis, therefore, is to develop a framework to determine relative vulnerable areas to flood and drought, within river basins and sub-catchments, using an index approach. This research will provide valuable insight to key local decision and policy makers to understand the factors that contribute to the vulnerability of a system.

The secondary intent of this study is to suggest the vulnerability map as an additional constraint in the design of hydrometric monitoring networks by assessing the adequacy of monitoring gauges (numbers and locations) to collect vital hydrometric information in vulnerable regions.

Based on these objectives, several groups of decision makers can take advantage of the results of this study for their own purposes in the following manner:

- By detecting vulnerable regions, decision makers who are responsible for natural hazard and disaster management will be able to prioritize their prevention, protection, and mitigation plans for flood and drought in a defensible, evidence-based manner which, in turn, will lead to efficient financial management.
- Mapping high risk zones allows water resources decision makers to evaluate the existing multipurpose water structures and disaster control structures in their proactive plans. Moreover, vulnerability maps help water resources decision makers with designing optimum monitoring networks to collect sufficient information by prioritizing locations of monitoring stations and allocating sufficient financial resources.
- To provide valuable insight for strategic managers in local, regional, and national governments to realize the mechanisms and factors contributing to vulnerability of a system using socio-economic data in the form of various indicators (Adger et al., 2004) and improve those processes that enhance the capacity of a community to cope with the consequences of disaster over a shorter period of time.

This research presents a framework to assess integrated vulnerability of sub-catchment and river basin areas for flood and drought with both biophysical and social dimensions of vulnerability. As a part of this study, new flood and drought indexes were developed for river basin and sub-catchment based on frequency analysis. Several indictors with demographic and physical basis were identified and determined for measuring sensitivity of a system to flood and drought hazard. Moreover, a number of socio-economic factors were determined to evaluate social vulnerability aspects of a system. Finally, integrated vulnerability assessment is constructed by aggregating all these different types of indicators.

This thesis compromises six chapters. Chapter 2 reviews historical research conducted in climate vulnerability field. Chapter 3 develops the methodology for conducting vulnerability assessment for flood and drought. Chapter 4 introduces the case study and its characteristics. Chapter 5 demonstrates the results of using the developed methodology for evaluating the vulnerability of the case study. Chapter 6 summarizes concluding remarks of this study and makes recommendations for future work.

CHAPTER TWO

LITERATURE REVIEW

This chapter presents an overview of the vulnerability concept to assess the risk of extreme events. The main focus of this chapter is to review and to detect the distinct characters of the vulnerability frameworks in recent years. Section 2.1 discuses the complexity of the vulnerability concept. Section 2.2 explains the difference between risk and vulnerability and then in section 2.3, the popularity of using indexes to express the vulnerability of a system in a particular field is discussed. Section 2.4 presents the major components of the vulnerability structures.

2.1 The Ambiguous Nature of Vulnerability

Vulnerability, as Kelly and Adger (2000) explained, is derived from the Latin word *vulnerabilis*, which was used by the Romans to describe a wounded soldier lying on a battlefield and susceptible to future attacks. Today, the word vulnerability is used extensively in various fields, including engineering, psychology, economics, ecology, public health, poverty and development, livelihood and food security, sustainability, land use change, and climate change impacts (Adger, 2006; Gain et al., 2012), to describe a system (household, community, group, sector, region, country) that, based on the current status, is subject to substantial risk in the future. However, because of ambiguity surrounding the concept of vulnerability, there is no universal consensus regarding its meaning (Adger et al., 2004). Generally, social scientists look at vulnerability as a response of a society to a radical change or stress, and the ability of people to cope with that change or stress. They argue that vulnerability is inherent to a system that creates the potential for harm and is independent of any particular hazard and exposure (Adger et al., 2004) that can be defined by a set of socio-economic factors. On the contrary, climate scientists present vulnerability as a magnitude and likelihood of occurrence of extreme climatic events and their impacts. In this approach, the role of humankind is neglected and vulnerability is measured merely by the amount of damage to a system (region, population/group, country, household, community, etc.) caused by a particular hazard. The term *hazard* here refers to the physical dimension of climate variability, and includes extreme events such as drought, flood, storm, extreme rainfall, shift in the mean value of a climate variable, or a potential future shift in a climate regime (Adger et al., 2004). Several attempts have been made to develop an integrated vulnerability assessment framework which can be applied to any scale and any community for a specific objective (Wilhelmi and Wilhite, 2002; Adger et al., 2004; O’Brien et al., 2004; Huang et al., 2005; Smit and Wandel, 2006; Gain et al., 2012). However, because of the dynamic characteristic of vulnerability and its scale-dependency (O’Brien et al., 2004), a comprehensive vulnerability framework has not yet been achieved. Instead, these attempts have led to a number of conceptual frameworks.

Due to complexity of the human dimension, there is no general agreement for selecting adaptive capacity indicators among vulnerability researchers. Between 1996 and 2005, a considerable amount of literature was published on adaptation and adaptive capacity (Janssen et al., 2006), particularly in the context of climate change at different scales (Kelly & Adger, 2000; Yohe & Tol, 2002; Adger et al., 2004; O'Brien et al., 2004; Adger, 2006; Paavola & Adger, 2006; Eakin & Luers, 2006; Alessa et al., 2008; Balica et al., 2009; Gain et al., 2012). Although the majority of these studies focused on climate change, the conceptual frameworks and insight that they provided for vulnerability assessment are valuable and valid for current, as well as future, extreme climate variables. Janssen et al. (2006) statistically analyzed publications in the three knowledge domains of vulnerability, resilience, and adaptive capacity of global environmental change and concluded that vulnerability and adaptive capacity are more scientifically correlated than resilience is with either domain. Gallopín (2006) concentrated on socio-economic systems in an investigation into the relationships between vulnerability, resilience, and adaptive capacity. Analyzing each factor independently, Gallopín concluded that there is no general accepted meaning of each of these concepts but that vulnerability and resilience do not necessarily have opposite meanings and, instead, that their relationship is unclear. Adger (2006) studied the evolution of vulnerability research and argued that the traditional perception of vulnerability and hazard research should be modified to integrate social systems in order to build a relatively more comprehensive framework to better understand the climatic vulnerability of a system.

2.2 Risk versus Vulnerability

The terms *vulnerability* and *risk* are generally used to express the potential adverse effects of climate change or extreme climatic variation on a specified system unit, including region, community, ecosystem, economic sector, social group, or infrastructure. Although both terms are acceptable in a general context, it is necessary to distinguish the two in a scientific context, and in particular for their use in quantitative assessment.

Risk is defined as probability multiplied by consequence or expected loss (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period, where the hazard here is a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area (Adger et al., 2004). This definition is similar to the type of vulnerability referred to in some literature as "physical" or "biophysical vulnerability", which is a function of exposure, hazard, and sensitivity (Adger et al., 2004). On the contrary, "social vulnerability" (also known as "inherent vulnerability") is defined as an inherent property or natural characteristic of a system that exists within the system regardless of external exposure (Adger et al., 2004). Inequality, poverty, marginalization, health, access to resources, and housing quality are examples of factors that are used to examine the social vulnerability of a system.

The vulnerability assessment for climate variation and change should, to some extent, integrate both physical and social vulnerability, since this type of vulnerability is the result of the interaction between both physical processes and the human dimension. For example, vulnerability to flood and drought is measured as the extent to which a system is susceptible to flood and drought based on exposure, in conjunction with the system's capacity to cope with, recover from, or adapt to the temporal or permanent adverse effects of these hazards (Balica et al., 2009).

2.3 Popularity of the Index Approach

The index approach is extensively used in economics, the social sciences, and environmental and water resources management. One of the most famous international indexes is the Human Development Index (HDI), which was developed by the United Nations Development

Programme (UNDP) to evaluate welfare by measures of well-being based on education, health, income, and inequality (Adger et al., 2004). There are several other good examples of indicators that are used to investigate interactions between different factors, each providing a useful tool for decision makers with which to evaluate the sustainability of a project or assess the vulnerability of a community to a natural hazard. For example, the Environmental Vulnerability Index (EVI) was developed by the South Pacific Applied Geosciences Commission (SOPAC) to evaluate the vulnerability of small island developing states to a range of hazards (Adger et al., 2004). This index consists of 47 indicators in different categories chosen based on expert judgment rated on a scale of 1 to 7. Another famous index is the Water Poverty Index (WPI) developed by Sullivan (2002) to evaluate water stress at the household and community level by combining a wide variety of data relevant to water stress into a single number. Some proxies that are used to construct the WPI include: access to water, water quantity, water quality, water variability, water uses, and capacity for water management (Adger et al., 2004). The Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI) was developed by the CCME as a tool to combine complex data on water quality into an overall integrated score ranging from poor to excellent. This index contains three elements measuring scope of evaluation, frequency of failure, and amplitude of aggregation failure (Lumb et al., 2006).

The index approach also is very popular in the evaluation of alternative designs for complex water resources projects. Hashimoto et al. (1982) applied the concepts of vulnerability, resilience, and reliability to select among different design and policy alternatives for a wide variety of water resources projects. Fanai and Burn (1997) also proposed a framework to assess the sustainability of a project by measuring reversibility, which is defined as the degree to which the aggregated undesirable social, ecological, and economic impacts of a development project can be mitigated. They combined indicators of three categories with appropriate weights to form one aggregated index to facilitate decision makers through the process of selecting between development project alternatives. Based on the concept of vulnerability, Loucks (1998) developed a framework to measure relative sustainability of water resources projects with multiple physical, economic, environmental, ecological, and societal indicators engaged to evaluate based on the judgment of experts. Building upon Loucks' sustainability framework, Mckinney et al. (2011) developed the Sustainability Index, which facilitates comparison among alternative water policies and designs based on the requirements of each project.

The index approach has been generally applied in many types of studies consisting of various components and requiring evaluation of the impacts of one stressor on different socio-economic, physical, or ecological aspects using a wide variety of data. The main challenges involved in index formulation include detecting appropriate indicators, determining meaningful thresholds, and assigning rational weights. The indicators should be robust over time and should reflect significant characteristics of the system. In the assessment of vulnerability, indicators should also be capable of showing the status quo and/or future trend of exposure and adaptive capacity as precisely as possible (Adger et al., 2004). Although quantitative indicators are preferred for a vulnerability study, a qualitative analysis is sometimes required to portray specific characteristics of a system due to difficulties in quantifying the physical and social components of vulnerability. Based on availability of information and access to data, the best indicators are selected among a list of identified factors to express relationships between exposures and adaptation.

2.4 Major Components of Vulnerability Structure

Without a conceptual framework, choosing rational indicators for vulnerability can become even more problematic (Adger et al., 2004). The most common framework for vulnerability includes three main components: *exposure, sensitivity,* and *adaptive capacity* (IPCC, 2001, p. 995). Smit and Wandel (2006) indicated that exposure, adaptive capacity, vulnerability, and sensitivity are interrelated and described how sometimes local efforts to improve adaptive capacity may be nullified by decisions of broader geo-political systems, such as federal or national systems. Exposure is recognized as an external dimension of vulnerability, whereas adaptive capacity is identified as an internal element of it (Gopplin, 2006). Quantifying physical and social factors presents a real challenge due to multilevel interactions between the major components of vulnerability (Adger, 2006). The definition and characteristics of these major components of vulnerability are explained in the next sections.

2.4.1 Exposure

Exposure is a central component of both traditional and modern vulnerability studies. Vulnerability is always defined with respect to a specific hazard or set of hazards and hence vulnerability and exposure cannot be separated (Kelly and Adger, 2000). Exposure, in a climate context, is defined as the nature and degree to which a system is exposed to significant climatic variations (IPCC, 2001) or the degree of climate stress upon a particular unit of analysis (Smit et al., 2000). Climate variation or climate stress is related to magnitude, frequency, and duration, or even spatial extent of the hazard (Adger, 2006). Adger et al. (2004) argued that hazard and exposure are not equal. They explained that the exposure of a region to frequent flood hazards can be controlled if populations are settled away from flood-prone areas. In the case of drought, they clarified how a lack of dependency on rainfall-sensitive livelihoods may lead to a low exposure in a drought-prone area. From this point of view, the combination of exposure and sensitivity is considered one component. However, due to complexity of the vulnerability concept, researchers generally prefer to consider exposure and sensitivity seperately.

2.4.1.1 Flood Index

In a study of flood vulnerability, Huang et al. (2005) employed hydrological and rainfall-runoff models to determine the exposure component of a flood hazard, using spatial extent and frequency. Since they did not concentrate on the socio-economic aspects of flood, their vulnerability study can be categorized as a traditional biophysical vulnerability study. Similar to Huang et al. (2005), Simonovic and Li (2004) investigated flood sensitivity of the Red River Basin in Canada; despite using terms such as reliability, vulnerability, and sensitivity, they focused only on the biophysical aspect of flood vulnerability by deploying a hydrological model. Balica et al. (2009) developed a methodology for measuring the flood vulnerability index at various spatial scales of a river basin, sub-catchment, and urban area by using a list of indicators associated with physical, social, economic, and environmental factors.

2.4.1.2 Drought Index

Drought is one of the most significant natural hazards and ranks first among natural disasters in terms of the number of people directly and indirectly affected due to impacts to a number of sectors and systems, including the natural ecosystem, water resources, hydroelectric energy, and agriculture (Wilhelmi and Wilhite, 2002). Drought is a general phenomenon that can be classified as meteorological, hydrological, atmospheric, and agricultural. Hydrologic drought is generally defined as a deficiency in water supply that is associated with decreased river flow, reduced reservoir and lake storage, and lowered groundwater levels (Yevjevich, 1967). Drought affects both society and the ecosystem through its negative impacts on water quality, power generation, water supply, irrigation and agriculture, recreation, and wildlife habitats. The temporal and spatial dimension of drought is considerably wider than other extreme hydrologic events, thus, determining the severity of a drought is considerably more complex than measuring flood quantity, for example.

Several studies have aimed to develop indexes to measure a drought's severity based on a combination of factors, including magnitude, duration, and spatial domain (Mishra and Singh, 2010; Fleig et. al., 2006; Vicente-Serrano et al., 2012; Nalbantis and Tsakiris, 2008; González and Valdés, 2006). The Palmer Hydrological Drought Index (PHDI), Surface Water Supply Index (SWSI), Standardized Precipitation Index (SPI), Drought Frequency Index (DFI) (González and Valdés, 2006), and Reconnaissance Drought Index (RDI) are just a few examples of drought indexes (Nalbantis and Tsakiris, 2008).

There are two main approaches for determining a hydrological drought index. One approach is based on low flow characteristics, such as a time series of the annual minimum *n*-day discharge, mean annual minimum *n*-day discharge, or a percentile from the Flow Duration Curve (FDC) (Fleig et al., 2006). This approach is based on characteristics of extreme values corresponding to the lower tail of the drought probability distribution and the low flow part of streamflow regime (González and Valdés, 2006). The second approach, known as deficit characteristics, considers both duration and deficit volume of droughts and can be explained by indexes. This approach is based on the theory of runs, and, in contrast to the first approach, also considers the time identity of drought events (Fleig et al., 2006).

2.4.2 Sensitivity

Sensitivity is defined as the degree to which a system is affected either positively or negatively by a climate-related driver. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise) (IPCC, 2001). The more sensitive of an exposure unit is to climate change or variation, the greater the potential impacts, and hence the higher the vulnerability (Smit et al., 2000). The severity of consequences of an exposure depends on the locations where populations choose or are forced to live (Adger et al., 2004) and the extent to which they will be subjected to the specific hazard. Populations that settle in low-lying lands or coastal areas, for example, are more likely to be exposed to destructive hazards such as hurricanes, floods, and storm surges. One of the key indicators for sensitivity is therefore population. Population is an element that entails many important factors, such as social activities, economic activities, public services, and infrastructure (Barroca et al., 2006). Vulnerability will increase where dense populations live in hazard-prone areas. The concentration of populations residing in flood- or drought-prone areas raises the risk of spreading infectious diseases, in turn increasing the adverse consequences of these hazardous events (i.e., due to lack of access to healthcare, sanitation facilities, and clean water resources for a period much beyond the duration of hazard).

Municipal capacity can be considered as beneficial sensitivity components in the flood vulnerability assessment. Particularly, flood control infrastructure such as dams and dikes, play significant role to mitigate damages including economic cost and loss of life caused by floods. However, it could be argued that in spite of its enormous benefits, the existence of a dam increases the risk of flooding for its downstream population due to its failure in extreme events.

The multipurpose dams in a watershed also can be helpful in drought events by releasing their stored water to maintain the ecological flow and meet water demands.

2.4.3 Adaptive Capacity

Adaptive capacity, also denoted as coping capacity, capacity of response, and capacity of adaptation, is the ability of a system to adjust to exposure (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (IPCC, 2001). The concept of adaptive capacity is the most important component of vulnerability, and distinguishes modern vulnerability research from traditional methods based on physical factors. Adger (2006) argued that adaptive capacity and adaptation are not equivalent, where adaptation is not a long-term strategy and does not contain any changes in policy or behaviour. Luers (2005) also recognized the difference between adaptive capacity and adaptation, defining adaptive capacity as the potential to reduce the future vulnerability of a system, and adaptation as the current vulnerability of the system. However, there is no real consensus among hazard researchers regarding the definitions of these terms. For example, Metzger and Schröter (2006) explained that adaptation can be autonomous and planned, but described adaptive capacity as the potential to implement planned adaptation to cope with change. Thus, from this point of view, the difference between adaptation and adaptive capacity is not related to time but rather depends on planning and is therefore a relevant concern to policy making (Kelly and Adger, 2000). The concept of adaptive capacity in human-environment systems has been reviewed by Smit and Wandel (2006). They pointed out that a key feature of adaptive capacity is that it demonstrates how biophysical, social, economical, and political processes contribute to vulnerability. In order to quantify these complex and inter-related elements, often surrogate measures or proxy indicators are estimated and then aggregated to construct the vulnerability score. The analysis involves selecting a set of meaningful indicators (measures) for each socio-economic element to facilitate evaluation of adaptation and its impact on the vulnerability of a system. Several indicators (or proxies) of adaptive capacity have been applied by researchers for various hazards and different scales. The relationship between adaptive capacity and the scale is unclear. For example, the level of household income as an adaptive capacity indicator has a significant correlation with national level policies in providing job opportunities, level of insurance, and defining the taxation structure.

Although there is no standard and unique set of indicators for hazard vulnerability studies, some general socio-economic indicators are explained in the following.

2.4.3.1 Age

Human mobility, physical ability, and immediate reaction are important factors that should be taken into account when considering many severe hazards, including flood, storm, tsunami, and hurricane. Generally, age has a great impact on mobility. The elderly and young children, for example, are at a greater level of risk due to limited mobility and physical ability. These age groups are also more susceptible to waterborne infectious diseases, which are common consequences of many disasters. Moreover, the elderly often suffer from chronic diseases which make them even less resistant to the psychological and physical health effects of a hazard. Furthermore, young children are legally, mentally, and physically dependent, and have difficulties acting without support during emergencies. These are a few reasons that make the recovery time of these age groups longer than others. Accordingly, age is one of most common determinants of vulnerability and has been considered by several researchers (Cutter et al., 2000; Wu et al., 2002; Chakraborty et al., 2005; Rygel et al., 2006;).

2.4.3.2 Economic Wellbeing and Income

Poor communities and low-income groups are often more likely than wealthier communities to be exposed to potential hazards. People in low bracket of income often sacrifice their safety for financial security, and live in hazardous areas such as flood-plains or unstable hill slopes in low quality and hastily constructed homes. In many countries, they often have no or little access to health care resources, clean water, or sanitation facilities, and lack the financial support necessary to protect themselves and their assets from hazards. Flood and disaster insurance are not a priority for financially insecure people. Several studies have examined income as a determinant of vulnerability using various proxies, including Gross Domestic Product (GDP), Gini index, debt repayment (national scale), and household income (local scale) (Adger et al., 2004; Vescovi et al., 2005).

2.4.3.3 Education

Education and marginalization are highly correlated (Adger et al., 2004). Low-educated and low-skilled people are more likely to be placed in a lower income bracket and are therefore more vulnerable. Also, education improves problem-solving skills (Muttarak and Lutz, 2014). Hence, when disaster occurs, educated individuals might be more capable to manage and react to events. Moreover, education is strongly related to access to useful information, which plays an important role in understanding the nature of hazard(s) which, in turn, is essential for reliable forecasting (Adger et al., 2004). Highly-educated individuals have diverse sources of information and better access to weather forecasts and warnings. Apparently, access to forecast and early warnings provide enough time for individuals to respond and prepare for hazardous events. Educated people have better access to social networks, which are very important in assuring effective emergency planning and preparedness. In general, education helps people to obtain knowledge and values, and to set priorities to resources allocation in order to plan for crucial future (Muttarak and Lutz, 2014). Furthermore, low-educated and low-skilled people are generally less aware of risk and less flexible to relocation and/or evacuation operations and are less likely to undertake disaster preparedness. On the other hand, recently the value of indigenous knowledge has been increasingly recognized and emphasized by scientists in adaptation and vulnerability studies. Education expenditure (Adger et al., 2004), literacy rate (Adger et al., 2004; O'Brien et al., 2004a), and number of people with a high school diploma or college degree (Flax et al., 2002) can be considered as suitable determinants for education.

2.4.3.4 Health and Nutrition

Poor public health is directly associated with poverty and inequality. Communities with poor health status and poor nutrition are more vulnerable and less likely to be able to cope with disaster consequences. The existence of epidemic disease in a society undermines the health of the public, which in turn leads to a lower adaptive capacity of the population to extreme changes. Health expenditure per capita, disability adjustment, and life expectancy can all be considered measures of health and nutrition (Adger et al., 2004).

2.4.3.5 Physical Infrastructure

The quality and location of transportation systems, water resources, and communication infrastructure play a significant role in amplifying or reducing overall loss of lives and livelihoods in emergency events, such as storms, flash floods, tsunamis, and coastal inundation (Cutter et al., 2000). For rescue operations, the quality, diversity, and density of transportation systems such as roads, railroads, and rivers will influence the efficiency of aid distribution programs and revival of economic activities in regions affected by extreme events. The availability of water resources infrastructure, such as clean water and sanitation, water distribution, water supply reservoirs, flood control, and flow regulating infrastructure, has a great impact on recovery time. Examples of determinants that can be representative of the physical infrastructure indicator include length of roads, railroads, and power transmission lines, sanitation and drinking water facilities (Adger et al., 2004).

2.4.3.6 Social Capacity

Social capacity is defined as the aggregation of the actual or potential resources which are linked to possession of a durable network of a more or less institutionalized relationship of mutual acquaintance or recognition (Meyer, 2013). Social capacity consists of features such as the norms and trusts of society, and represents how individuals, groups, organizations, and institutions within a system interact, cooperate, and work together during disasters (Alessa et al., 2008). Social capacity is one of the most important and complicated factors that influences a community's response to a certain hazard, and can be explained through a combination of elements, including the institutions, governance, culture, and values that form the collective behaviour of the community. Cultural components of each community also play an important role in response of that community in crucial time after an event. Some factors such as hope, trust, problem-solving, cooperation, charity, responsibility and accountability are very helpful cultural elements to improve the efficiency of a society to reorganize resources and thus the ability to cope. Inequality, poverty, mismanagement, marginalization, and lack of physical infrastructure are generally expected in corrupt systems with inefficient and weak institutional structures. Without proper governance or political stability, there is little or no security for individuals and governments to invest in their property and physical infrastructure, respectively. In addition, a political system with more environmental regulations is more likely to have appropriate physical infrastructure and strong institutional structures which, in turn, lead to better adaptation. The proportion of land area that is legally determined as protected areas, national parks, or reserves (Alessa et al., 2008) can also be considered a measure of environmental regulation under social capital. In developing countries, lack of institutional capacity is one of main reasons of the vulnerability (Adger, 2006).

2.4.3.7 Agriculture Dependency

Drought is one of the principal climate-related hazards and particularly affects populations and communities engaged in the agricultural industry (Adger et al., 2004). The significant role of agriculture (both nationally and regionally) in both the economy and well-being (i.e., by providing food security) of a system is undeniable. Hence, it is important to consider a measure of the system's dependence on agriculture in a vulnerability study. Rural populations, number of agricultural employees, and type and volume of agricultural exports can be used as representative determinants of agriculture dependency in a system (Adger et al., 2004).

2.4.3.8 Technology Capacity

A wide range of scientists, including climatologists, hydrologists, geoscientists, agricultural scientists, and social scientists, as well as technologies, such as advanced electronic devices, radars, and advanced communication tools, are required to study climate-related vulnerability and hazard assessments and to determine and develop adaptation policies (Adger et al., 2004). Adaptation and adaptive capacity of a system therefore depend on the extent of the system's investment in the required technology and research. On the other hand, internet social networks play important roles in the vulnerability of a system by increasing access to information and providing links among community members (Alessa et al., 2008). Communities with strong and diverse social networks are likely to be less vulnerable to climate hazard. Therefore, the penetration of social networking and internet access in a system can be considered a measure of technology capacity. Moreover, factors such as investments in research and development (R&D) and the number of scientists and engineers employed in R&D can also be suitable proxies (Adger et al., 2004).

2.4.3.9 Network Diversity

Strong social networks substantially increase the access of information in a society (Alessa et al., 2008). Therefore, households and individuals in a community have the opportunity to access information of other communities who have experienced a certain hazard. Also by increasing social links among members of a system, the tendency of the system to cooperate in order to recover after an event is potentially increased and subsequently, its adaptive capacity is likely increased.

CHAPTER THREE

METHODOLOGY

In this research, a methodology is developed for assessing the vulnerability to flood and drought at river basin and sub-catchment scales. Figure 3-1 displays the framework of the tasks undertaken to manage and analysis the data. Figure 3.1 can be summarized as the following steps:

- Specifying the scale of the vulnerability assessment
- Determining different components of the vulnerability map
- Identifying the indexes related to the vulnerability components
- Aggregating the indexes and developing a vulnerability map
- Analyzing of the maps for monitoring network design

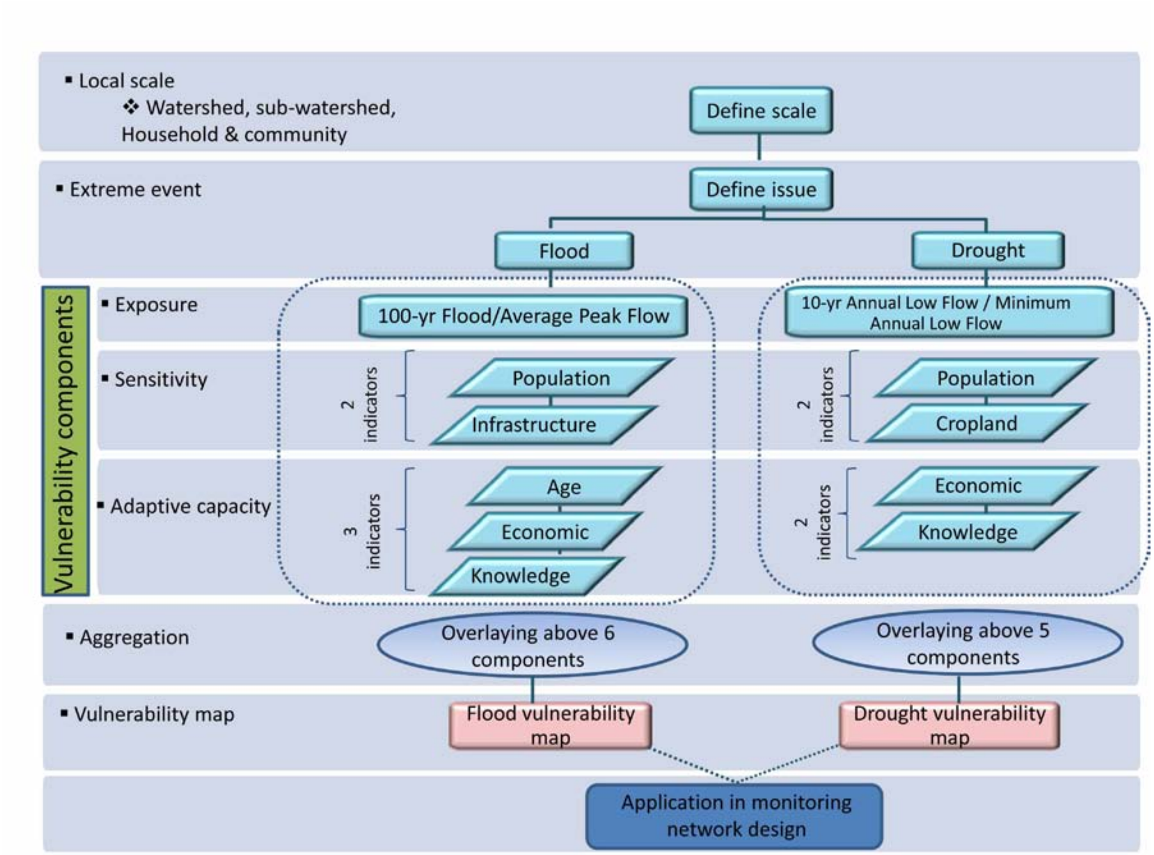

Figure 3-1: The framework of flood and drought vulnerability study

The above steps are explained in the following sections.

3.1 Scale

Vulnerability assessment is sensitive to the scale of the study. One of the first things that need to be agreed on is the spatial scale of the study based on the objectives of the research. The scale can be global, national, regional, or local. As physical and social characteristics of communities within a country are not uniform, vulnerability and societal adaptive capacity are commonly expected to be investigated at the local and community scale (Fekete et al., 2009). Although, it is sometimes argued that adaptive capacity and vulnerability of a community at local level are influenced by the national policies (Smit and Wandel, 2006).

This study looks closely at the vulnerability and adaptation of individuals, households, and communities to particular climate stresses of drought and flood in a scale of the river basin and sub-catchment.

3.2 Determination of Different Components of Vulnerability Map

Because of the ambiguity of the vulnerability concept, there is no universal consensus about it (Adger et al., 2004). However, as is discussed in Chapter 2, the main components of the vulnerability structures are exposure, sensitivity, and adaptive capacity. In this section of the study, the indicators used for mapping the vulnerability in the local scale are introduced.

3.2.1 Flood Exposure Indicator

Balica (2007) defines exposure for Flood Vulnerability Index (FVI) as "predisposition of a system to be disrupted by a flooding event" and the exposure is the value or quantity that presents the magnitude of threat of flood in a specified area. In some studies values including flood water depth, rainfall, flood duration, river discharge, runoff discharge, and historical monthly or daily average flow are used as exposures for flood vulnerability assessment (Balica et al., 2009; Huang et al., 2005). In this study, to introduce a new flood exposure index, annual maximum daily flows were extracted from data of the gauging stations to calculate the magnitude of the 100-year flood by using frequency analysis. The quantity of flood with a 100-year return period has been adopted as a flood base in several flood insurance programs and studies such as the United States National Flood Insurance Program (NFIP), floodplain mappings (Federal Emergency Management Agency website), and infrastructure design codes in many countries. The 100-year flood represents a flood event that has 1 in 100 chance of occurring in any given year. The flood value can be affected by many factors in a watershed, including basin size, slope, and biophysical features. In order to normalize the flood magnitude, several scaling factors such as area of watersheds, mean daily flow, and average peak flow can be employed. However, since the intention of this study is to define an index with ability of reflecting the severity of flood, average peak flow was selected as a normalize factor in the denominator of the exposure index. In other words, the magnitude of 100-year flood was divided by the average peak flow in order to develop a dimensionless ratio as a new flood exposure index to determine and compare the relative flood risk among various areas. Thereafter, the obtained flood exposure index was classified in three levels: the lowest tercile shows the low risk, middle tercile represents moderate risk, and the highest tercile indicates the high risk of flood.

3.2.2 Drought Exposure Indicator

In this study, the new drought index to identify the high risk areas was developed based on the characteristics of extreme values corresponding to the lower tail of the droughts' probability distribution and the low flow part of streamflow regime (González and Valdés, 2006). Based on the available historical data, time series of the annual minimum n-day discharge, mean annual minimum n-day discharge, and frequency analysis method were used to develop an appropriate drought exposure index. Therefore, the annual minimum 7-day discharge that occurs on average once every 10 years ($Q_{7,\,10}$) was applied to the daily streamflow discharge of gauging stations for drought calculations. In addition, in order to normalize the new drought exposure index and to facilitate an unbiased comparison among watersheds, mean annual minimum 7-day low flow (MALF) were calculated based on the moving average filter of 7 days (MA-procedure) as the denominator of the ratio where its numerator is ($Q_{7,\,10}$). The obtained dimensionless ratio is introduced as a new drought index in this study. The tercile approach was applied to categorize stressors for the drought exposure indexes the same as the flood exposure to identify the relative potential damages among different systems.

3.2.3 Indicators of Sensitivity

Sensitivity is described in climate vulnerability context as the degree to which a system is affected, either adversely or beneficially, by, or responsive to, an exposure (IPCC, 2001). Generally, sensitivity indicators represent a number of factors that change (increase or decrease) human and financial costs of an extreme event. However, sensitivity is an ambiguous component in most vulnerability frameworks. In some studies sensitivity is taken as the threshold or measuring level of a physical stressor at which the system is considered to be damaged (Luers et al., 2003) and in some others it is taken equivalent to the social vulnerability (Adger et al., 2004). Therefore, in order to evaluate the sensitivity some indicators were identified as is illustrated in Figure 3-1.

Apparently, areas with greater concentration of population are more sensitive to impacts of extreme events due to their large numbers of people, infrastructure, assets, and socioeconomic activities affected by these disasters. Hence, population exposed to drought and flood is used as a sensitivity indicator for both hazard events. Agricultural activities are very susceptible to a drought due to the decrease in surface water supplies including flow of rivers and streams, water level of reservoirs and lakes, and consequently decline of groundwater level. As a result, the consequences of the drought can be perceived more severely. Therefore, availability and density of the cropland areas was also mapped and selected as a sensitivity indicator for drought assessment. For flood assessment, the density of infrastructure that intrinsically must pass through diverse topography and land cover types and yet maintain integrity such as railroads, major highways, and power transmissions lines, were chosen as a sensitivity component in the flood vulnerability assessment due to the susceptibility to flood hazards.

3.2.4 Indicators of Adaptive Capacity

The term adaptation has been rooted in cultural ecology and social science context that describes the cultural adjustment to natural hazard (Smit and Wandel, 2006). Cultures that have adequate method to cope with and respond quickly to the stress are recognized to have a high adaptive capacity. Numerous definitions for adaptation and adaptive capacity can be found in environmental studies and climate change literature; many of them refer to adaptive capacity as ability or capacity of a system to modify or change its behaviour or response so as to cope better with existing or expected external stresses. Adaptive capacity refers to the potential, rather than an actual, adaptation and needs time to become effective in the near future (Adger et al., 2004). Smith and Wandel (2006) define adaptation as "process, action or outcome in a system (household, community, group, sector, region, country) in order for a system to better cope with, manage or adjust to some changing conditions, stress, hazard, risk or opportunity". Qualitative and quantitative indicators should be defined in the way that can fully represent the physical, social, cultural and economic characteristics of the community.

Some socio-economic factors are playing an influential role in the coping ability of people for a range of hazards. These factors are often referred to as generic indicators in the vulnerability context. At the local scale, access to financial, technology, information resources, status of managerial ability, and environmental institutions can be taken as adaptive capacity indicators. For example, poverty may force people to settle in high-risk areas where they are likely to be exposed to a range of stresses such as flood, storm, or unstable hilly slope.

Based on the availability of information, some of the indicators that can be used as the adaptive capacity in this vulnerability study are listed in the following sections.

3.2.4.1 Economic and Financial Capacity

A wealthy community can potentially better protect itself from future hazards relative to a poor and marginalized community (Alessa et al., 2008), which often have been at risk from natural hazards. In a wealthy community, financial resources for conducting mitigation and prevention plans are provided with less difficulties rather than poor communities. Also, wealthy communities normally select low-risk areas to settle down and to develop rather than poorer households that often have to sacrifice safety and security for financial issues. While this is generally true, there is an exception to this trend in wealthy communities where there is a tendency to purchase luxury-waterfront houses mostly for leisure time. Although these houses may be located in flood prone areas, the homeowners prefer to take the risk (or even ignore it) and sacrifice their safety for emotional reasons and enjoying the view. However, since the quality of these houses is typically good, they still have increased marginal safety relative to those poorer households who have to live in poor quality houses in a high-risk zone. Therefore, a wealthy community is generally expected to have more ability to cope with hazards, adapt to its new situation and retrieve its livelihood after an extreme climate event in comparison with poorer communities.

In this study, median total household income from census data 2006 provided by Statistics Canada was chosen as a proxy indicator to represent the economic and wellbeing capacity for the drought and flood vulnerability assessment at a sub-catchment scale.

3.2.4.2 Knowledge Capacity

"Knowledge is power" is a famous quote which is more than a simple sentence and can convey many things about knowledge adaptive capacity index. The quantity and quality of ecological knowledge of a community potentially increases its adaptive capacity. The level of education can directly influence the level of access to all types of information, particularly the ecological type, within a community. Therefore, there is higher chance to find more ways to cope with a hazard in a community with a higher level of knowledge (education).

Based on National Household Survey provided by Statistics Canada (Statistics Canada, 2006 Census of Population), the ratio of people who obtained a college degree, Collège d'enseignement général et professionnel (CEGEP), or other non-university certificate or diploma to the total population of the communities in a sub-catchment was used as a proxy indicator of the knowledge capacity.

3.2.4.3 Age

Mobility and immediate reaction are important indicators in flooding time having a great impact on the magnitude of loss. The elderly and young children are more vulnerable because of lack of mobility and physical disability in the time of disaster. They also have less ability to resist infectious diseases after disaster. Based on Age and Sex data from 2006 Census (Statistics Canada, 2006 Census of Population) provided by Statistics Canada, the population over 65 and less than 14 years old were selected as an indicator to evaluate the age factor in the flood vulnerability assessment of this study.

At the final stage, these several maps of adaptive capacity, sensitivity, and exposures were overlaid in ARC-GIS in order to develop a final vulnerability map.

3.3 Aggregation of the Indexes and Developing Vulnerability Map

In order to construct a vulnerability index or map, it is required to combine different indicators of vulnerability components. In order to have precise diagnostic tools, it is suggested to allocate appropriate weights for different indicators to convey the importance of parameters forming the vulnerability measure (Wescovi et al., 2005; Nelson et al., 2010). Although it seems very useful approach, determining the appropriate weights for various factors that form part of the vulnerability of a system needs a deep understanding of these components as well as high resolution of related information. In practice, precise determination of the value of weights to be applied in a system needs opinion of experts and consultants particularly from a given system (Sullivan et al., 2003). Accordingly, determining the weight in vulnerability studies is often subjective.

Disaggregated indexes for vulnerability structures and the process of identification of different socio-economic indicators contributing to vulnerability seem more helpful rather than a single score (Adger et al., 2004; Alessa et al., 2008). It may also assist policy makers to support improvement of the process and elements enhancing the adaption capacity of a system. In this study, simple (equal) weights were applied to compose indexes because of lack of either adequate information or expert judgments. However, differential weights can be easily applied with the existing framework if local information capable of indicating the importance of different parameters is available.

3.4 Analysis of Vulnerability Maps in Monitoring Network Design

The innovative aspect of this study is using vulnerability assessment of flood and drought as part of integrated monitoring network design. This objective is achieved by identification of vulnerable areas to extreme events (here flood and drought) and simultaneously evaluating the adequacy and quality of hydrometric data provided by existing monitoring gauges. Because of the importance of the vulnerable areas, it is crucial for decision makers to have sufficient information about characteristics of natural hazards there. Thus, vulnerability studies can play the role of additional constraint in monitoring network design and can help decision makers to choose wisely if any monitoring station had to be shut down because of financial shortages.

3.5 Other Information and Data

Vulnerability assessment plays a key role to analyze the relationship between hazards and society. Therefore, besides a robust framework, a powerful decision support system and broad range of high quality information is required for vulnerability studies. In following sections, the computer software programs that are used in this study are described.

3.5.1 GIS approach

Vulnerability assessment technique is based on evaluating diverse factors including physiographic, social, environmental and other factors like coping ability, awareness and regional economic activities (Hamouda et al., 2009). Geographic Information System (GIS) approach is a good candidate for vulnerability assessment based on the ability to provide efficient tool for processing and analyzing spatial data, managing information, and overlaying a set of decision criteria linked to a number of different parameters associated with natural hazards and social response. GIS facilitates a range of time-demanding activities such as gathering, geospatial analyzing, and integrating and aggregating of spatial information. GIS can improve the emergency response systems by facilitating the network analysis and emergency management and also visualize the emergency facilities' location. GIS also improves disaster mitigation and management by employing and visualizing a broad range of relevant data including infrastructure, socio-economic data, soil and geology, and land-use to identify the disaster prone area and to identify vulnerable populations. In this study, ArcMap software from ESRI version 10.1 is used as a decision support system tool.

CHAPTER FOUR

CASE STUDY APPLICATION

4.1 Background

The St. Lawrence River Basin is one of the largest hydrographic systems in the world (Environment Canada website, St. Lawrence River), which passes through the Canadian provinces of Ontario and Quebec and several states in the United States with the total area of over 1.3 million km^2. The Upper Ottawa River Basin, which is selected as the case study, is part of St. Lawrence River Basin and is located in the north-west of this basin as displayed in Figure 4-1. As can be seen in Figure 4-1, the Upper Ottawa River Basin is located north-east of Toronto and north west of Ottawa between 75°36′- 81°22′ W Longitude and 45°52- 48°44′ N Latitude, covering a total area of over 60,000 km^2. Since the Ottawa River defines the provincial boundary for most of its length, the Upper Ottawa River Basin is situated within both Ontario and Quebec provinces. The Ottawa River flows from its source in Laurentian Mountain west towards Lake

Timiskaming and passes thorough Ottawa and drains an area of around 145,000 km^2 into the St. Lawrence River at Montreal. The climate of the region is cold continental with the long-term mean daily temperature of about 3.8°C. The average precipitation is approximately 950 mm per year with about 20% falling as snow (Ottawa Riverkeeper's River reports, 2006).

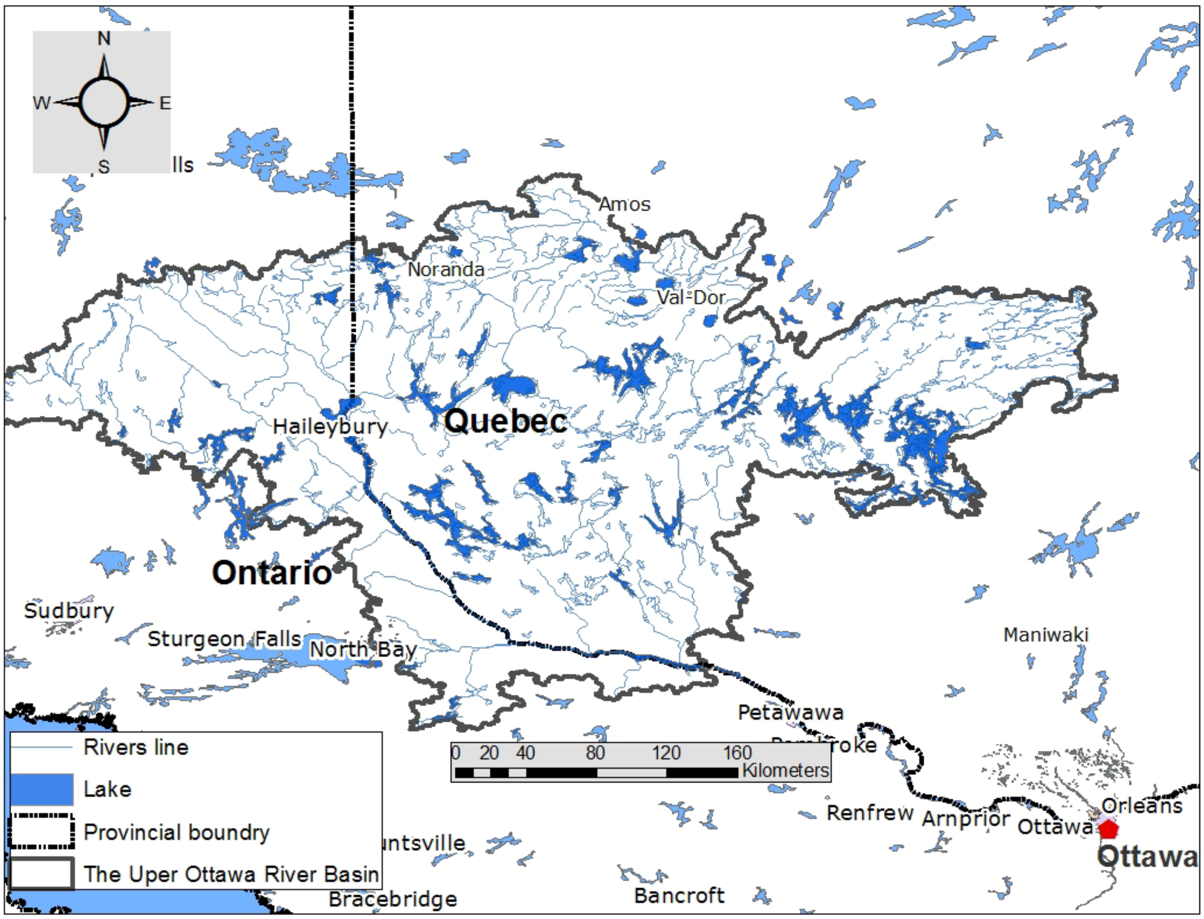

Figure 4-1: The Case Study; the Upper Ottawa River Basin.

4.2 Physiography of the Basin

The elevation map of the Upper Ottawa River Basin in Figure 4-2 is obtained from raw digital elevation model (DEM) by using spatial analysis in ArcGIS. As can be seen, most parts of basin are almost flat between 300 m and 450 m above sea level and the lowest elevation is associated with the valleys of the Ottawa River.

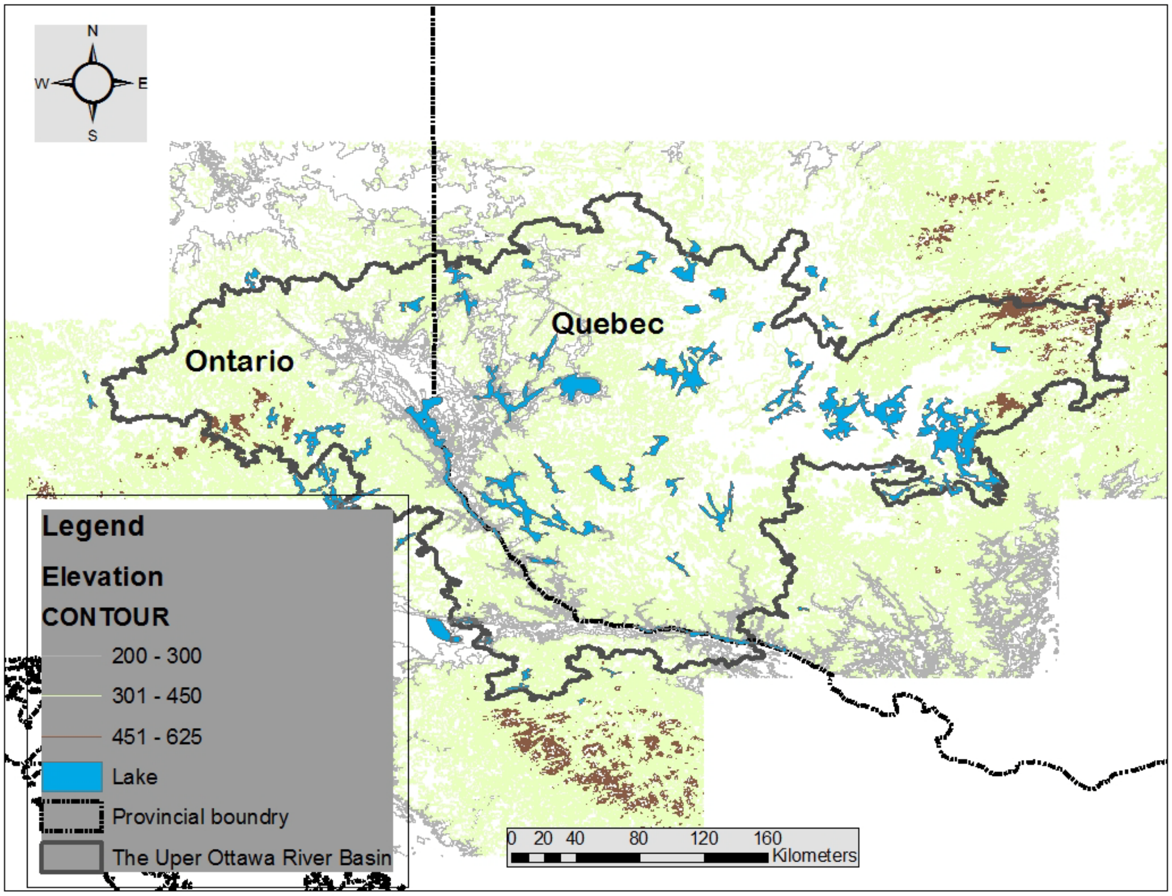

Figure 4-2: The elevation map of the Basin.

The land cover spatial data were obtained from the Commission for Environmental Cooperation (CEC). As Figure 4-3 shows, the landscape of the region is dominated by mixed forest with several small lakes scattered within these forests. Figure 4-4 shows CSD with population of 2000 up to near 55000 in the Basin. CSD is equivalent to a municipality and is the lowest level of geographic classification by Statistics Canada Standard. As can be seen from Figure 4-4, a considerable amount of the population in the Upper Ottawa River Basin is settled in lowland areas near rivers with significantly high risk of flood.

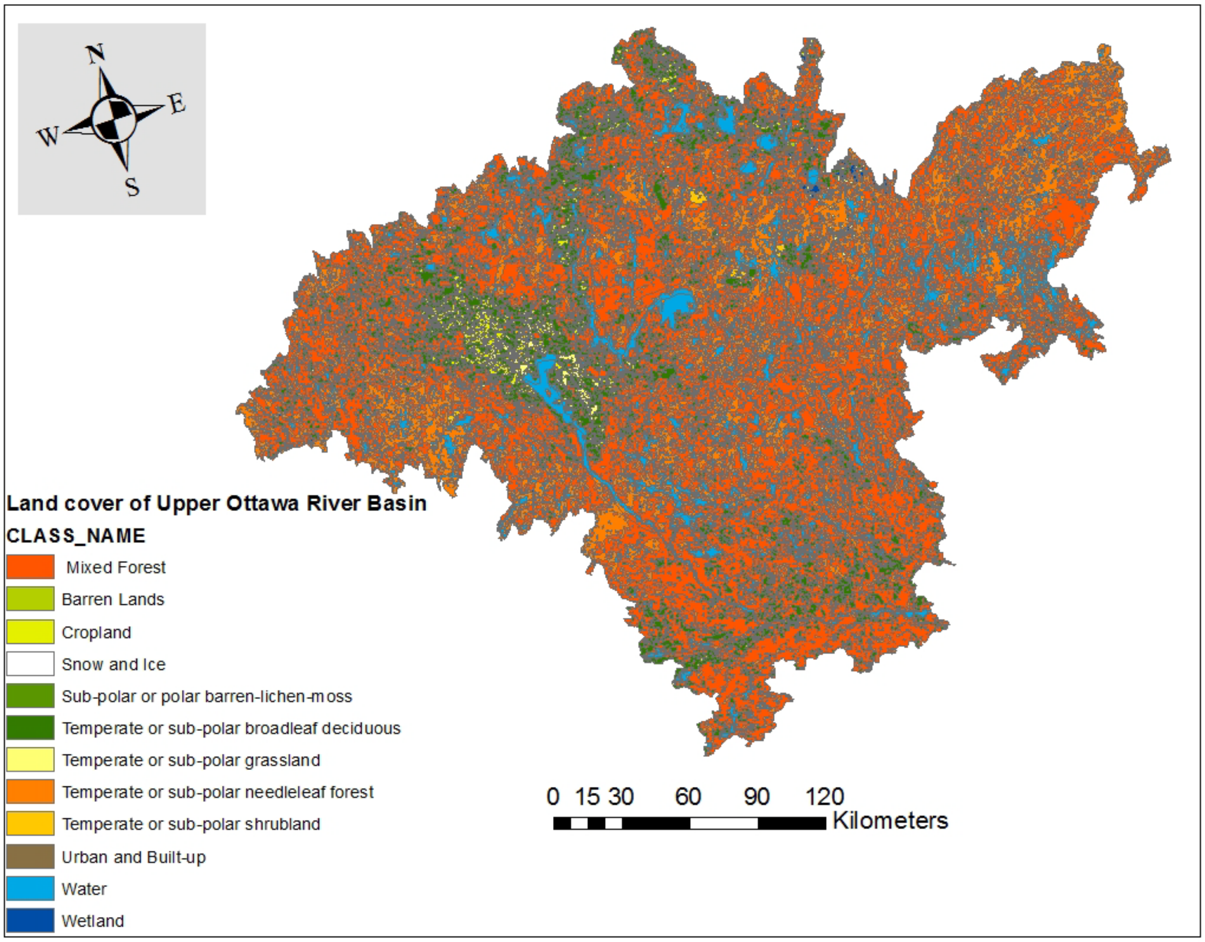

Figure 4-3: Land cover of the Upper Ottawa River Basin (Commission for Environmental Cooperation (CEC), Land Cover 2005).

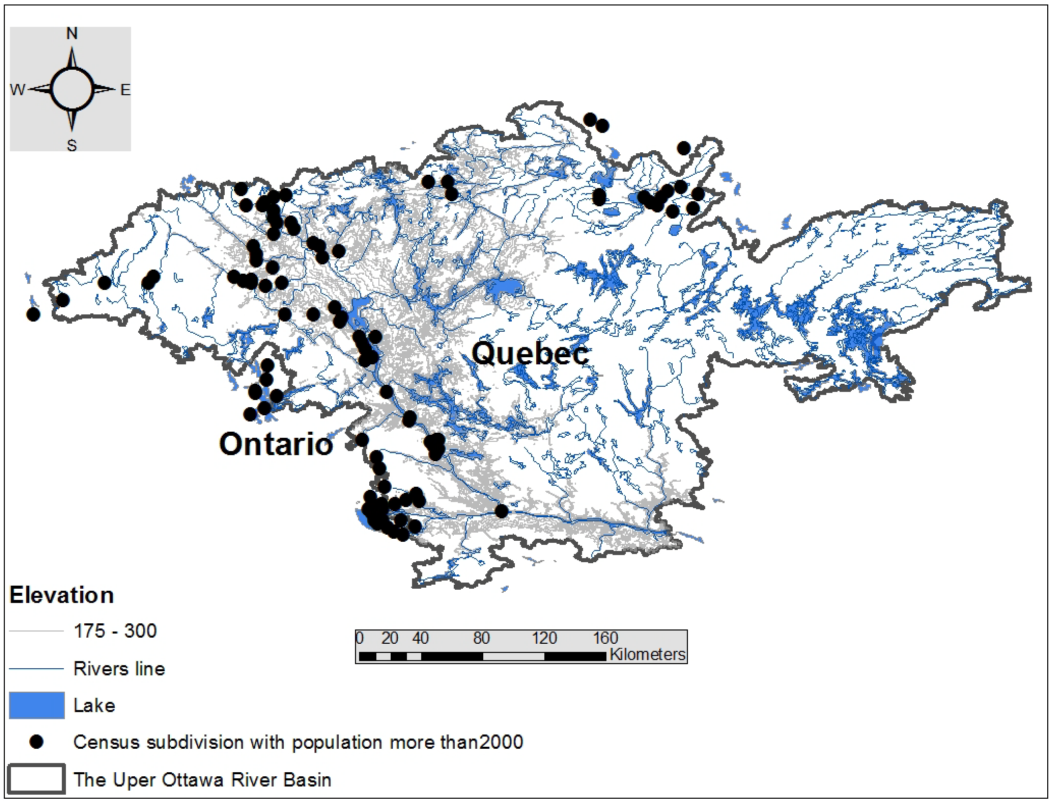

Figure 4-4: CSD with population more than 2000.

Because of the characteristics of the basin including the basin's shape, size, topography, and meteorological variation, flooding along the Ottawa River is an anticipated phenomenon (Ottawa River Regulation Planning Board). There are also 43 hydroelectric generating plants in the Ottawa River Basin that indicates the important role of this river in energy production and economy of both Quebec and Ontario (Ottawa River Regulation Planning Board). Therefore, studying flood and drought condition in this Basin can help the decision makers to reduce the adverse effects of the extreme events.

4.3 Hydrometric Gauging Stations of the Basin

Over 2500 hydrometric gauging stations across Canada record all types of hydrometric data including daily and monthly mean streamflow, peak flows, water level, and sediment concentrations. These data are collected, interpreted, and disseminated by the Water Survey of Canada (WSC). The density of monitoring stations decreases when going toward the northern part of the St. Lawrence River Basin. This distribution of monitoring stations is consistent with other parts of Canada since most of the stations are located in the southern portion of the country because major cities and socioeconomic activities are concentrated there (Environment Canada, The Hydrometric Network).

The status of the hydrometric monitoring network in the St. Lawrence River Basin is shown in Figure 4-5.

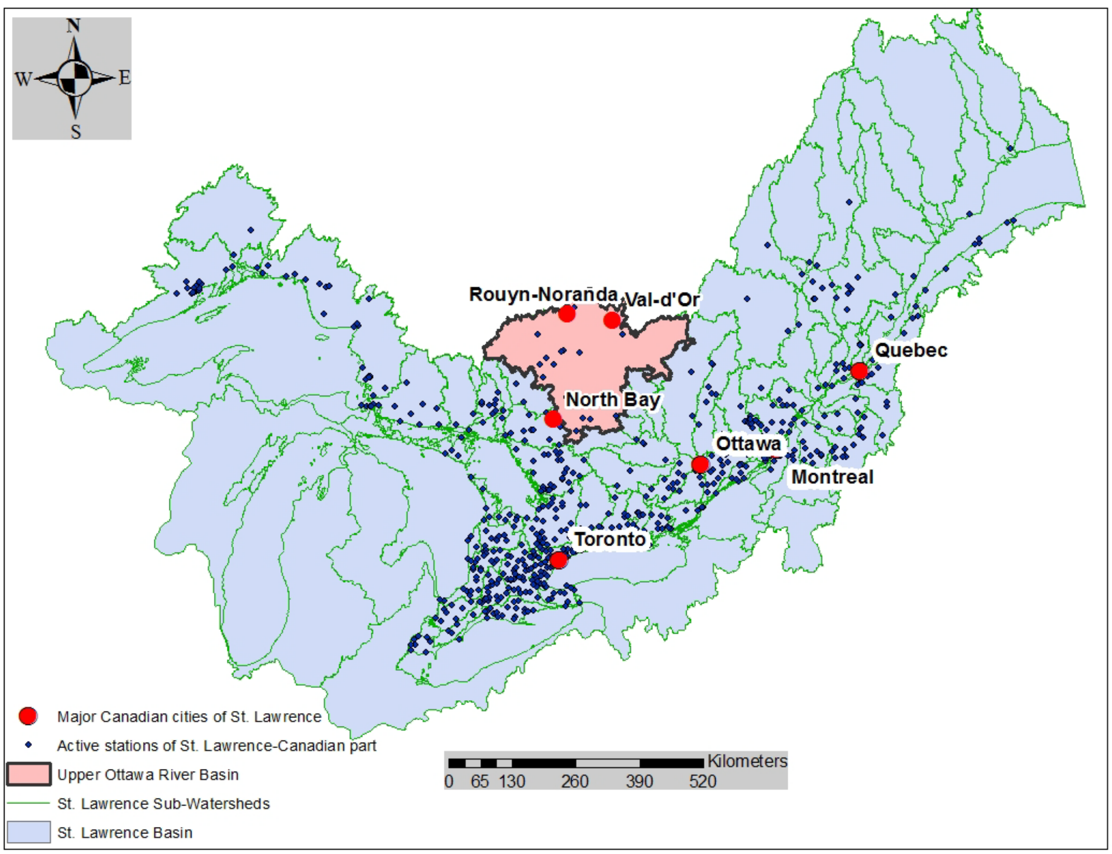

Figure 4-5: Map of St. Lawrence Basin in Canada and the active hydrometric monitoring stations for the Canadian portion.

As a result of insufficient hydrologic information, the north half of Canada is prone to uncertainties in design, planning, and water resources management. Thus, the case study is chosen from the northern watersheds of the St. Lawrence River Basin, which is often exposed to extreme events and does not have an adequate number of monitoring stations.

The hydrometric monitoring network within the Upper Ottawa River Basin consists of 67 streamflow stations with various lengths of record measuring flow and/or level. Currently, not all of the stations are active; however, in this study stations are selected based on the minimum record length of 20 years regardless of their active/inactive status. To study recent hydrologic variability, it is important to have recent information. Therefore, only those stations that have the discharge information after the year 1970 were determined appropriate. As a result, only 16 stations among 67 available streamflow gauging stations measuring daily and peak flows were selected to provide historical input data required for frequency analysis. Figure 4-6 shows the drainage area of the Upper Ottawa River Basin as well as the locations of streamflow gauging stations used in the analyses. The daily streamflow data were obtained from the national WSC archived Hydrometric Database (HYDAT) provided by Environment Canada (Environment Canada, 2010, HYDAT Database). The gross drainage area of the selected gauging stations varies between 575 km^2 and 23,400 km^2. The minimum recording length is 23 years between the years 1972 and 1994. The only Reference Hydrometric Basin Network (RHBN) station is 02JC008. The RHBN is a sub-set of the national network that has been identified for use in detection, monitoring, and assessment of climate change (Environment Canada, The Hydrometric Network). Further details about these streamflow gauging stations are summarized in Table 4-1.

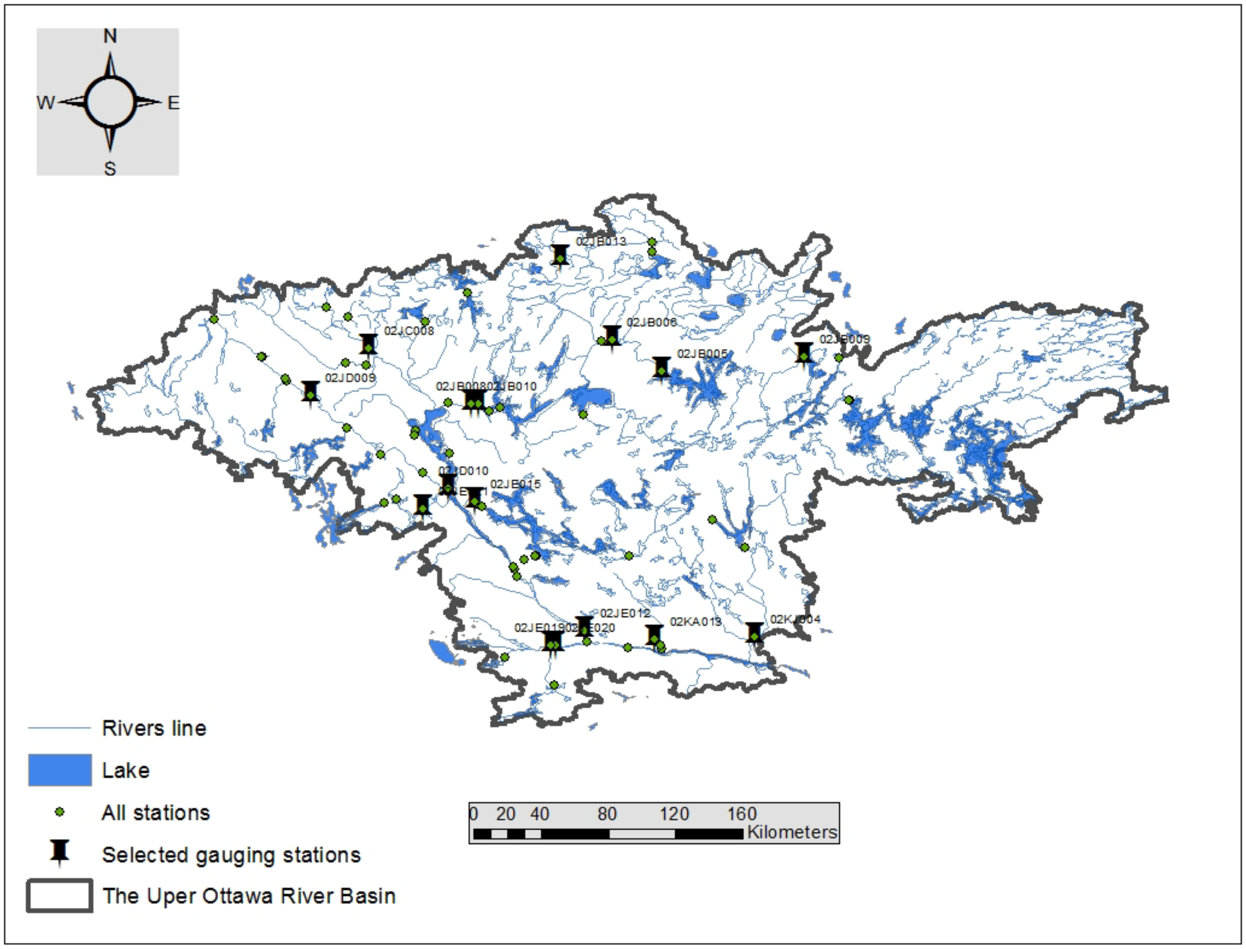

Figure 4-6: Map of the Upper Ottawa River Basin and the location of streamflow gauging stations.

Table 4-1: Summary of streamflow gauging stations

#	STATION_CODE	STATION_NAME	PROV_TERR	LATITUDE	LONGITUDE	DRAINAGE_A	RHBN	YEAR_FROM	YEAR_TO	RECORD_LEN	REGULATED
1	02JB005	OUTAOUAIS (RIVIERE DES) AU BARRAGE DE RAPIDE-SEPT	QC	47.77	-78.31	13,100	N	1939	1994	56	Y
2	02JB006	OUTAOUAIS (RIVIERE DES) AUX RAPIDES 2	QC	47.93	-78.58	14,000	N	1954	1994	41	Y
3	02JB008	OUTAOUAIS (RIVIERE DES) BARRAGE DES RAPIDES DES	QC	47.59	-79.30	23,400	N	1965	1994	30	Y
4	02JB009	OUTAOUAIS (RIVIERE DES) A LA SORTIE DU LAC GRANET	QC	47.84	-77.55	10,300	N	1977	2013	37	Y
5	02JB010	OUTAOUAIS (RIVIERE DES) AU BARRAGE DES RAPIDES DES ILES	QC	47.59	-79.33	23,400	N	1967	1994	28	Y
6	02JB013	KINOJEVIS (RIVIERE) A 0,3 KM EN AMONT DU PONT-ROUTE A	QC	48.37	-78.85	2,590	N	1965	2001	37	N
7	02JC008	BLANCHE RIVER ABOVE ENGLEHART	ON	47.89	-79.88	1,780	Y	1968	2010	43	N
8	02JD009	MONTREAL RIVER AT MOUNTAIN CHUTES	ON	47.64	-80.19	4,300	N	1968	1995	28	Y
9	02JD010	MONTREAL RIVER AT LOWER NOTCH GENERATING STATION	ON	47.14	-79.45	6,600	N	1972	1994	23	Y
10	02JD012	MONTREAL RIVER AT MISTINIKON LAKE DAM	ON	48.03	-80.70	1,780	N	1946	1994	49	Y
11	02JE015	KIPAWA (RIVIERE) EN AVAL DE LANIEL	QC	47.07	-79.31	6,023	N	1962	2011	50	N
12	02JE019	AMABLE DU FOND RIVER AT SAMUEL DE CHAMPLAIN	ON	46.30	-78.88	1,130	N	1972	1995	24	Y
13	02JE020	MATTAWA RIVER BELOW BOUILLON LAKE	ON	46.30	-78.91	909	N	1971	1998	28	Y
14	02JE021	MATABITCHUAN RIVER AT RABBIT LAKE DAM	ON	47.03	-79.59	749	N	1946	1994	49	Y
15	02KJ004	DUMOINE (RIVIERE) A LA SORTIE DU LAC ROBINSON	QC	46.35	-77.82	3,760	N	1982	2013	32	Y
16	02KA013	MAGANASIPI(RIVIERE) AU LAC JOHNSON	QC	46.33	-78.35	575	N	1982	2013	32	N

4.4 Data

A range of information from historical hydrometric and geophysical data to demographic and socio-economic information is used in this study. In the first step, delineation process of watershed and spatial analysis were conducted to produce a map of all sub-catchments of the watershed. This process is conducted using DEM and series of analysis under spatial analyst extension of ArcMap including filling sinks, creating flow direction, creating flow accumulation, creating pour points, and finally delineating watersheds. The DEM data were obtained from GeoBase (Canadian Council on Geomatics, CCOG, 2008) with the resolution of 1:50,000.

A statistical software package developed by Hydrologic Engineering Center of US Army Corps of Engineering, HEC-SSP (Hydrologic Engineering Centre, US Army Corps of Engineers), was used for frequency analysis in this study. The HEC-SSP can perform several statistical analyses of hydrologic data including the flood flow frequency analyses based on Bulletin 17B, “a guideline for determining flood flow frequency” (1982), generalized flow frequency analyses, and volume frequency analyses on high and low flow.

Required socio-economic and demographic information were obtained from 2006 Census data in Statistics Canada’s website (Statistics Canada, 2006 Census of Population). From the census data of 2006, the status of income and earnings of individuals, and their education level were derived besides demographic information. The Statistics Canada 2006 Census data at Census Subdivision (CSD) level were used for vulnerability assessment. A CSD is “the general term for municipalities (as determined by provincial/territorial legislation) or areas treated as municipal equivalents for statistical purposes” (Statistics Canada, Census Dictionary 2006). Based on the scale of this study (river basin and sub-catchment), this census scale is useful and appropriate for local policymakers.

CHAPTER FIVE

RESULTS AND DISCUSSION

This chapter presents the results obtained from the case study application. The disaggregated components of the vulnerability study, along with the final vulnerability map and the current status of the monitoring network were analyzed. The spatial analysis that was conducted by ArcMap to delineate the Upper Ottawa River is explained and then the results of this study are divided in two parts based on the exposures: flood and drought. The results of the flood vulnerability assessment are presented in sections 5.2.1 to 5.2.4 and the results of the drought vulnerability assessment are described in sections 5.2.5 to 5.2.8 of this chapter.

5.1 Spatial Analysis by GIS

Hydrologic Analysis tool in ArcMap 10.1 developed by Esri's Arc GIS is capable of establishing a topological network that includes flow direction, connectivity, and upstream/downstream relationships of stream segments using the Digital Elevation Model (DEM), stream network, and snap pour points to distinguish watershed outlets. Using this tool, Upper Ottawa River Basin was delineated with a series of latitude-longitude points that correspond to WSC hydrometric gauging stations. As a result, the Upper Ottawa River Basin consists of 16 sub-catchments corresponding to 16 WSC gauging stations, used as outlet points for creating the sub-catchments.

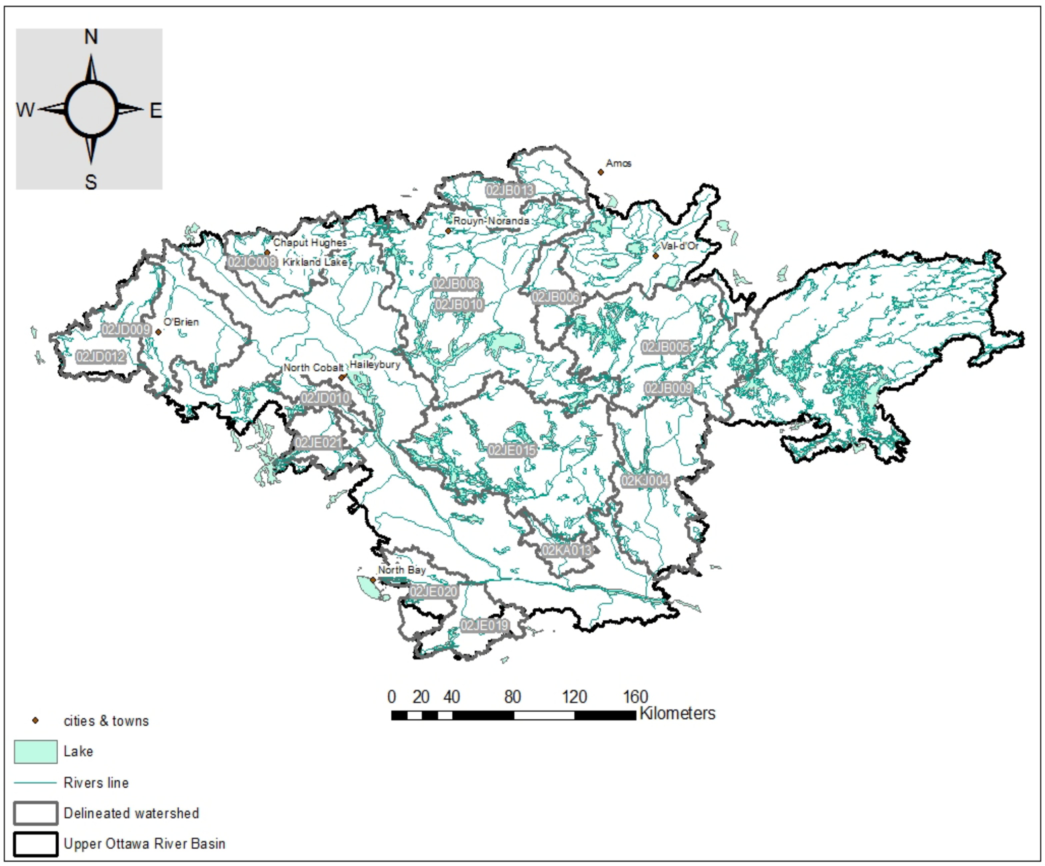

Figure 5-1: The delineated watersheds of the Upper Ottawa River Basin obtained by the ArcMap.

From now on, the WCS IDs for stations were used for identifying the sub-catchments. Figure 5-1 shows the delineated watershed obtained from the ArcMap hydrological tool.

5.2 Flood Vulnerability Assessment

5.2.1 Flood Exposure Map

The first step for the flood vulnerability assessment, which is the essential element for any flood hazard study, is to develop or to determine a flood exposure. As discussed in Chapter 3, magnitude and frequency are two principal features that the flood exposure indicator has to clearly explain. In this study, the flood exposure indicator was determined based on the flood frequency analysis and the annual maximum flood (AMF) index which was calculated by finding 100-year flood magnitude and average annual maximum flow for stream gauging stations. To carry out flood frequency analysis, HEC-SSP was used. The probability plots resulting from frequency analysis for all stations are provided in Appendix A. The average of annual maximum streamflow was used as a scaling factor in the denominator of the newly-developed flood index where the numerator was the quantity of flood with return period of 100 years. This dimensionless value was introduced as the flood exposure index categorized in three levels using tercile pattern to facilitate the comparison among sub-catchments. The relative flood risk can be investigated with the new flood exposure indicator, in a river basin and a sub-catchment scale. Table 5-1 shows the results of the flood exposure indicator in the sub-catchments of the Upper Ottawa River Basin.

Table 5-1: The results of the flood exposure index, the red, green, and yellow colours represent the sub-catchments with high flood risk, low flood risk, and moderate flood risk sub-catchments, respectively.

General				Flood Frequency	
#	station_ID	meanflow	Ave. Peakflow	100-yr flood	100yr /Ave. Peakflow
1	02JB005	206	452	1140	2.52
2	02JB006	221	438	888	2.03
3	02JB008	353	698	1345	1.93
4	02JB009	187	346	597	1.73
5	02JB010	373	757	1449	1.91
6	02JB013	38	255	491	1.93
7	02JC008	22	164	283	1.73
8	02JD009	48	265	567	2.14
9	02JD010	76	335	590	1.76
10	02JD012	21	126	298	2.37
11	02JE015	72	236	330	1.40
12	02JE019	16	76	137	1.80
13	02JE020	15	88	168	1.91
14	02JE021	10	43	114	2.67
15	02JK004	52	201	393	1.95
16	02KA013	14	39	144	3.68

The map of the flood exposure in the Upper Ottawa River Basin is depicted in Figure 5-2. As can be seen in Figure 5-2 (highlighted in red colour), six watersheds of 02JB005, 02JB006, 02JD009, 02JD012, 02JE021, and 02KA013 were identified with high-risk of flood occurrence and some watersheds including 02JB008, 02JB010, 02JB013, 02JE020, and 02KJ004 were determined with medium-risk of flood exposure. Based on the obtained results, cities such as North Bay and Rouyn-Noranda are situated in a moderate flood risk sub-catchments. The rest of watersheds were placed under the category of the low risk areas.

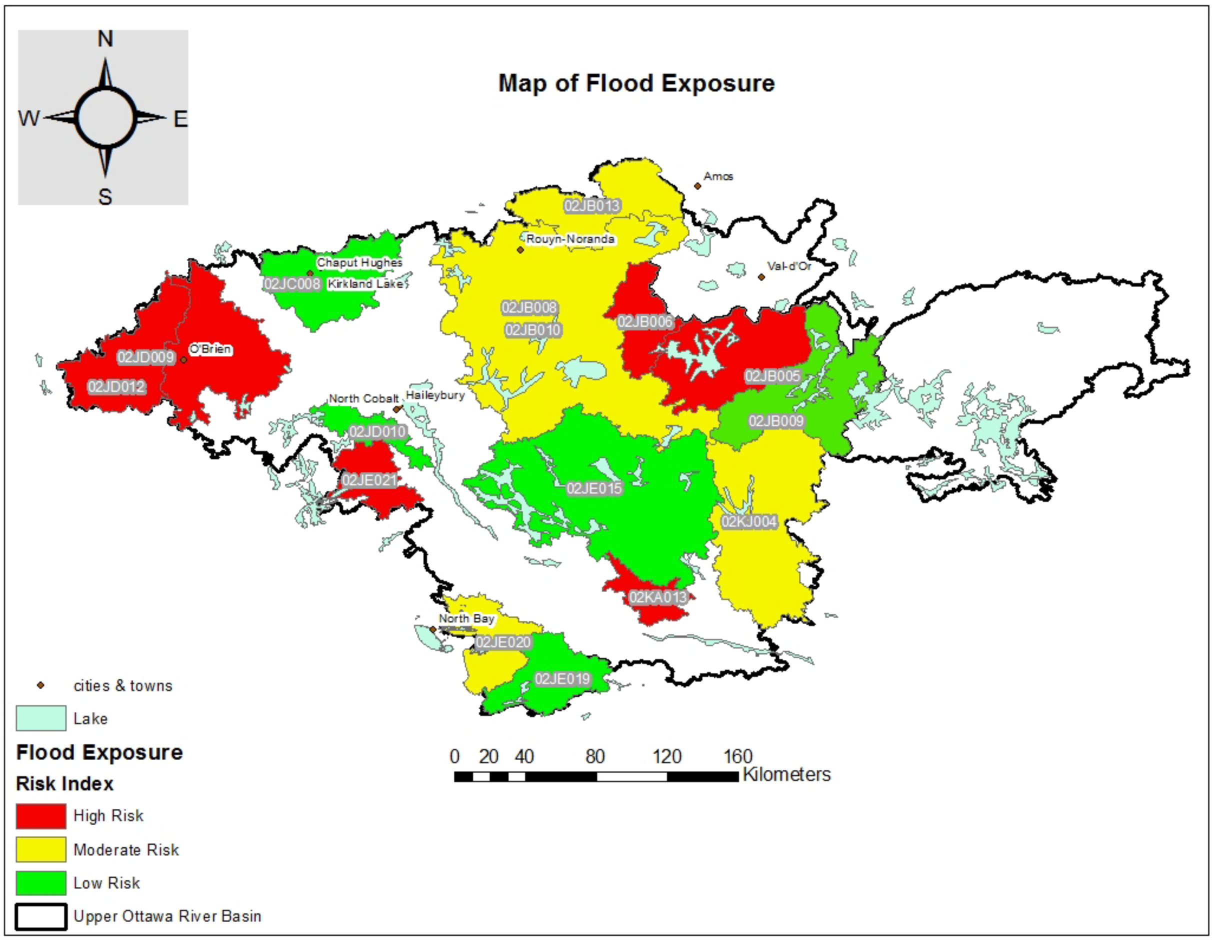

Figure 5-2: The flood exposure map of the Upper Ottawa River Basin. The red, yellow and green colours show watersheds with high-risk, medium-risk and low-risk flood exposure, respectively.

The elevation is an important geophysical feature of a watershed that can influence the climate variables. Figure 5-3 shows the topographic map of the Upper Ottawa River Basin. A part from two small relatively highland areas in east and west of the Basin, the majority portion of the

Upper Ottawa River Basin is at moderate elevation where the lowest portion corresponds to the Ottawa River Valley.

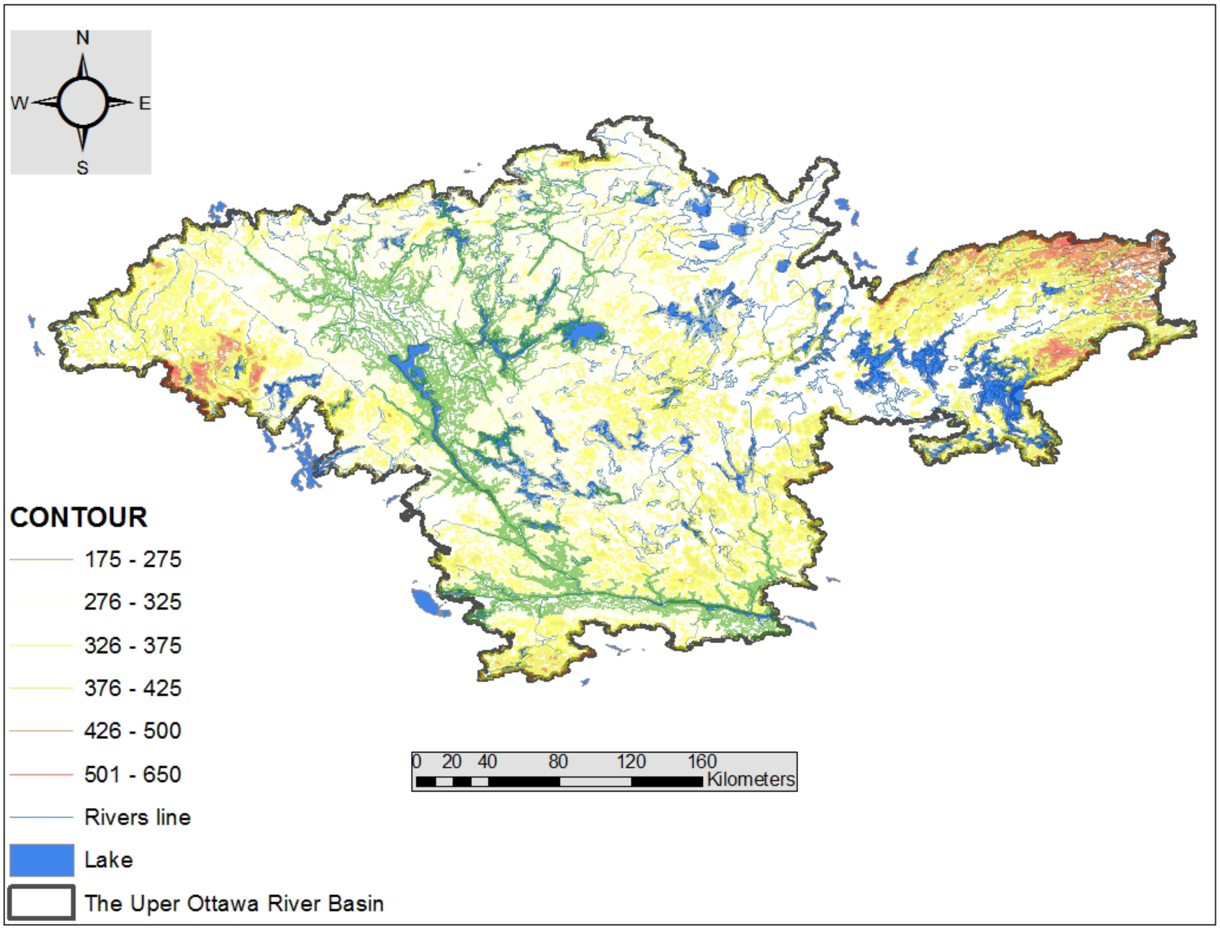

Figure 5-3: The elevation map of the Upper Ottawa River Basin.

The Ottawa River is one of the more highly regulated rivers in Canada with over 50 dams (Ottawa Riverkeeper's River reports, 2006) with over one third of them located in the upper part of the Basin. The majority of these dams are for hydroelectric power generation and only two of these dams are constructed as flood control structures that play a significant role in mitigation planning (Canada Centre for Remote Sensing, the Atlas of Canada, 2008). The location of these dams is shown in Figure 5-4.

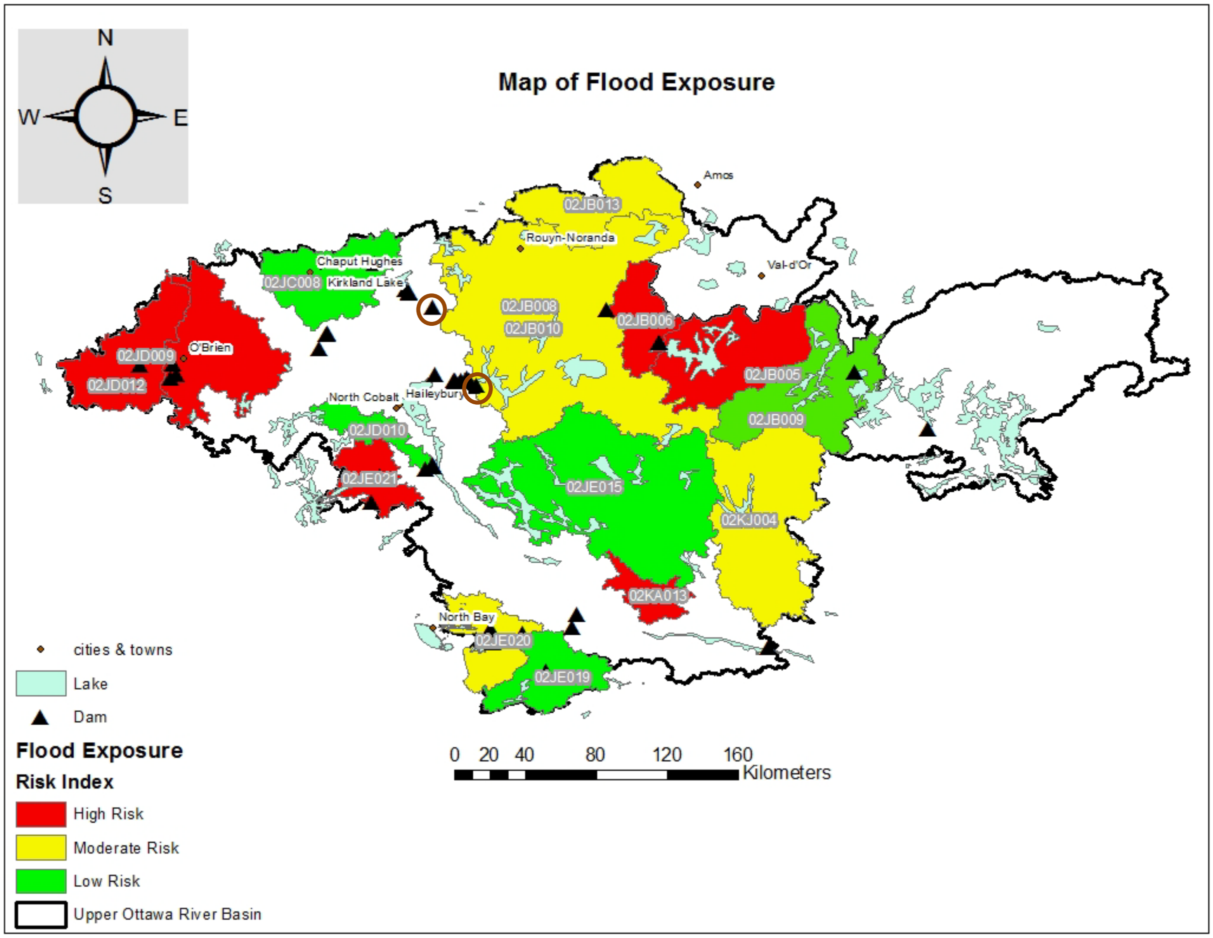

Figure 5-4: The location of dams in the Upper Ottawa River watersheds, the only two flood control dams are shown with red colour circles. The purpose of other dams is hydroelectric (Canada Centre for Remote Sensing, the Atlas of Canada, 2008)

5.2.2 Flood Sensitivity Map

The severity of a risk cannot exclusively be conveyed by the exposure. To estimate the risk, sensitivity factors are required to portray how significant the risk and damages will be if the study area is exposed to a particular hazard. In this study, the population density settled in the high-risk areas and infrastructure such as highways, railways, and power transmission lines were chosen as flood sensitivity factors.

5.2.2.1 Sensitivity Factor of Population

Figure 5-5 shows the map of Census Subdivision (*CSD*) with population more than 2000 people based on census data of year 1996 to assess the degree of severity of the consequences of flood. Population is concentrated in four socio-economically active areas within the case study: North Bay, Temiskaming Shores, Kirkland Lake, and Rouyn-Noranda (Figure 5-5).

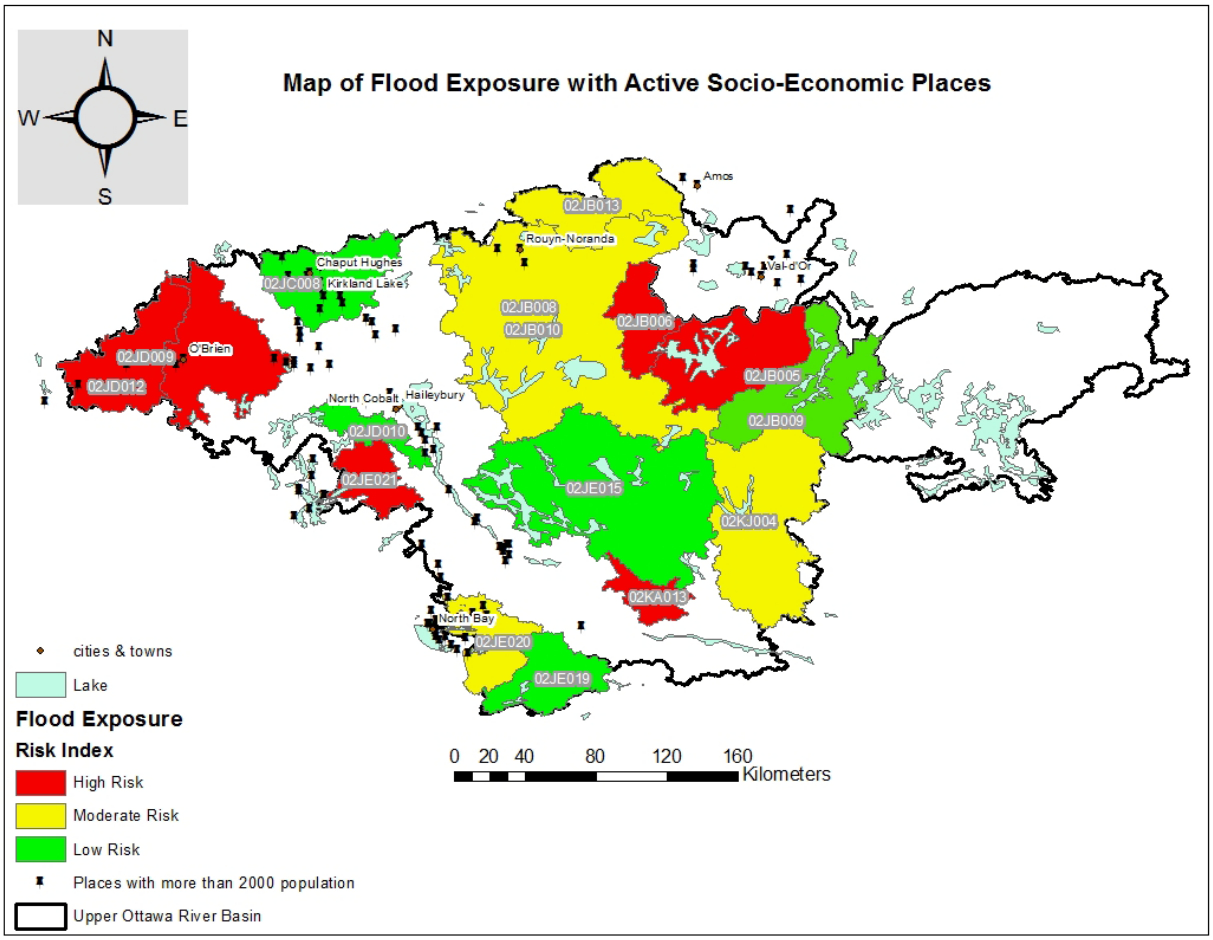

Figure 5-5: The map of regions with population of more than 2000 people in the Upper Ottawa River Basin based on Census Subdivision (CSD) 1996.

Towns such as Cobalt, Deep River, Haileybury, Mattawa, and New Liskeard are some of the other population centers within the Upper Ottawa River Basin. The population of these regions is generally active in industries such as mining, forestry, and agriculture. All of these areas are located in or adjacent to the high or moderate flood risk areas. For further analysis of this sensitivity factor, the distribution of population was also investigated. As it was pointed out before, in this study, 2006 census of population and dwelling statistics in CSD were used for this purpose. There are two kinds of subdivisions among all that are more popular based on the objectives of studies; dissemination area and CSD. A dissemination area is “a small, relatively stable geographic unit composed of one or more adjacent dissemination blocks, with a population of 400 to 700 persons. It is the smallest standard geographic area for which all census data are disseminated (Statistics Canada, *2006 Census Dictionary*). A CSD is “the general term for municipalities (as determined by provincial/territorial legislation) or areas treated as municipal equivalents for statistical purposes. Municipal status is defined by laws in effect in each province and territory in Canada.” (Statistics Canada, *2006 Census Dictionary*).

In Figure 5-6, the population was mapped and overlaid on the flood exposure. There are some places on the map with no data. According to the Census Dictionary, places with less than 250 people are not reported and therefore, there are no data about the population, number of dwellers, and their income. As Figure 5-6 illustrates, among the high flood risk area, part of 02JB005 and 02JB006 are highly populated (between 10,000 and around 54,000) and therefore, are highly sensitive. In the next level of sensitivity, 02JB008, 02JB010, 02JE020 and 02JB013 are ranked with moderate flood risk and high population between 10,000 and 54,000. Also 02JD009 and 02JD012 are considered highly sensitive with high flood risk and moderate population of between 5,000 and 10,000.

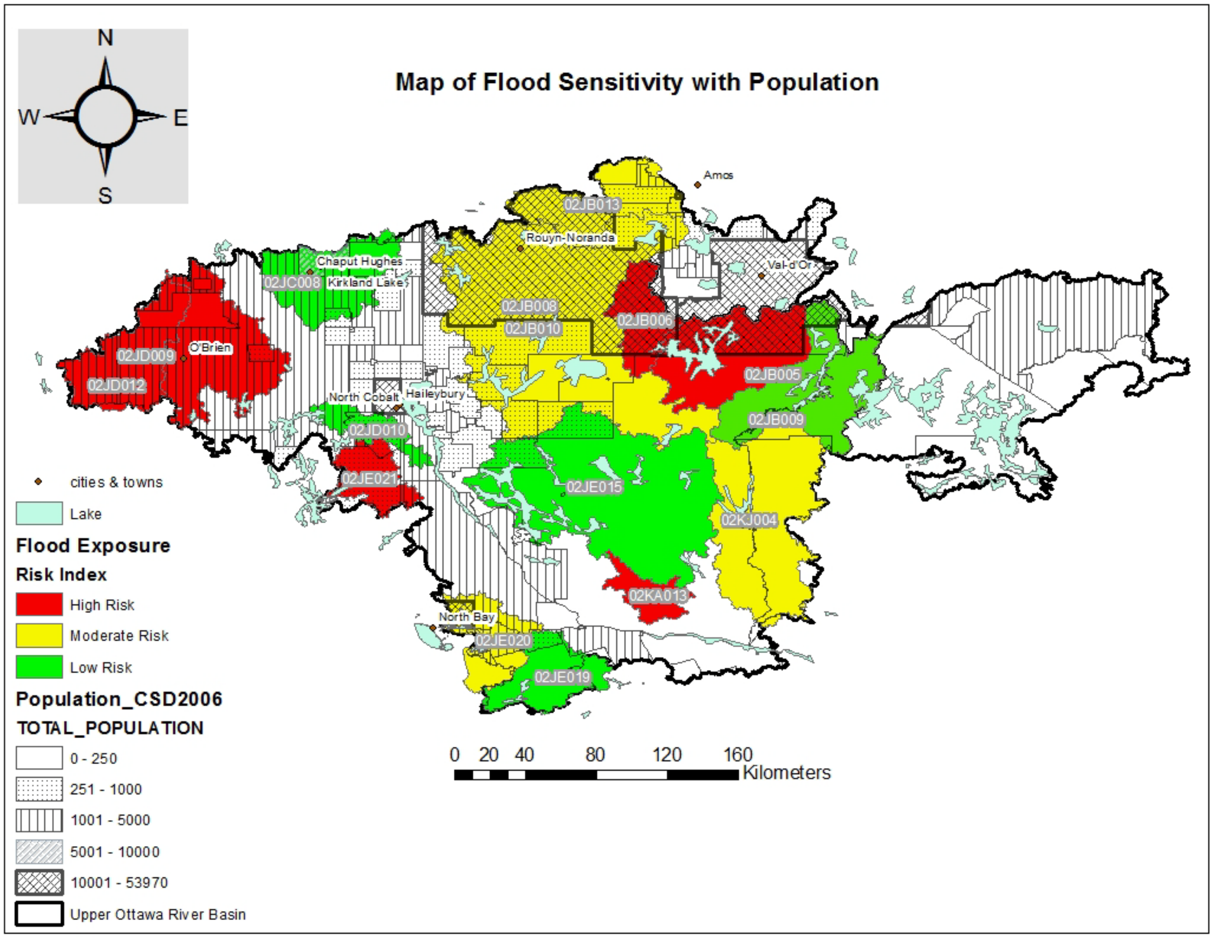

Figure 5-6: Census Population 2006 in Census Subdivision (CSD) and sensitivity maps of the Upper Ottawa River Basin

Areas with high flood risk and high population are categorized highly sensitive. Also high sensitivity occurs where high or moderate flood risk areas coincide with moderate or high population, respectively.

5.2.2.2 Infrastructure as Sensitivity Factor

Railroads, highways, and power transmission lines are major infrastructure on which most human activities in all societies directly or indirectly depend. However, as these kinds of infrastructure mainly work in the form of a network, they must pass across several areas with various types of landscapes and hence, they are highly susceptible to natural disasters. The map of railroads, major roads and highways, and power transmission lines within the Upper Ottawa River Basin is shown in Figure 5-7.

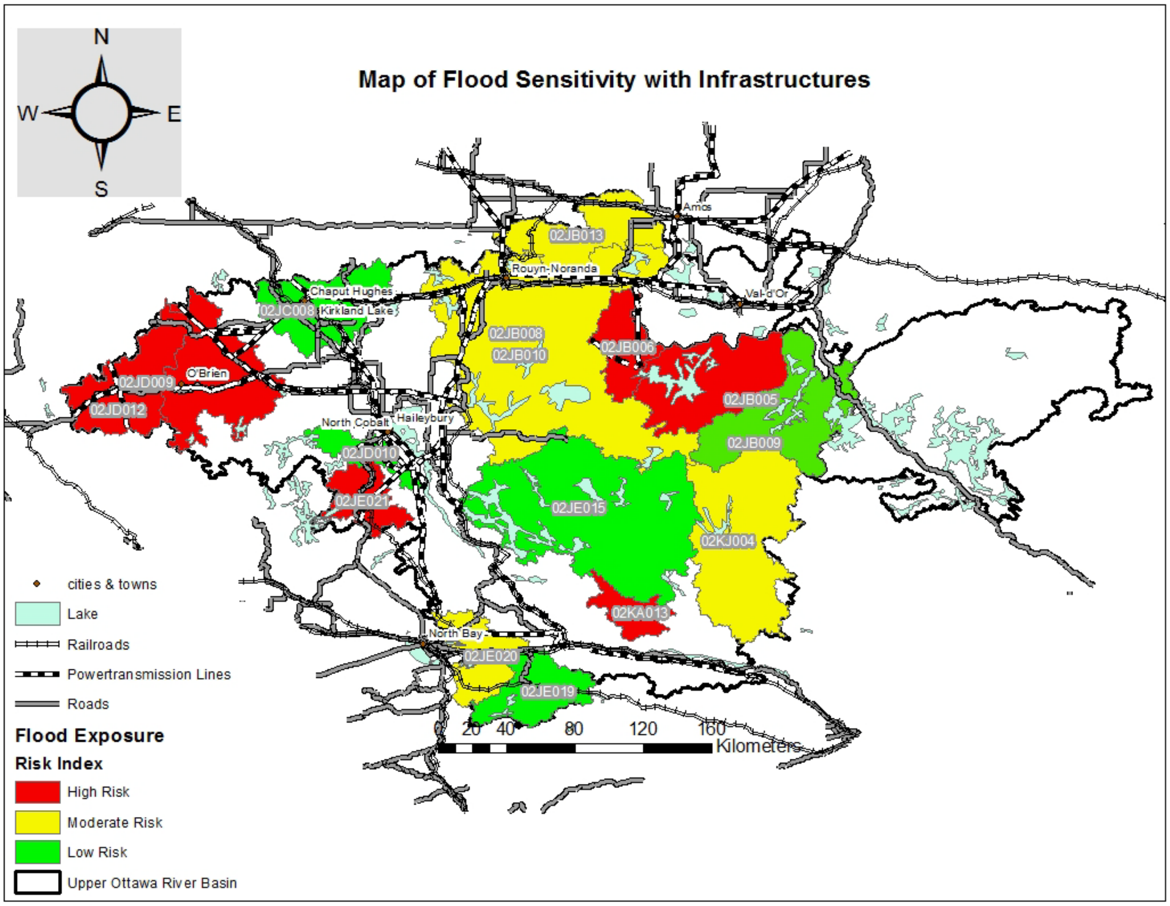

Figure 5-7: The map of major roads, rail ways, and power transmission lines overlay to the flood exposure of the Upper Ottawa River Basin

These infrastructure networks are dense in the north and west of the Upper Ottawa River Basin particularly in 02JE020, 02JC008, 02JB008 and 02JB013 sub-catchments. It is clear that the infrastructure is built as a corridor link between high populated cities such as North Bay, Hailey Burry, Rouyn-Noranda, and Amos. To evaluate the infrastructure sensitivity, the cumulative length of the infrastructure networks was calculated for each sub-catchment. To compare the flood sensitivity of these sub-catchments the density of infrastructure (km per km^2) was used.

After analyzing the population and the infrastructure as the sensitivity factors, the aggregated sensitivity map to flood was constructed by overlaying these two layers. As Figure 5-8 illustrates, 02JB005, 02JB006, 02JB008, 02JB013, 02JC008, 02JD010, and 02JE020 were identified as highly sensitive sub-catchments to flood in the Upper Ottawa River Basin.

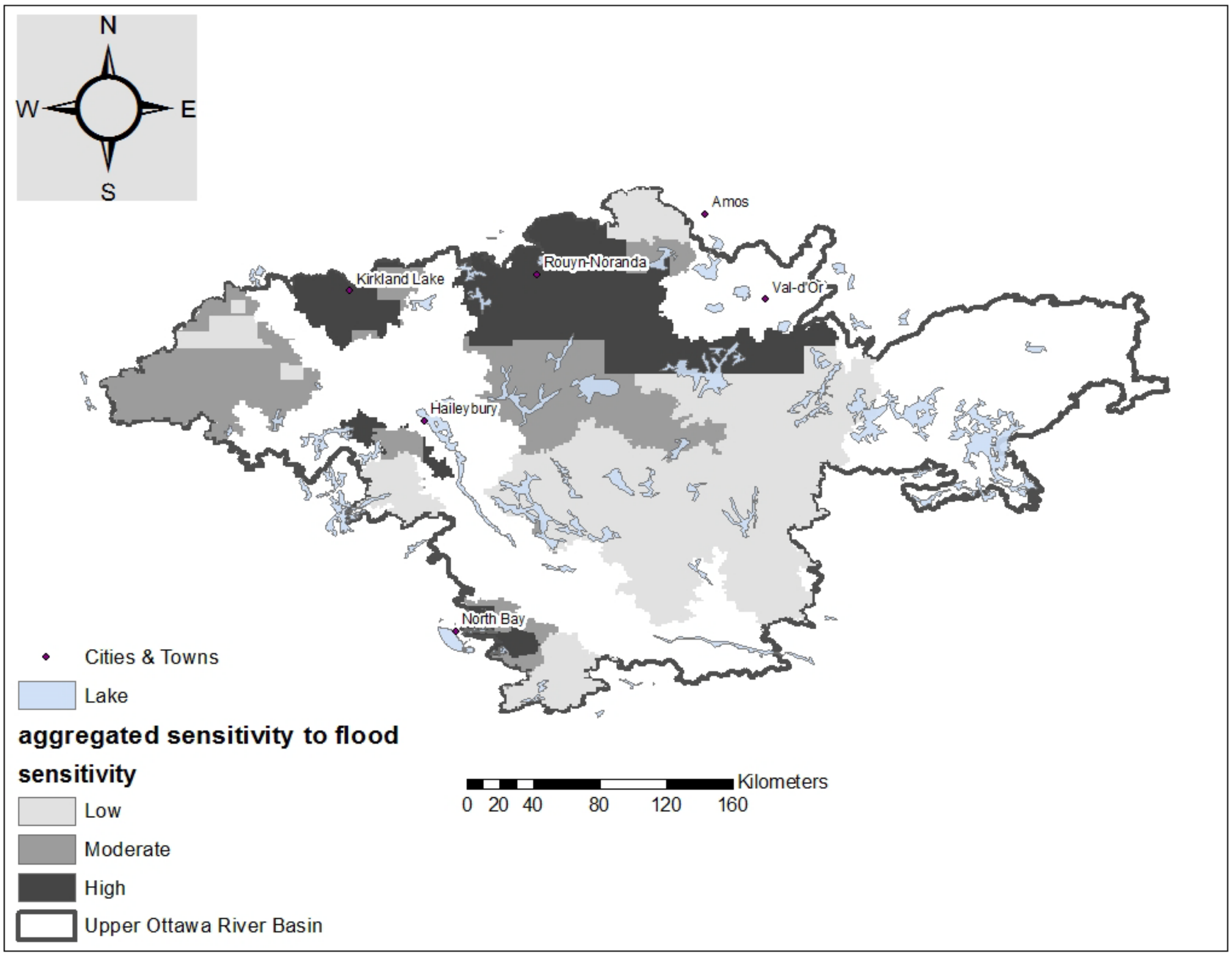

Figure 5-8: The aggregated sensitivity map of the Upper Ottawa River Basin to flood.

This means that the consequences of flood can be significant in these seven sub-watersheds. North Bay, Kirkland Lake and Rouyn-Noranda are located in these highly sensitive watersheds to flood. Before analyzing adaptive capacity and introducing its indicators, the two layers of exposure and sensitivity were aggregated. By combining the exposure and the sensitivity, decision makers can observe the most susceptible locations where the risk and the physical damages of flood are significant. The flood hazard map is shown in Figure 5-9.

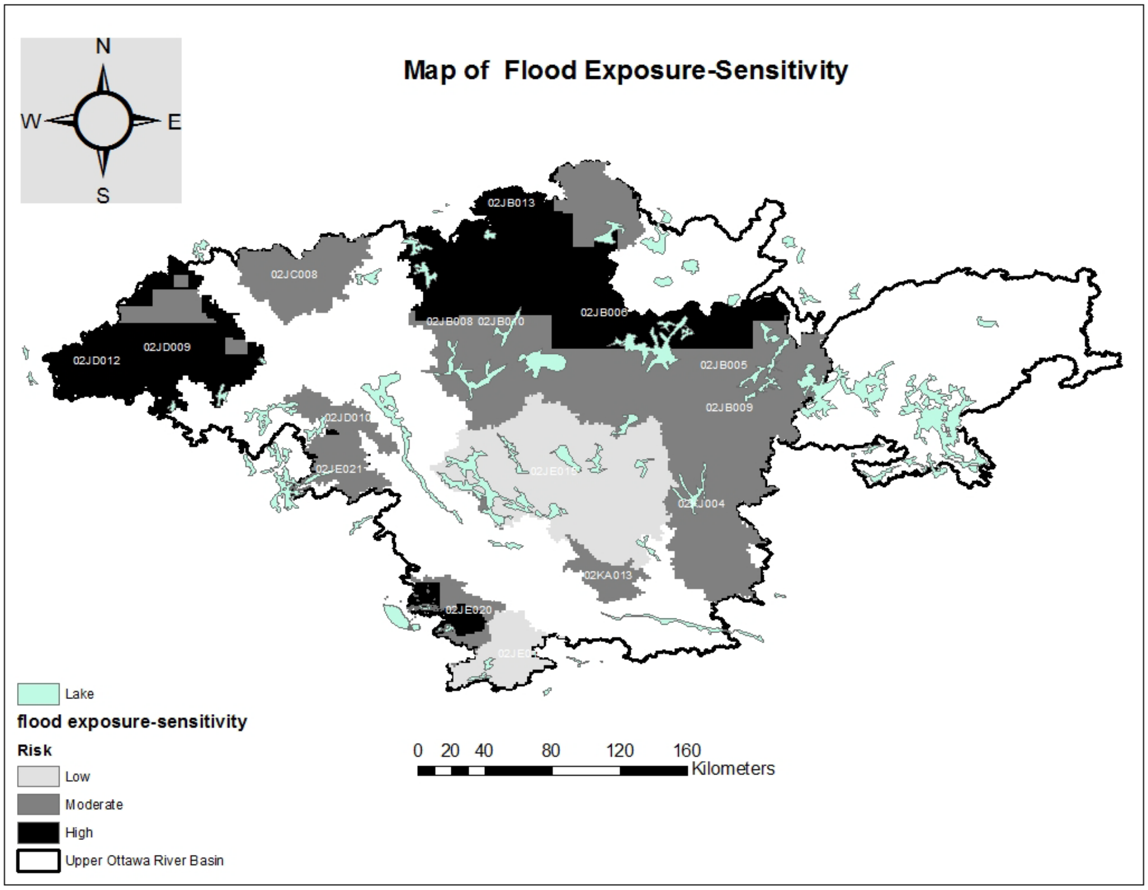

Figure 5-9: The flood hazard map in the Upper Ottawa River Basin.

5.2.3 Flood Adaptive Capacity Maps

Adaptive capacity is the distinguishing component of the vulnerability framework, which contains all human aspects of the study. Due to the complexity of human features, identifying and evaluating adaptive capacity in a system is the most challenging part of the vulnerability assessment, which is achieved by a set of appropriate social and economic indicators. However, there are no universal factors that can be applied everywhere in every situation as adaptive indexes. Therefore, adaptive capacity of each society to potential hazards should be analyzed by social and environmental scientists with respect to the scale of study and based on complex social characteristics, availability and quality of information. Economic capacity, knowledge capacity, institutional capacity, cultural capacity, and governmental capacity (fair local or national government) are some of these factors that can reveal social characteristics and thus construct a better image of possible public reactions in a disaster and recovery time. In this research, economic capacity, knowledge capacity, and age are considered as adaptive capacity for flood.

5.2.3.1 Economic Capacity

In general, systems (communities, individuals, and households) with diverse sources of income and better financial situation have a higher capacity to cope with a disaster and its consequences. Low income households, due to lack of financial support and lower levels of savings, cannot protect themselves and their assets from disasters. These people generally live in low-quality houses and have less interaction with society. Thus, the recovery time for individuals with lower levels of income takes longer in comparison with wealthy people. In this study, as Figure 5-10 depicts, the median household income was investigated as a proxy for analyzing the economic capacity in household and sub-catchment scale.

To facilitate comparison of the economic capacity, households of different communities within the Upper Ottawa River Basin were categorized into three levels based on their status. The threshold for the lowest level should basically be determined by the definition of the poverty line. In Canada, the poverty line is not officially defined. Therefore, the Low-Income Cut-Offs (LICOs) published by Statistics Canada is typically used instead of poverty line. The LICO indicates the level of income at which a family will likely allocate a larger share of its income on basics of life (food, shelter, and clothing) compared to an average family (Statistics Canada, Income Research Paper Series).

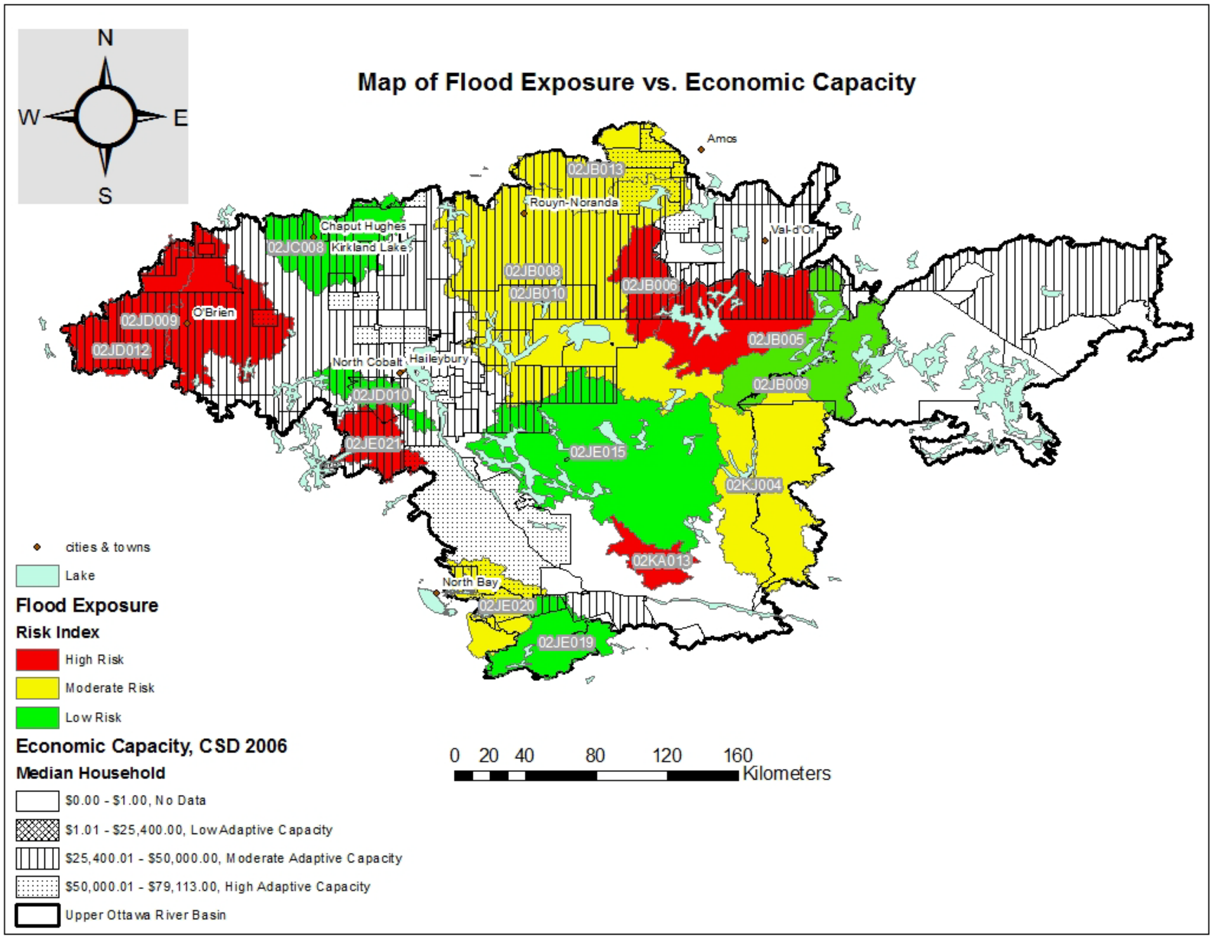

Figure 5-10: The economic adaptive capacity map of the Upper Ottawa Basin illustrating the median household income overlaid on the flood risk map.

Table 5-2 shows before-tax LICO information based on population of a community and family size. From Table 5-2, the threshold was selected for a family size of three (in average) in a community with less than 30,000 populations for the year 2006. Based on this threshold, households with an income less than $25,400 will be recognized as low economic adaptive capacity. It should be emphasized that this amount is only enough to provide the basics of life. Therefore, even households categorized within moderate economic capacity with the income between $25,400 and $50,000 in Figure 5-10, have not much chance to invest in their resilience capacities. As Figure 5-10 shows, households in many sub-watersheds such as 02JB013, 02JC008, 02JD009, 02JD010, 02JD012, 02JE020, and 02JE21 have moderate economic capacity.

Table 5-2: Before Tax Low Income Cut-offs (LICOs, 2006) calculated based on 1992 data.

	Population of Community of Residence				
Family size	500,000+	100,000-499,999	30,000-99,999	Less than 30,000	Rural
1	$21,202	$18,260	$18,147	$16,605	$14,596
2	$26,396	$22,731	$22,591	$20,671	$18,170
3	$32,450	$27,945	$27,773	$25,412	$22,338
4	$39,399	$33,930	$33,721	$30,855	$27,122
5	$44,686	$38,482	$38,245	$34,995	$30,760
6	$50,397	$43,402	$43,135	$39,469	$34,694
+7	$56,110	$48,322	$48,024	$43,943	$38,626

Source: Statistics Canada’s publication number 75F0002M, Table 2.

5.2.3.2 Knowledge Capacity

The ratio of people with a college degree to total population was considered as a measurement of knowledge capacity. For the comparison, again, the results were divided into three classes: the highest tercile as a high knowledge capacity, the middle tercile as a moderate knowledge adaptive capacity, and the lowest tercile as a low knowledge adaptive capacity. As Figure 5-11 illustrates, among the high flood risk areas, people living in 02JB005, 02JB006, 02JD012 and 02JE021sub-catchments have moderate and low knowledge adaptive capacity. In the sub-catchments such as 02JB008, 02JB010, 02JB013, and 02JB020 with moderate exposure, the knowledge capacity is low or moderate. The knowledge capacity in North-Bay and Rouyn-

Noranda, two of the most populated cities within the case study, is high and moderate, respectively.

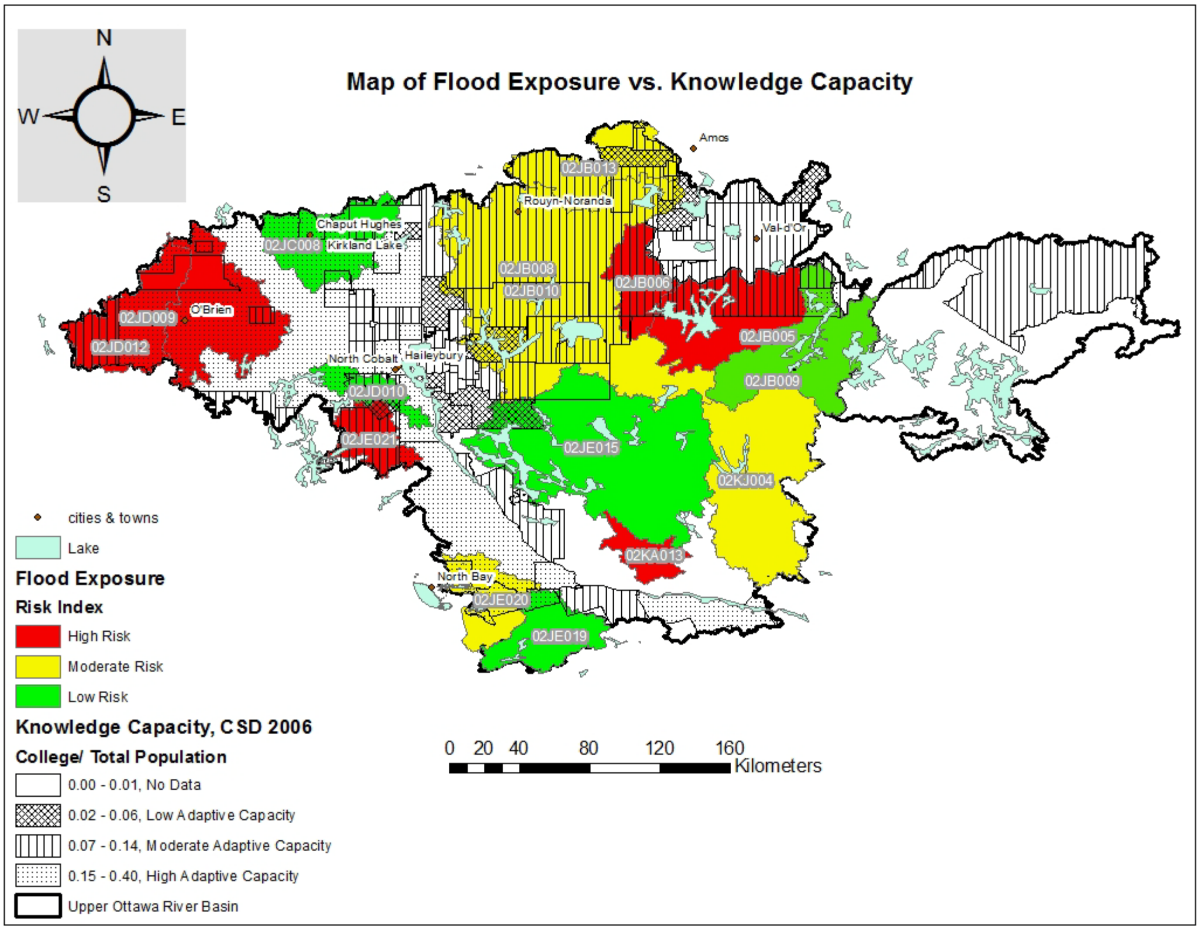

Figure 5-11: The knowledge adaptive capacity of the Upper Ottawa River Basin; the ratio of people with college certificate to total population is overlaid on the flood risk map.

5.2.3.3 Age

Generally, the elderly and children are considered as vulnerable groups in sudden disasters such as floods. Physical mobility and health condition are important factors in preparing and responding to disasters. People over 65 years old are more likely to have difficulties in moving quickly in rescue and evacuation operations in comparison with younger people and are less likely to help other household members, especially children. It is also common among the elderly to have chronic health-related problems that makes the recovery time longer. Also, children less than 14 years old have the same problem of physical weakness in moving, which put them at higher level of risk in crucial disaster times. In Figure 5-12, by using census data 2006, the ratio of sum of population with age of less than 14 and over 65 years to total population is depicted in the Upper Ottawa River Basin. This ratio is divided into three levels to show high, moderate, and low age adaptive capacity.

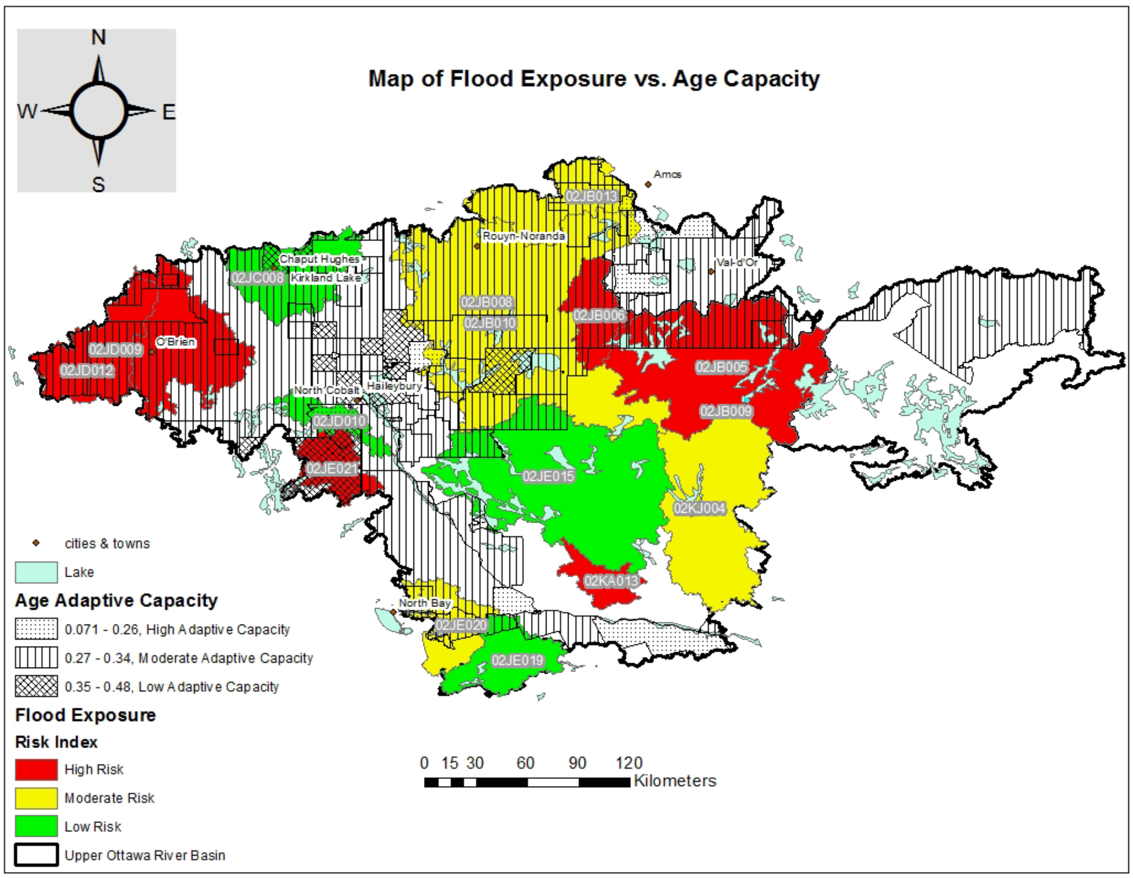

Figure 5-12: The age capacity map depicting the ratio of sum of population with the age of over 65 years and less than 14 years to total population in the Upper Ottawa River Basin.

Before building the vulnerability map, all the three adaptive capacity indicators including economic capacity, knowledge capacity, and age were overlaid to construct the aggregated adaptive capacity map. Most parts of the Upper Ottawa River, as Figure 5-13 demonstrates, were identified with moderate adaptive capacity. Only small parts of the Upper Ottawa River Basin including the upstream of North Bay and the upstream Haileybury were identified with high adaptive capacity.

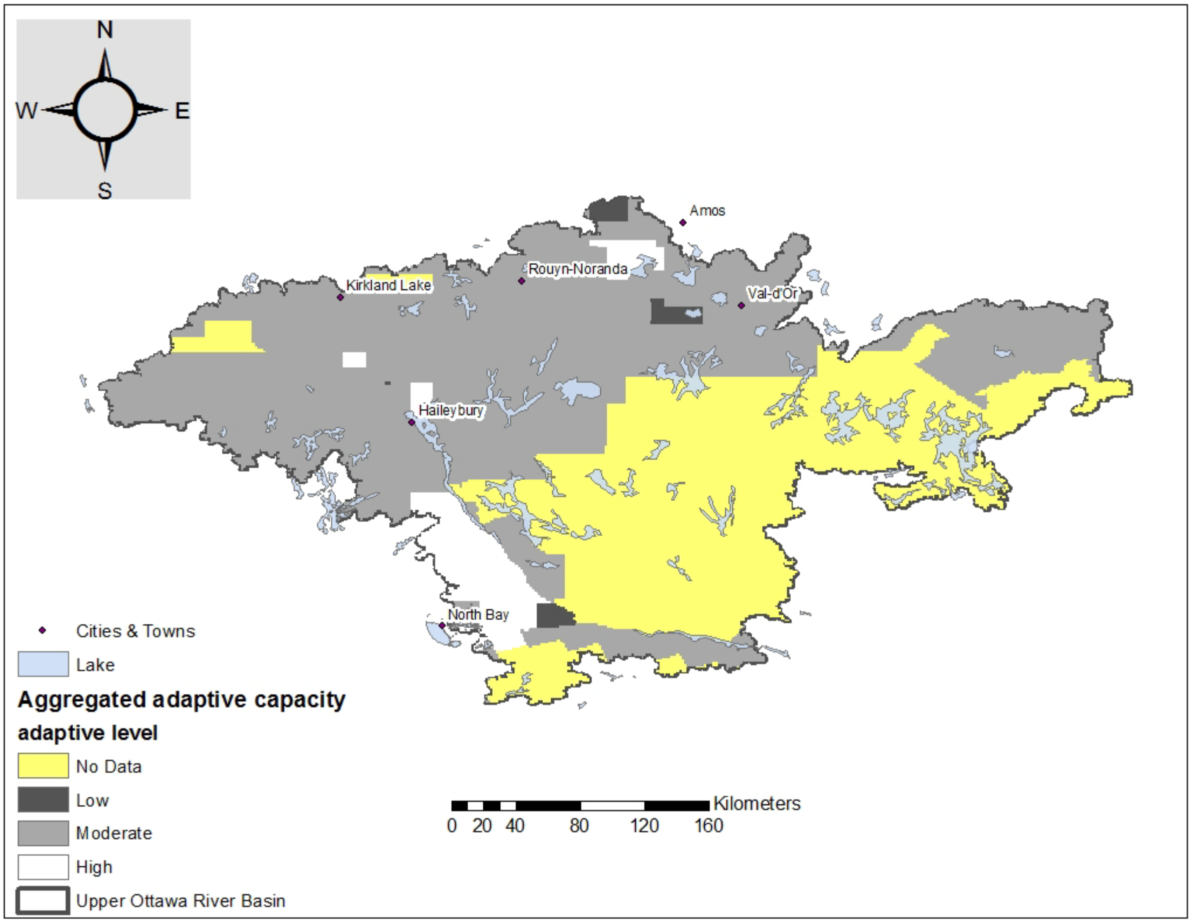

Figure 5-13: The map of aggregated adaptive capacity to flood in the Upper Ottawa River Basin.

5.2.4 Flood Vulnerability Map

The flood vulnerability map was constructed by combining the flood exposure and sensitivity with the adaptive capacity. Therefore, in addition to the flood index, other demographic and socio-economic information, including population, infrastucture, education, economic status, and age, were summarized in the vulnerability map. The intersection of high exposure-sensitivity and low or moderate adaptive capacity leads to high vulnerability. The combination of moderate exposure and low adaptive capacity also led to high vulnerability.

For aggregating exposure, sensitivity, and adaptive capacity indicators, there is a tendacy to allocate appropriate weight for different indicators to convey the importance of the parameters forming vulnerability. The weighting process is subjective and these weights are typically developed using local knowledge and experts judgement. Often, the availablity of expert knowledge is limited particularly in small communities. Therefore, in this study, equal weights were applied to indicators in calculating total vulnerability score. It is worth to mention that dissagregated indexes and the process of indentification of different socio-economic indicators that contribute to vulnerability can assist policy makers in allocating the required resources for improving particular socio-economic indicator.

As Figure 5-14 illustrates, 02JB013, 02JD012, and part of 02JB005, 02JB006, 02JB008, 02JB010, 02JE020, and small part of 02JC008 were specified as highly vulnerable sub-watersheds to flood in the Upper Ottawa River Basin. North Bay and Rouyn-Noranda are located in high vulnerable areas. 02JD009, 02JE021 and part of 02JD010 were identified as moderate vulnerable areas. Comparing the vulnerability map to the hazard map (Figure 5-9) reveals how hazard/impact modelling can mislead decision makers in prioritizing areas for implementing mitigation plans and how integrated vulnerability assessment provides a valuable insight for policy makers.

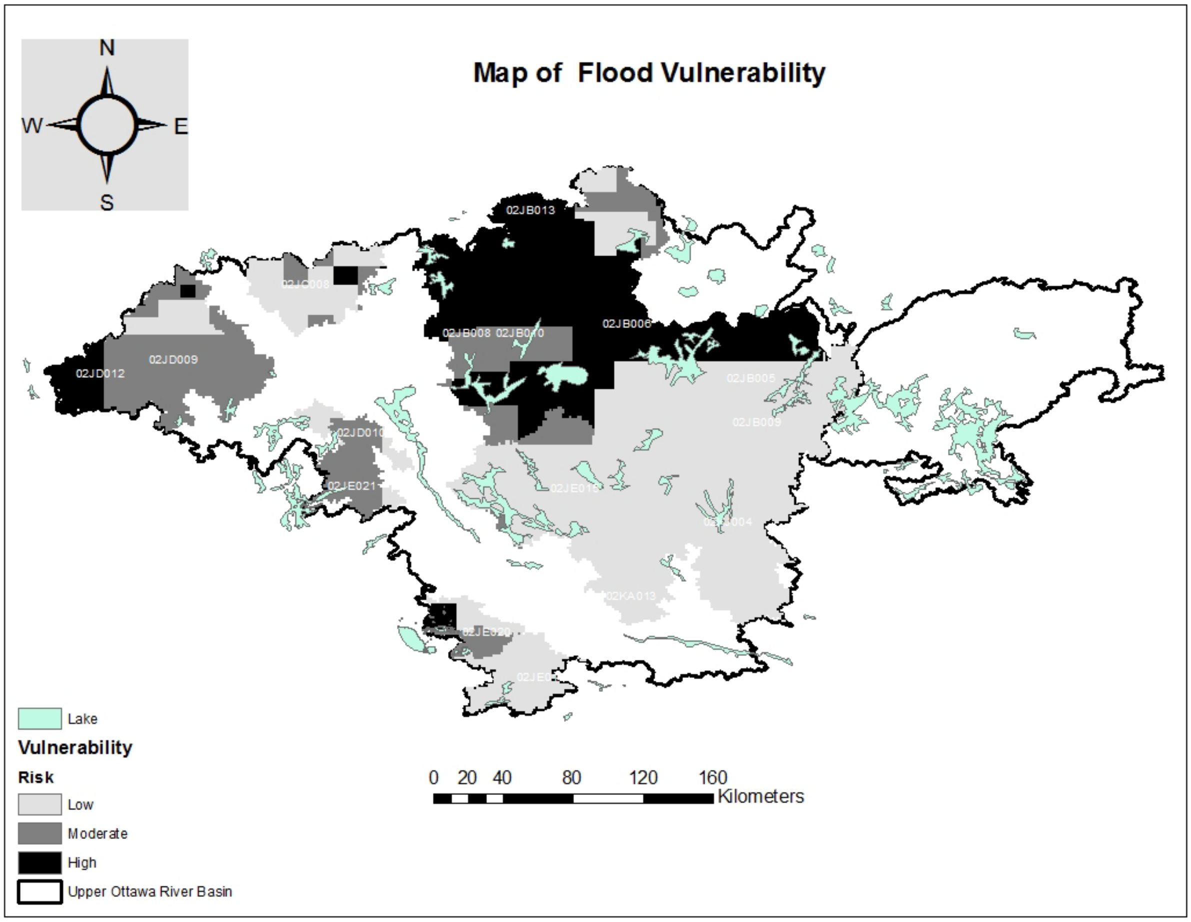

Figure 5-14: The flood vulnerability map of the Upper Ottawa River Basin. The intersection of high exposure-sensitivity and low or moderate adaptive capacity leads to high vulnerability. Versus, the intersection of low exposure-sensitivity and high or moderate adaptive capacity causes low vulnerability.

The most exposed sub-watersheds to flood are not necessarily the most vulnerable ones to flood. For example, 02JD009, 02JE021, and 02KA013 are highly exposed to flood based on Figure 5-2. However, most of these regions have moderate adaptive capacity (Figure 5-13) which leads to moderate vulnerability (Figure 5-14). Figure 5-15 shows the relatively populated cities in the Upper Ottawa River Basin and the level of their vulnerability. The identification of different socio-economic indicators contributing to vulnerability are more helpful rather than a single score and can assist policy makers as a supporting decision making tool for mitigation planning.

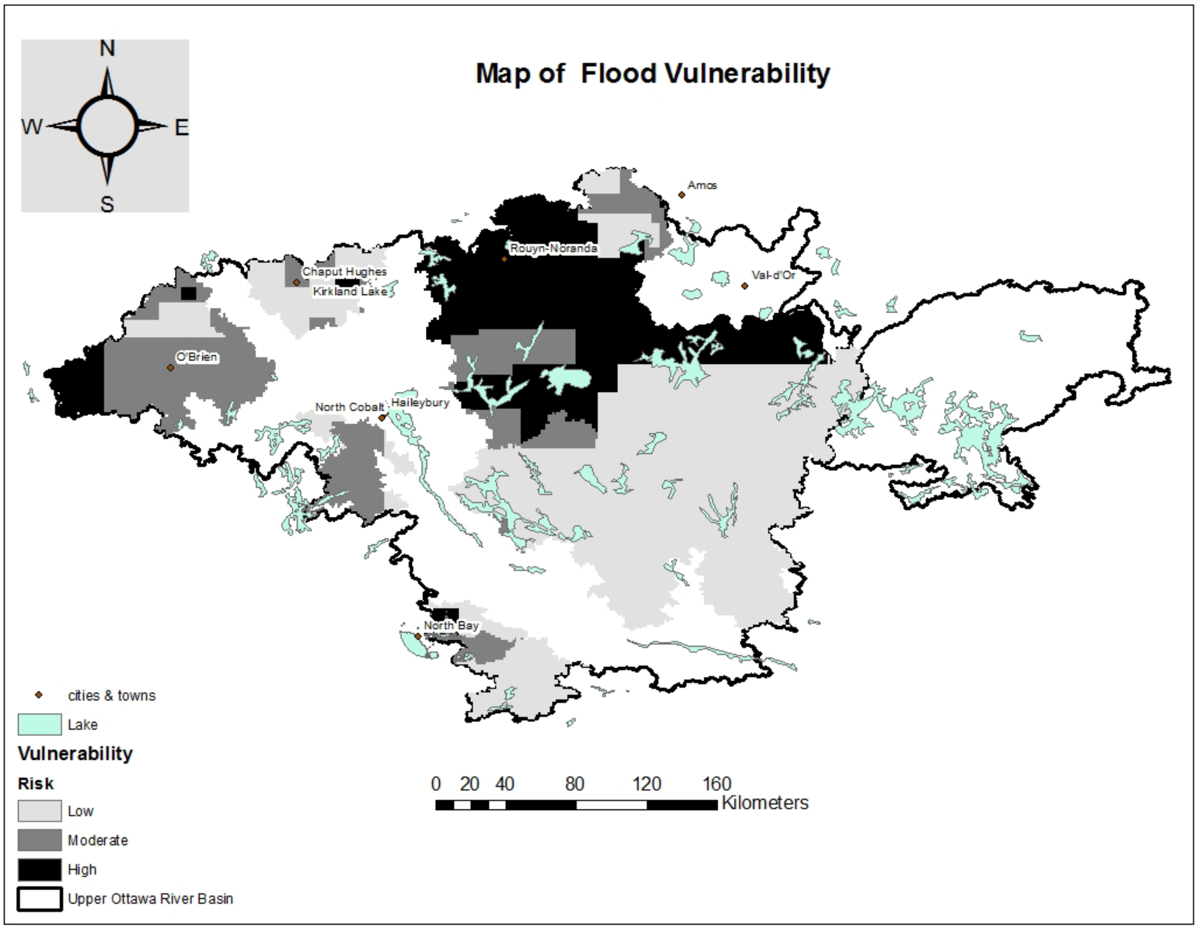

Figure 5-15: Populated cities and their flood vulnerability in the Upper Ottawa River Basin.

5.3 Drought Vulnerability Assessment

5.3.1 Drought Exposure Map

Drought is a frequent extreme event that has severe impacts on local and national livelihoods due to its wide spatial dimension. In this study, the drought exposure index was developed by calculating the annual minimum 7-day discharge that occurs on average every 10 years ($Q_{7,\ 10}$), which was then divided by the mean annual minimum 7-day discharge (MALF). The obtained dimensionless ratio was introduced as the drought exposure index and was categorized into three terciles to facilitate comparison of drought risk among sub-catchments. For frequency analysis, 16 gauging stations that have at least 23 years recorded data were selected to obtain historical low-flow data. The drought exposure index is tabulated in Table 5-3.

Table 5-3: The results of drought exposure: red, green, and yellow colours represent high, low, and moderate drought risk.

#	station ID	$(Q_{7,10})$	(MALF)	$(Q_{7,10})/(MALF)$
1	02JB005	45.39	81.15	0.56
2	02JB006	52.93	100.14	0.53
3	02JB008	127.92	197.92	0.65
4	02JB009	16.98	60.24	0.28
5	02JB010	132.53	210.07	0.63
6	02JB013	7.43	10.56	0.70
7	02JC008	2.38	3.95	0.60
8	02JD009	4.07	11.95	0.34
9	02JD010	4.40	13.27	0.33
10	02JD012	0.84	3.03	0.28
11	02JE015	2.75	9.86	0.28
12	02JE019	1.52	4.00	0.38
13	02JE020	0.74	2.16	0.34
14	02JE021	0.20	1.02	0.19
15	02KJ004	7.12	20.00	0.36
16	02KA013	0.43	1.23	0.351

The drought exposure in the Upper Ottawa River Basin is mapped in Figure 5-16; 4 sub-watersheds of 02JB009, 02JD012, 02JE015, and 02JE021 were identified as the high drought risk areas. There are also 5 sub-catchments of 02JD009, 02JD010, 02JE020, 02KJ004, and

02KA013 that were categorized with moderate risk of drought in the Upper Ottawa River Basin based on the drought exposure index. North Bay and Haileybury are located in these moderate risk areas.

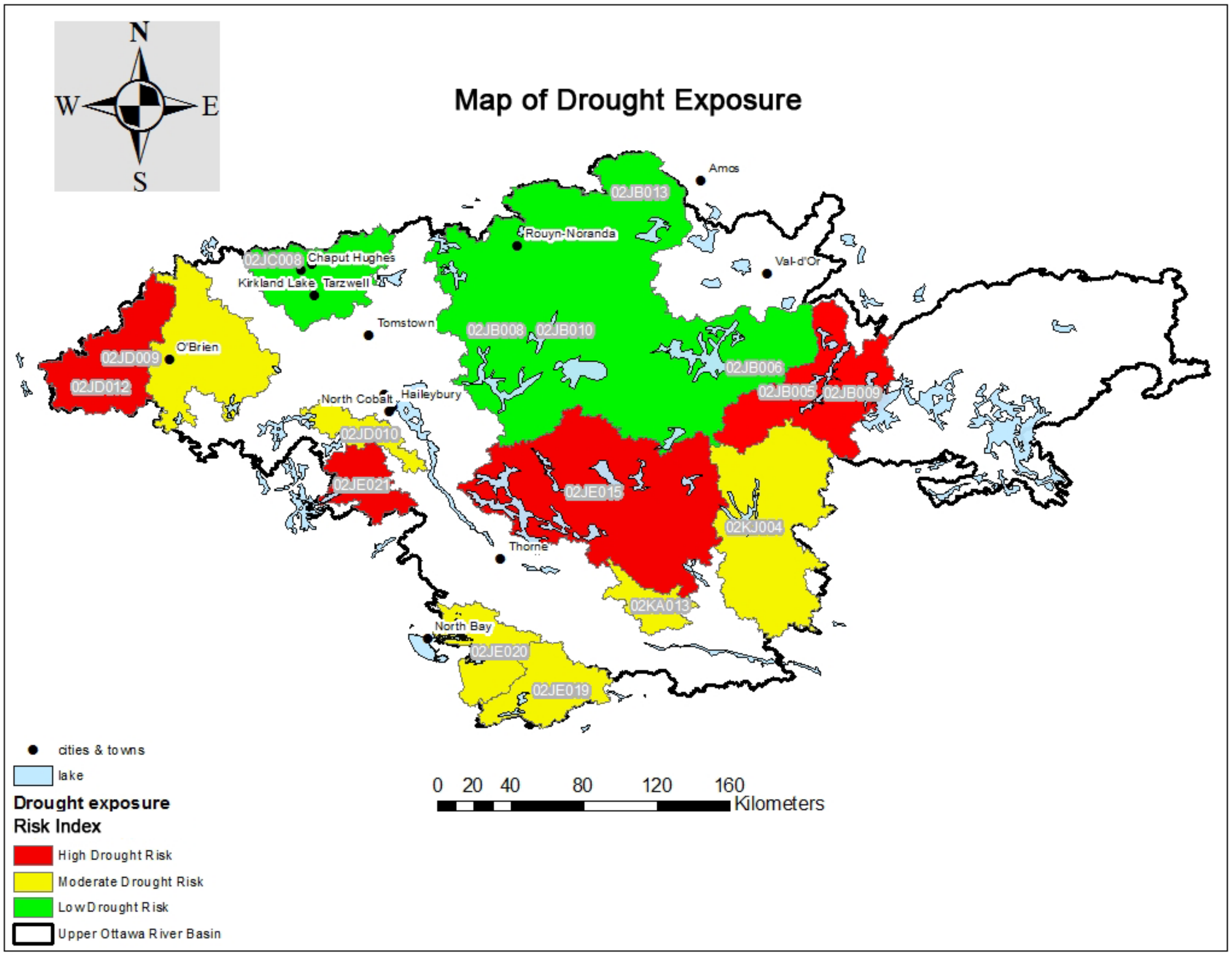

Figure 5-16: The map of drought exposure of the Upper Ottawa River Basin. Red, yellow, and green colours show high-risk, medium-risk, and low-risk drought exposure.

5.3.2 Drought Sensitivity Map

To evaluate how serious the socio-economic consequences of the possible drought might be, information of the distribution of population, the places with major population, and also the location of croplands were used.

5.3.2.1 Sensitivity Factor of Population

Population is a proxy data that can be representative of water demand, which is very significant issue during drought period. Therefore, the number of people who might be influenced by drought events can be considered as a sensitivity factor to evaluate its destructive impacts on a society.

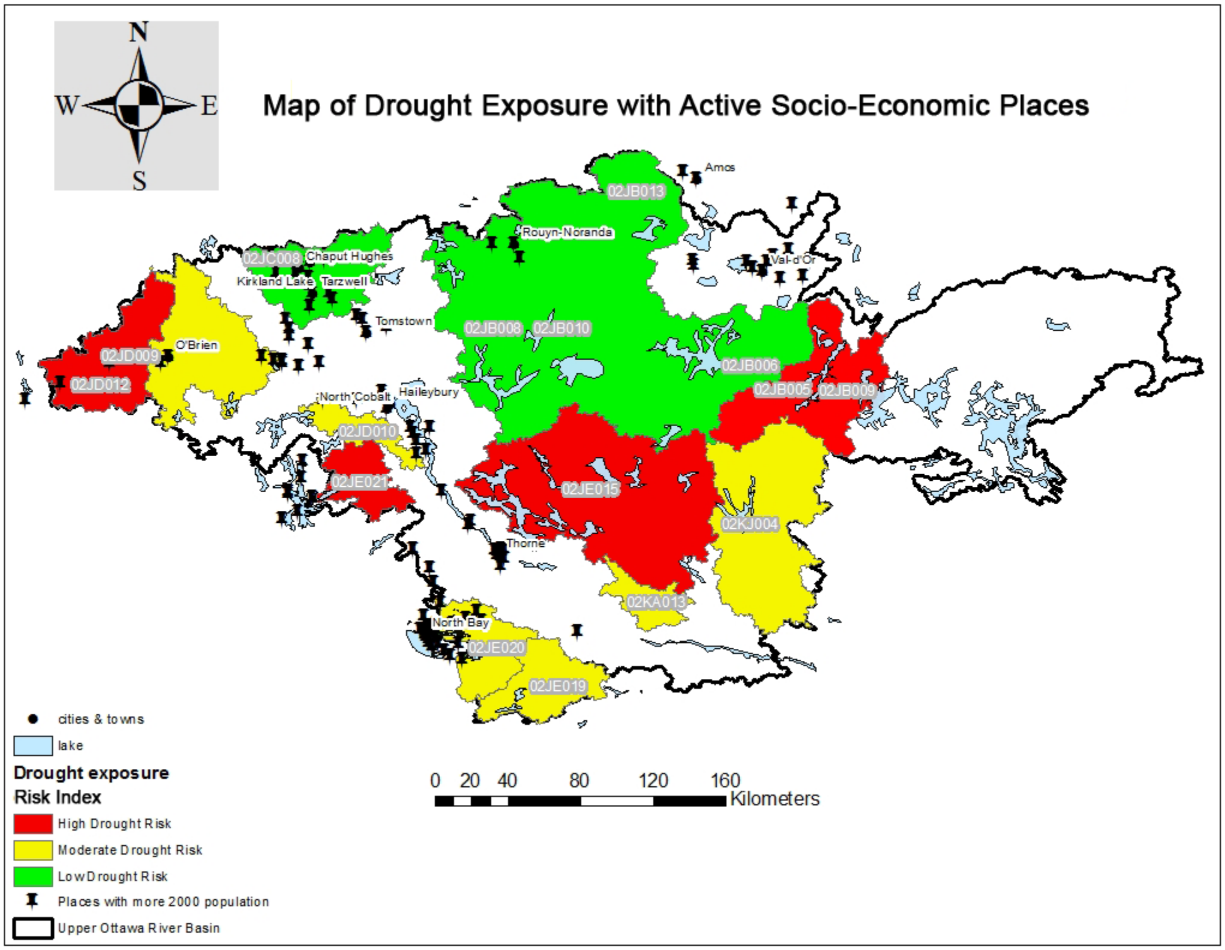

Figure 5-17: The drought exposure map and regions with more than 2000 population in the Upper Ottawa River Basin based on Census Subdivision (CSD) 1996.

Figure 5-17 shows that the major human activities in the Upper Ottawa River Basin are placed in north and west of the region and can be summarized in four major areas; in Ontario North Bay Area, Haileybury Area, and Kirkland Lakes Area, and in Quebec Rouyn-Noranda Area. By studying the distribution of population of the Upper Ottawa River Basin who are exposed to drought risk, it was found that there is only one high drought risk sub-watershed, 02JD012, because of having medium population between 1000 to 5000 people. Among the moderate drought risk areas, North Bay, which is located within the 02JE020 sub-catchment, and also Haileybury, which is situated next to the 02JD010 sub-watershed, are highly sensitive with population between 10,000 to around 54,000. As Figure 5-18 shows, there is no significant sensitivity with other high risk or moderate risk areas due to their low population.

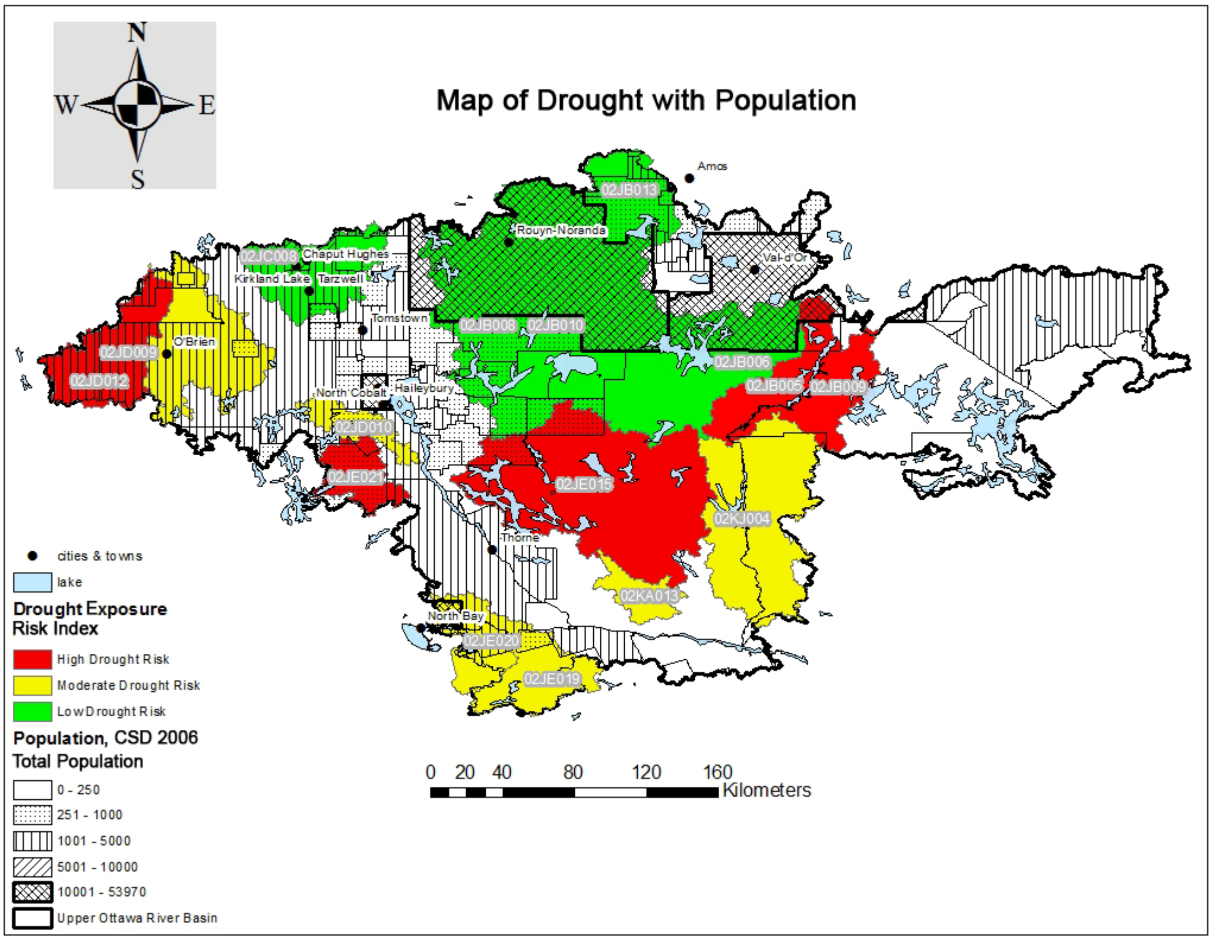

Figure 5-18: The sensitivity map of population distribution overlaid on drought map in the Upper Ottawa River Basin (census data, CSD 2006).

5.3.2.2 Sensitivity Factor of Croplands

One of the important factors indicating the severity of the impacts of the drought is the land-cover. Agriculture, fishery, and recreation industries are directly influenced by hydrological drought's impacts.

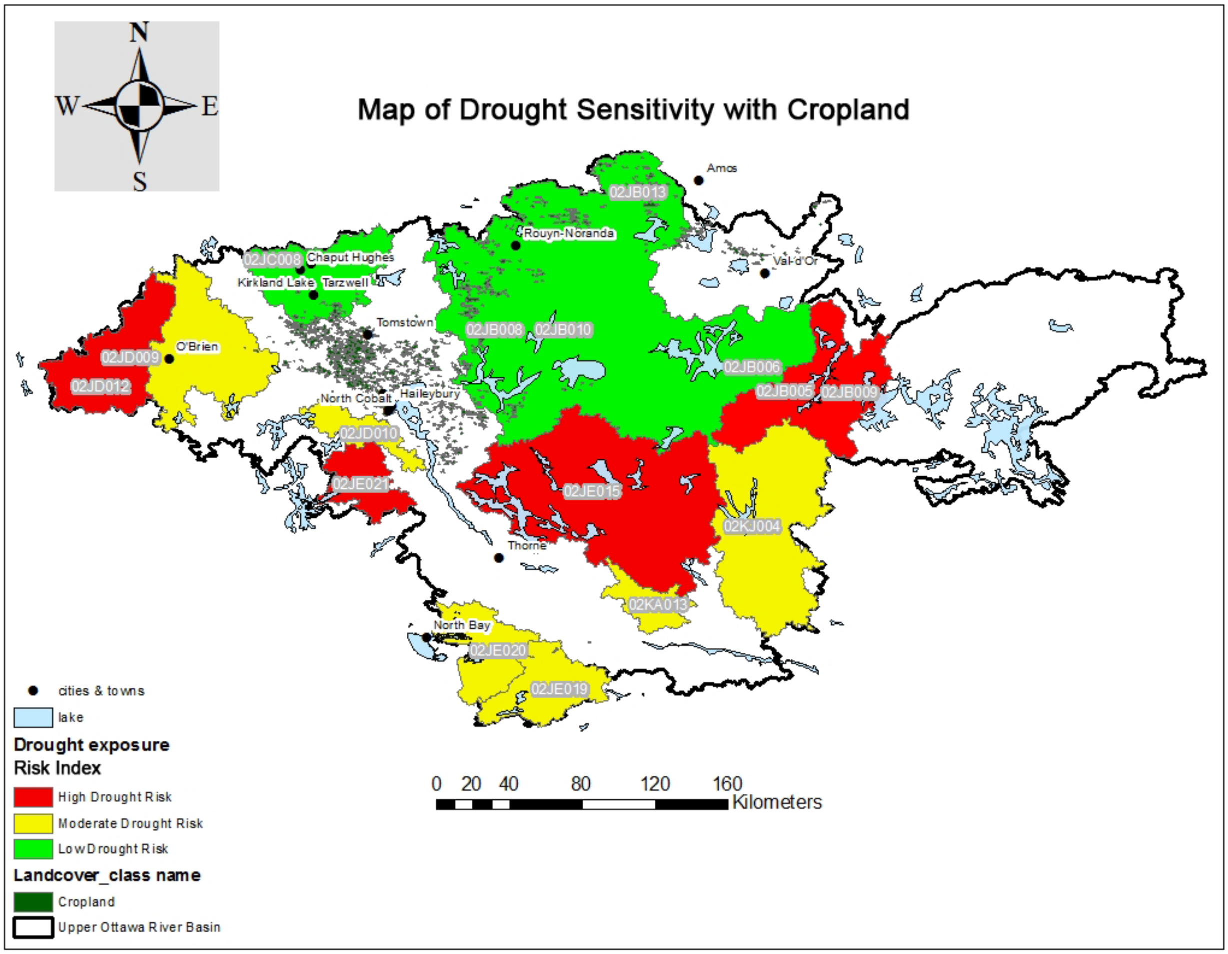

Figure 5-19: The sensitivity map of cropland overlaid on drought map in the Upper Ottawa River Basin.

The location of cropland was evaluated with level of drought hazard. Figure 5-19 shows the location of the cropland in the Upper Ottawa River Basin. The majority of the croplands are located in the Temiskaming Shores region. These lands are not precisely located in identified risky areas. However, since the nearby sub-catchments have high or moderate drought risk, these croplands can be expected to be susceptible to drought.

After analyzing the sensitivity factors of population and cropland, the exposure-sensitivity map was created by overlaying these two layers of information in the Upper Ottawa River Basin. Based on the exposure-sensitivity map, as Figure 5-20 illustrates, North Bay is located in the high-risk zone.

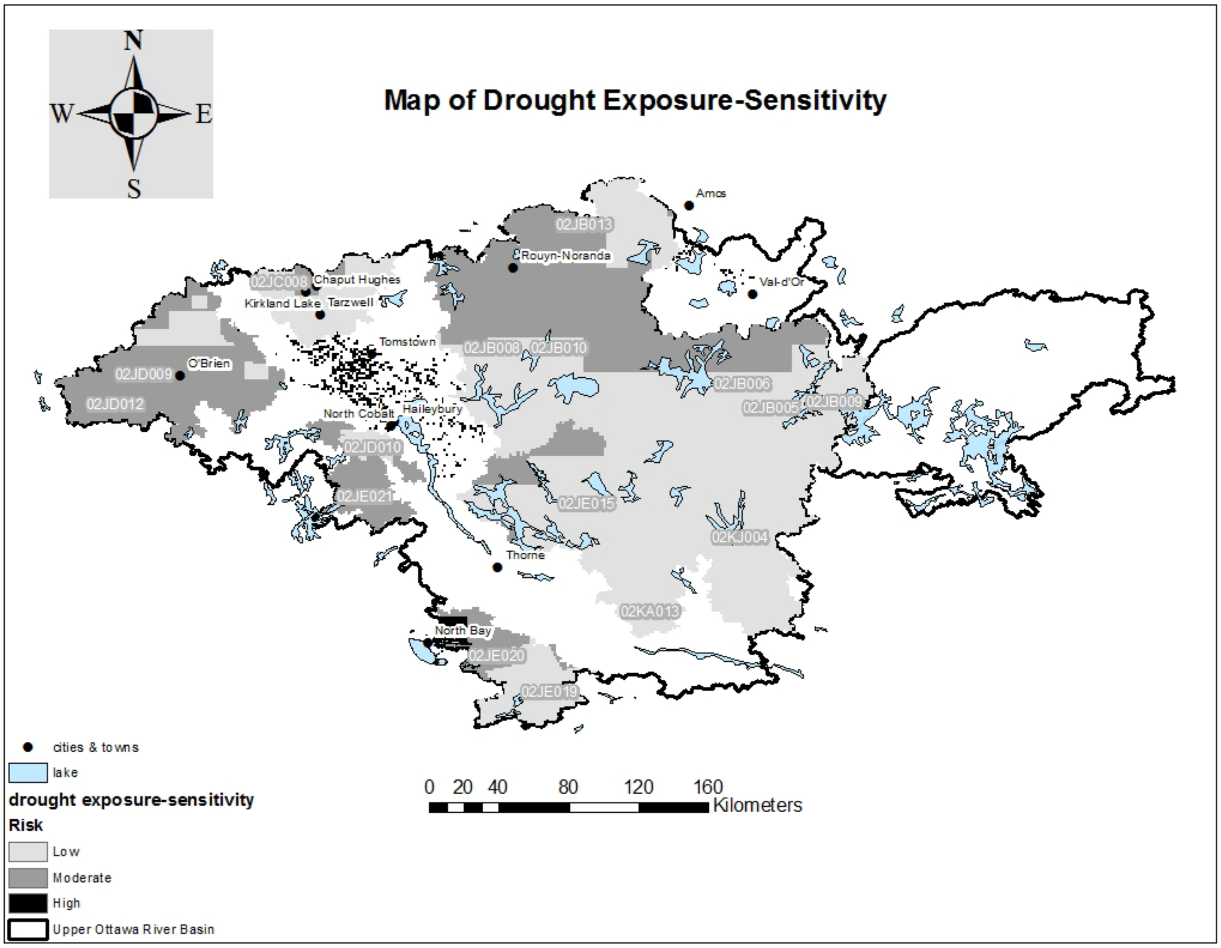

Figure 5-20: Map of drought exposure-sensitivity (hazard-impact) in the Upper Ottawa River Basin.

5.3.3 Drought Adaptive Capacity

Economic capacity and knowledge capacity were applied in household scale as adaptive capacity.

5.3.3.1 Economic Capacity

Similar to flood, a system with diverse source of income and better financial situation has the higher capacity to cope with a disaster. As Figure 5-21 shows, all the high sensitive sub-catchments of 02JD009, 02JD010, 02J012, 02JE020, and 02JE021 have moderate economic adaptive capacity.

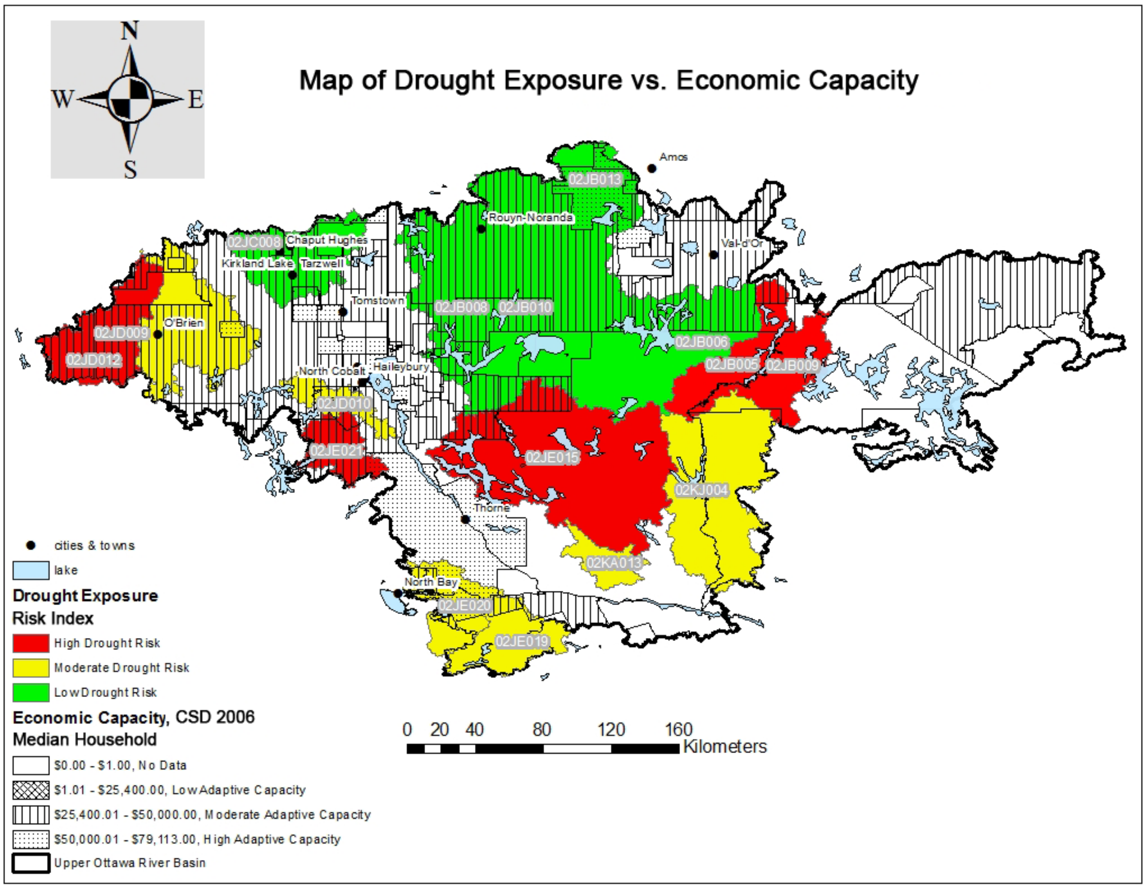

Figure 5-21: The economic adaptive capacity of the Upper Ottawa River Basin; Median household income overlays on drought risk map. All sensitive sub-watersheds to drought have moderate economic adaptive capacity.

The same census information of median household income from Statistics Canada (2006) and LICOs (Table 5-2) were used as economic capacity and its threshold, respectively.

5.3.3.2 Knowledge capacity

Local knowledge and previous experiences of coping with negative impacts of a natural hazard can be considered as a general adaptation. The level of education influences the access to information and sharing ecological information has a great impact on implementing and planning of mitigation strategies. It should be mentioned here that all institutional and non-institutional knowledge would be helpful and can be considered as knowledge indicators. Particularly in northern Canada, due to their lifestyle which communities still harvest natural resources, and due to lack of western institutions, all northern cultures retain a strong relationship with the environment. Accordingly, Aboriginals and First Nations are naturally able to detect and observe environmental variables and climate change.

In recent years, the value of indigenous ecological knowledge in implementation of sustainable development has been increasingly recognized by researchers (Nyong et al., 2007). However, using indigenous knowledge as a measurement of knowledge adaptive capacity needs more in depth knowledge from Indian and Native communities and more efforts to document their historical experiences in natural hazards.

The ratio of people who have a college degree to the total population was used as the knowledge adaptive capacity to drought and the obtained ratios were categorized in three levels. As the Figure 5-22 reveals, among the highly sensitive sub-catchments to drought, 02JE021 and 02JD010 were determined with moderate knowledge capacity and 02JE020, 02JD009 and 02JD012 were categorized with high knowledge capacity.

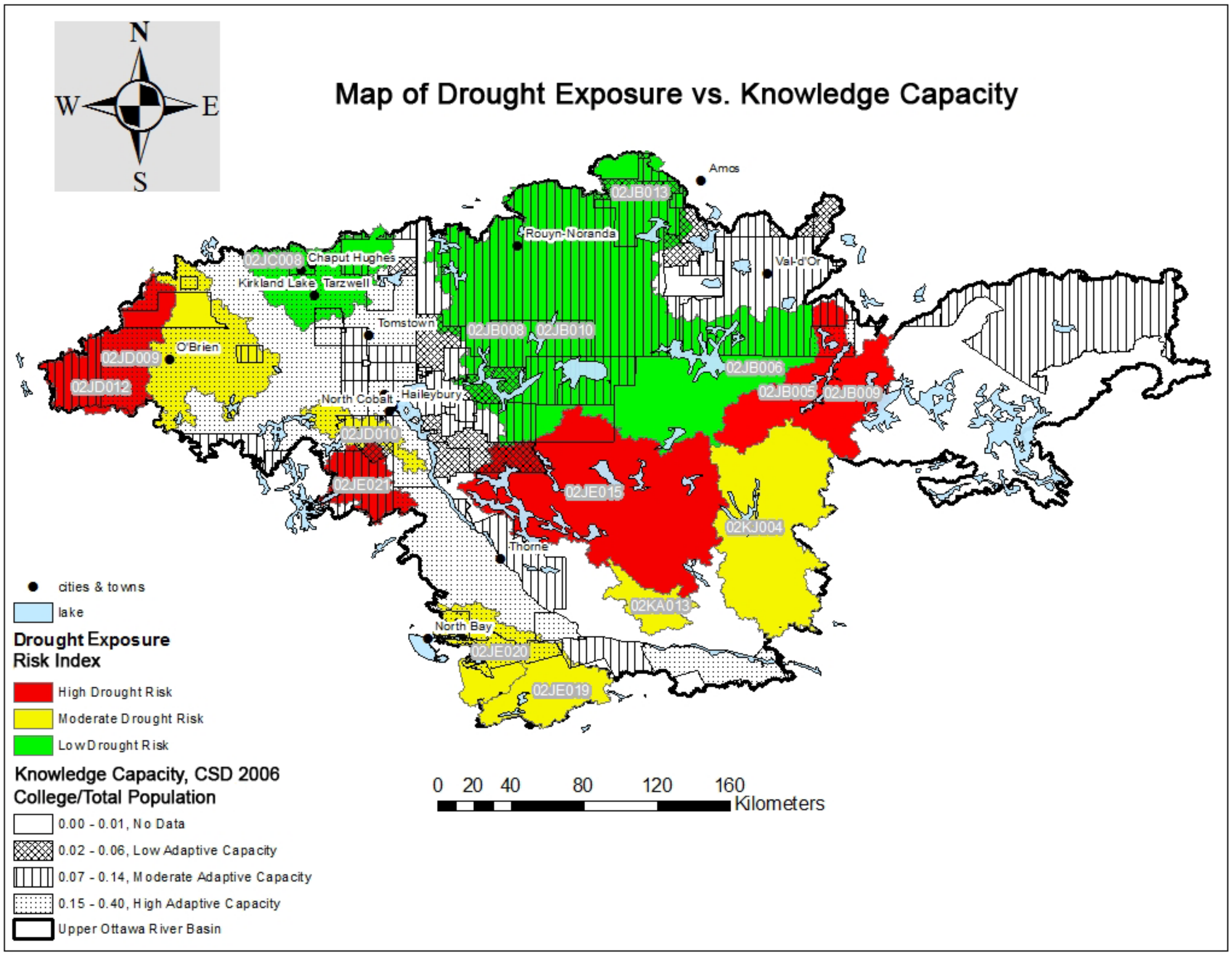

Figure 5-22: The knowledge adaptive capacity of the Upper Ottawa River watershed; the ratio of people with college certificate to total population overlays on drought risk map.

Aggregated adaptive capacity to drought is shown in Figure 5-23. The knowledge capacity and the economic capacity were overlaid to generate the aggregated adaptive capacity. Most parts of sub-catchments 02JB005, 02JB006, 02JB009, 02JD012, 02JB013, 02JE021, and 02JD010 were categorized as moderate adaptive capacity. In addition, small parts of 02JB008, 02JB010, and 02JE020 were specified as low adaptive capacity.

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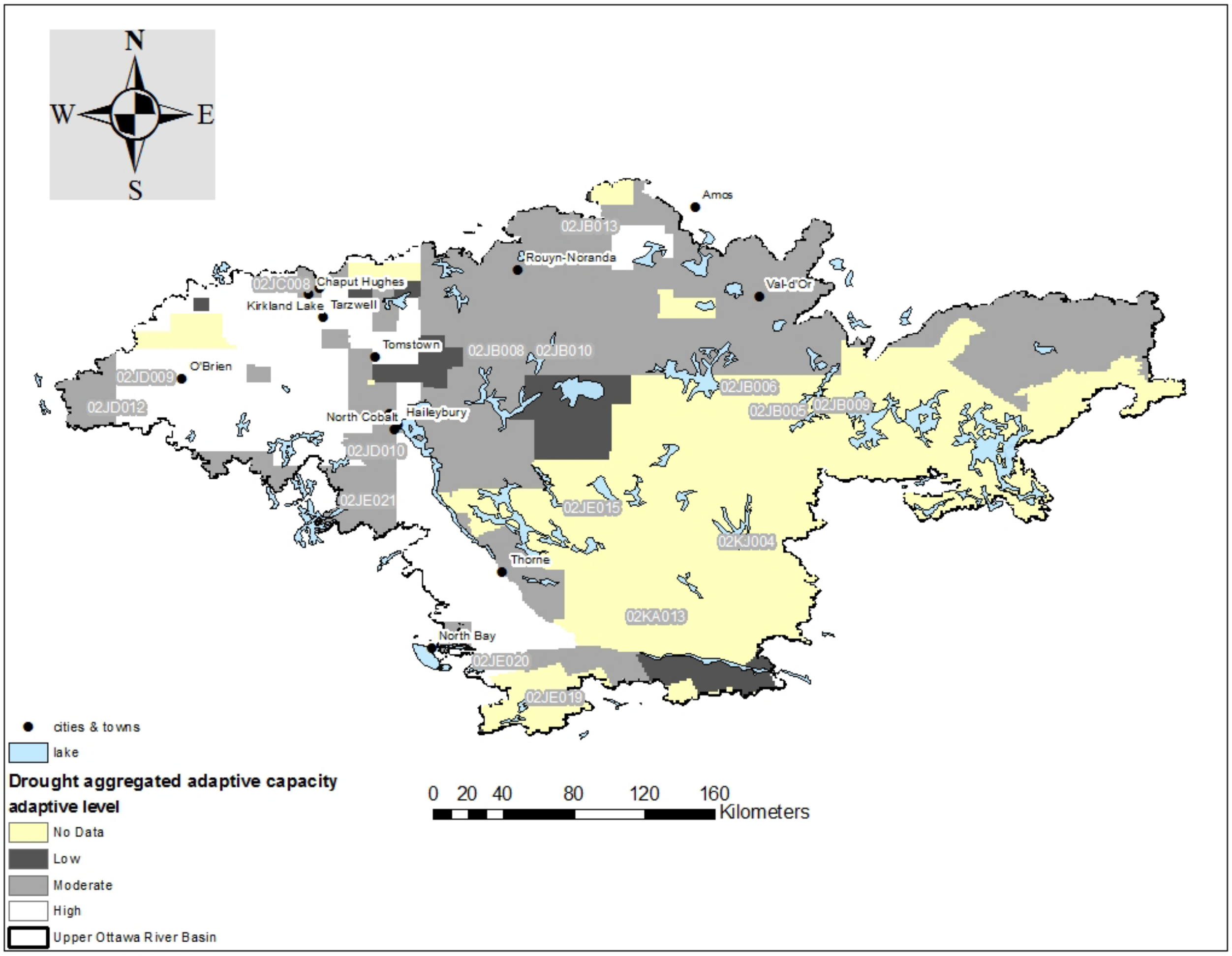

Figure 5-23: The map of integrated adaptive capacity to drought in the Upper Ottawa River Basin

5.3.4 Drought Vulnerability Map

Vulnerability map to drought was constructed by intersection of the exposure-sensitivity and adaptive capacity. By combining several layers related to exposure, sensitivity, and adaptation that were extracted from socio-economic data, the better estimation of the vulnerable areas was achieved. By comparing the vulnerability results with the drought exposure-sensitivity map (Figure 5-20), it is revealed that there is a substantive difference between the two models due to the influence and interaction of the social and economic components on the biophysical model. As Figure 5-24 demonstrates, by considering adaptation indexes as well as sensitivity factors, 02JE020 and part of 02JB010 were determined as highly vulnerable areas to drought. North Bay is located in 02JE020 and therefore it will be significantly affected by the negative consequences of a potential drought. In addition, although 02JD009 and 02JD010 had been identified with moderate drought risk in hazard-impact model, their vulnerability was determined low. The sub-catchments of 02JB005, 02JB006, 02JB008, 02JD012, and 02JE021 were determined with moderate vulnerability to drought and Rouyn-Noranda is a city identified with moderate vulnerability.

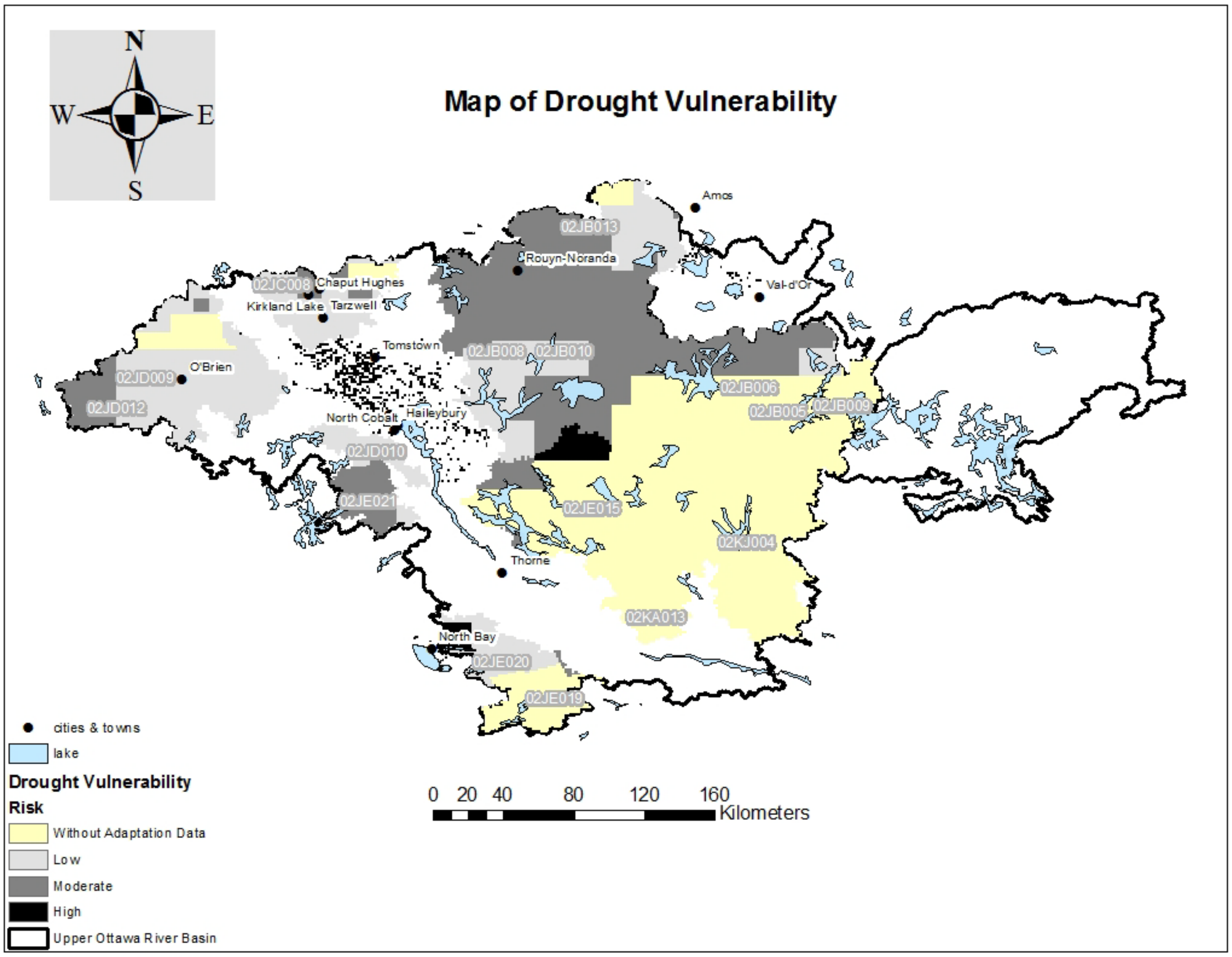

Figure 5-24: The drought vulnerability map of the Upper Ottawa River Basin.

5.4 Application of the Vulnerability Study in Decision Making

The structure of the vulnerability study consists of a wide variety of indexes that are able to evaluate different aspects of a system when subjected to an extreme shock. Therefore, it provides a powerful detection tool to prioritize resources, equipment, and operations in hazard mitigation action plans. Thus, decision makers can set their priority based on more comprehensive models that consider the external stressor (exposure) as well as the internal capacity (adaptive capacity). The process of recognizing the diverse rational set of adaptation and sensitivity components provides a powerful insight for decision makers. Through the disaggregated components of vulnerability studies, policy makers are able to detect and support the factors that enhance the adaptive capacity of a system.

More importantly, the decision makers are able to evaluate the infrastructure adequacy by hazard exposure and vulnerability framework. For instance, hydrometric monitoring network can be evaluated by vulnerability studies. Hydrometric monitoring networks play a significant role in design of various water resources infrastructure such as reservoirs, irrigation systems, urban drainage and storm water systems, and hydropower plants by providing a fundamental input. Figure 5-25 and Figure 5-26 demonstrate the distribution of active hydrometric gauging stations overlaid on the vulnerability to drought and flood of the Upper Ottawa Basin, respectively. If the decision makers decide to allocate budget to install a new monitoring station in this basin, the results from the vulnerability study form an additional constraint in optimization of the network design. Similarly, if based on budgetary restraints the decision makers decide to shut down any active hydrometric monitoring station, this vulnerability study, along with other decision support tools, can help them to find the solution with the least possible consequences

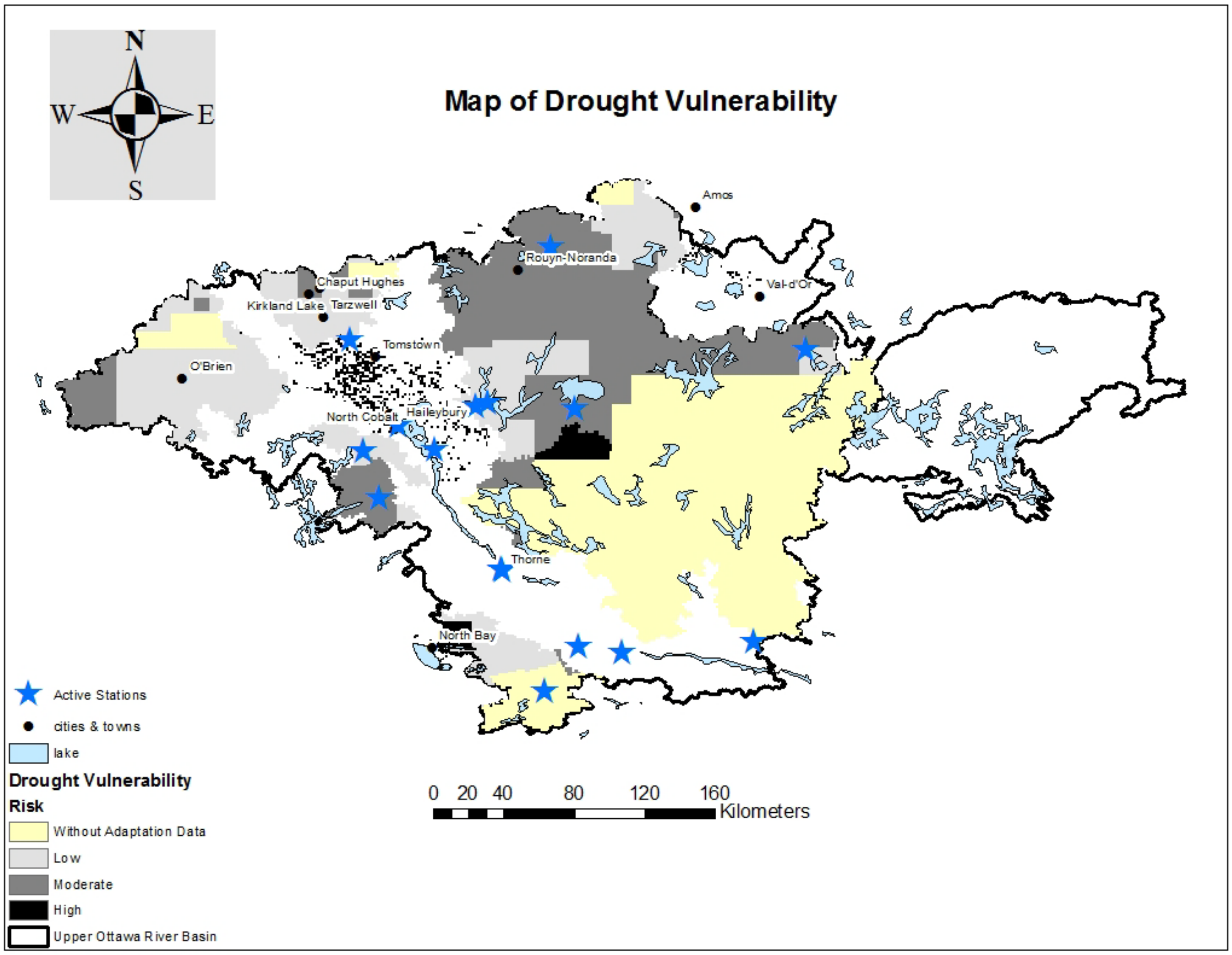

Figure 5-25: The drought vulnerability map of the Upper Ottawa River Basin and active hydrometric monitoring stations.

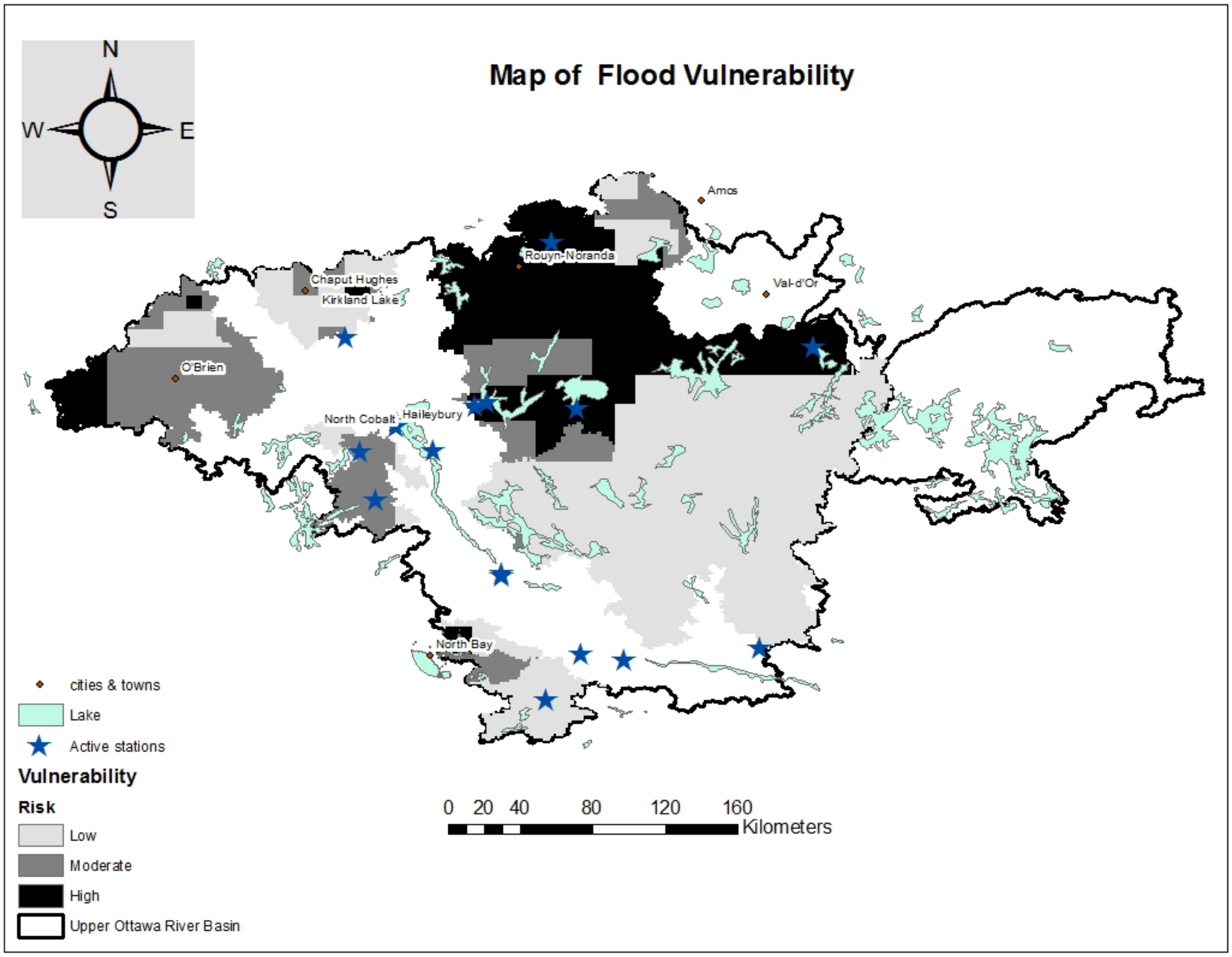

Figure 5-26: The flood vulnerability map of the Upper Ottawa River Basin and active hydrometric monitoring stations.

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CHAPTER SIX

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The difference between hazard-impact models and vulnerability studies has been discussed. The results show how decision makers can be misled by conventional hazard-impact evaluations. To modify hazard-impact modelling, measures of adaptive capacity are added to provide insights on the complicated and inter-related human dimension of vulnerability.

While the majority of previous studies have tried to develop an appropriate framework for integrated vulnerability assessment at a national scale, this investigation has argued that since the vulnerability varies from one place to another across a country, it is essential for decision makers to implement the vulnerability assessment at a local scale. Thus, the main purpose of the current study was to determine a number of appropriate indicators from physical elements to socio-economic factors to represent major components of the vulnerability structure (exposure, sensitivity, and adaptive capacity) and finally, to develop the analytical framework for assessing the relative vulnerability in a local scale.

The new flood and drought exposure indexes were defined in the sub-catchment and river basin scales using available gauging station data and frequency analysis approach. Since these indexes were developed from the perspective of water resources managers to identify those susceptible watersheds likely to be hit by these disasters, they provide valuable insights for decision makers to evaluate the effectiveness of current infrastructure and also to determine potential locations for constructing new water structures.

Due to the complexity of human features, identifying and evaluating adaptive capacity in a system is the most challenging part of the vulnerability assessment. Population, land use, and infrastructure were successfully examined as the sensitivity factors, and economic capacity, knowledge capacity, and age, were applied as the adaptive capacity indicators. In the case study of the Upper Ottawa River Basin, North Bay was identified highly vulnerable for both flood and drought and Rouyn-Noranda was determined highly vulnerable to flood. Apart from these cities, the sub-catchments of the Upper Ottawa River Basin were ranked into three levels (high, moderate, low) of vulnerability for flood and drought to provide a scientific basis for decision makers to efficiently prioritize their response to hazard.

Furthermore, this study shows that vulnerability assessment can be used for prioritizing and resource allocation. Precisely speaking, the results of the vulnerability assessment of the Upper Ottawa River Basin to flood and drought can be used to evaluate the adequacy of monitoring networks. The results of vulnerability assessment can be incorporated into optimization algorithms as an additional constraint to design a more comprehensive monitoring network that has a higher capacity to preserve and collect important information of the vulnerable areas to flood and drought.

The study has also shown that GIS is a useful tool to visualize and implement the vulnerability concept.

6.2 Future work

Although vulnerability approach is more integrated than conventional hazard impacts, its structure contains a high level of uncertainty. Therefore, it is recommended that further research be undertaken in reducing uncertainty of the vulnerability studies. These uncertainties can arise from sources such as qualitative assessment and the subjective threshold of adaptive capacity indicators.

Another possible area of future research would be to identify more appropriate socio-economic indicators particularly household and community scales to achieve a consensus measurement for adaptive capacity and to narrow down the list of indicators that currently have been used in the vulnerability research.

Also, investigation to determine an appropriate framework to allocate weights for different indicators helps to figure out more important factors in vulnerability and to reduce uncertainties associate with insignificant factors.

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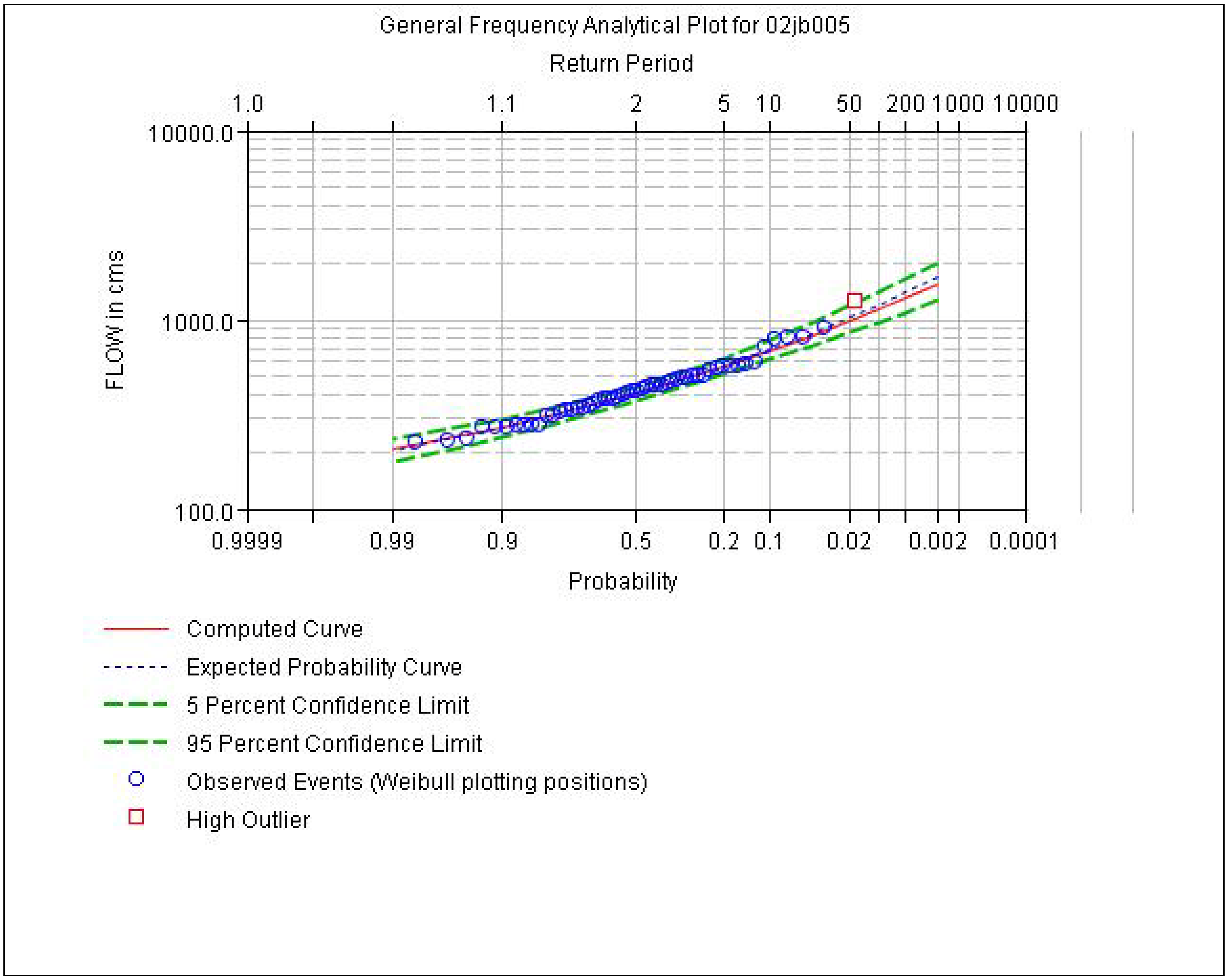
APPENDIX A:

PROBABILITY PLOTS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1.1
2
5
10
50
200
1000
10000
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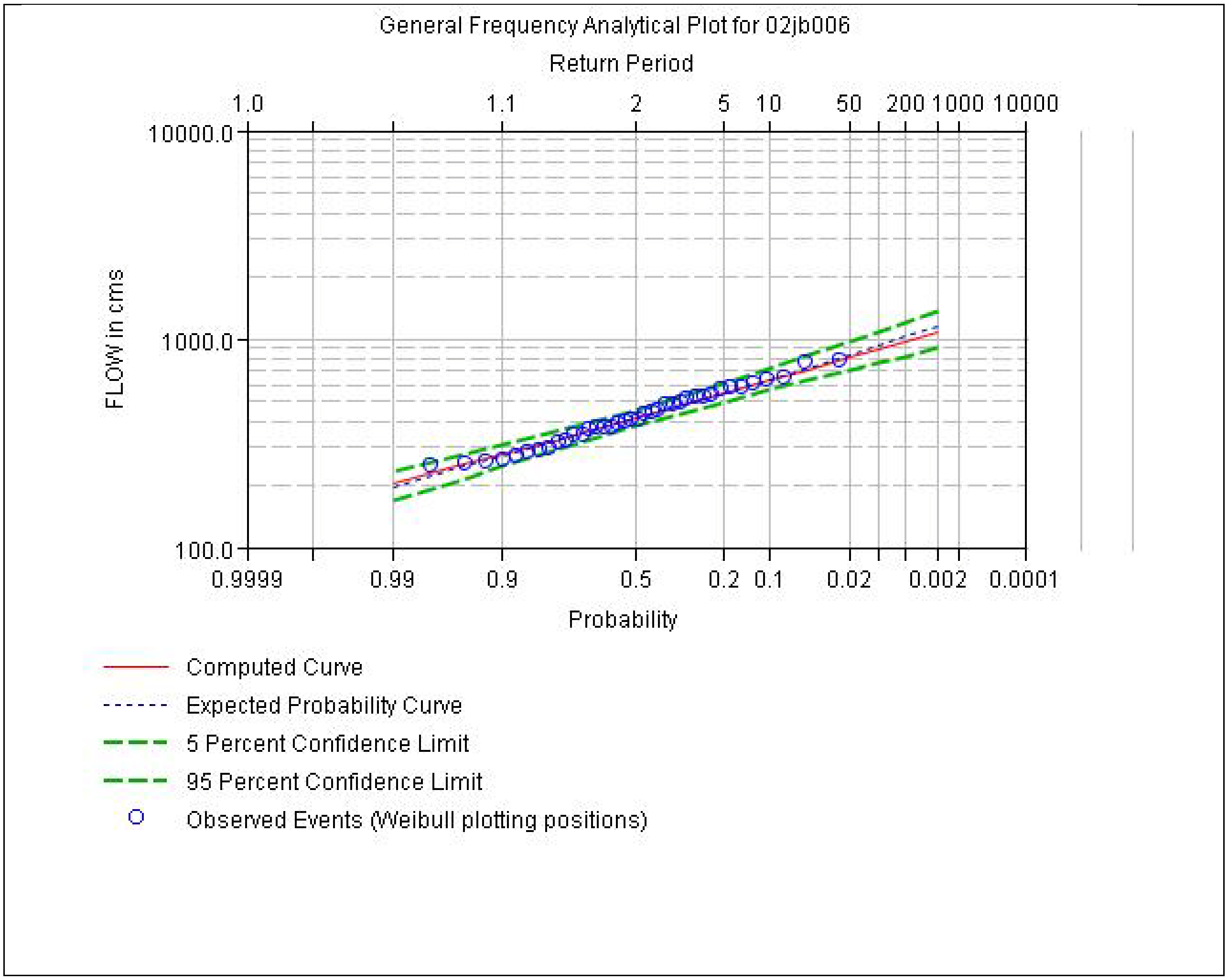
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)
High Outlier



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FLOW in cms
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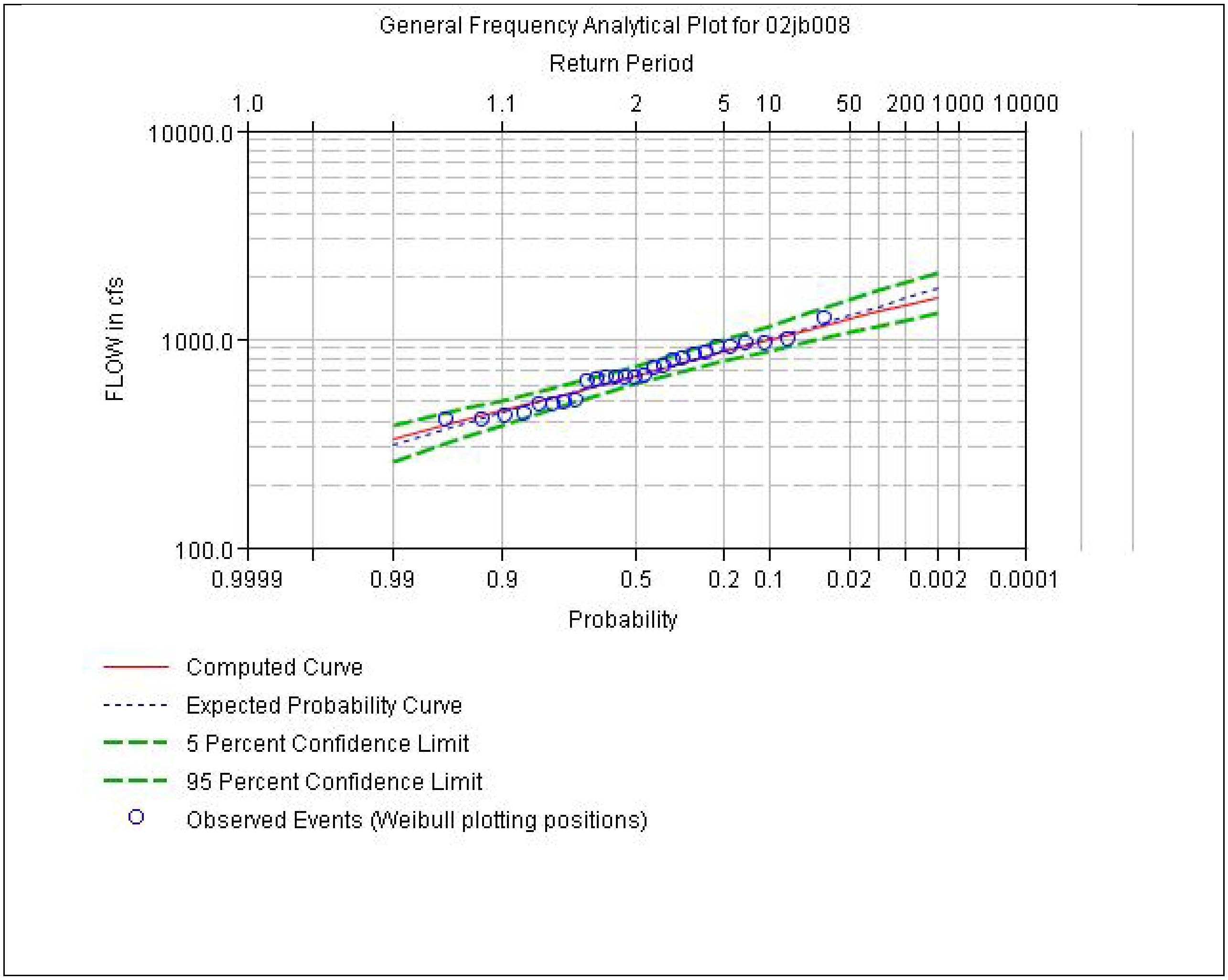
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)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FLOW in cfs
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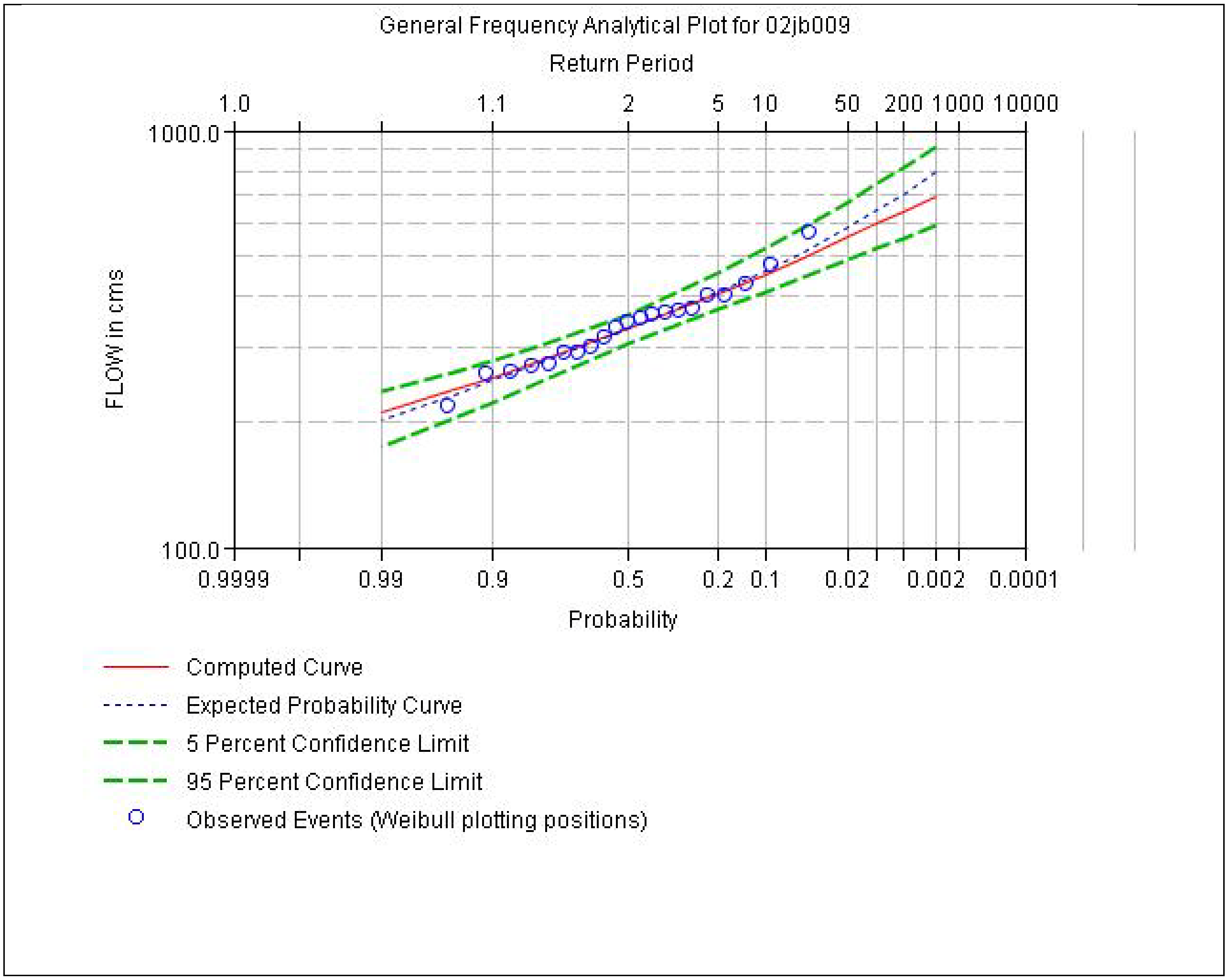
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)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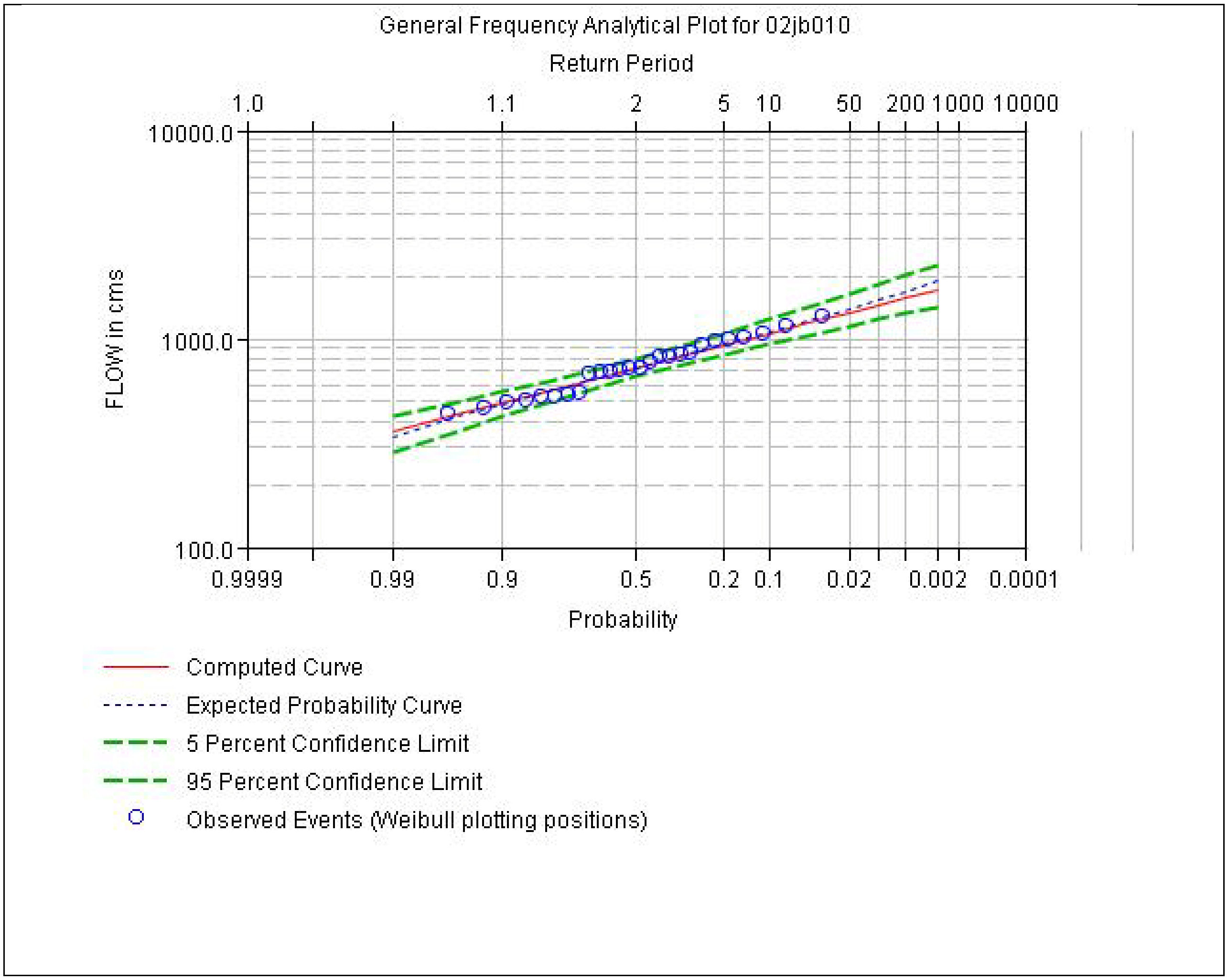
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)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FLOW in cms
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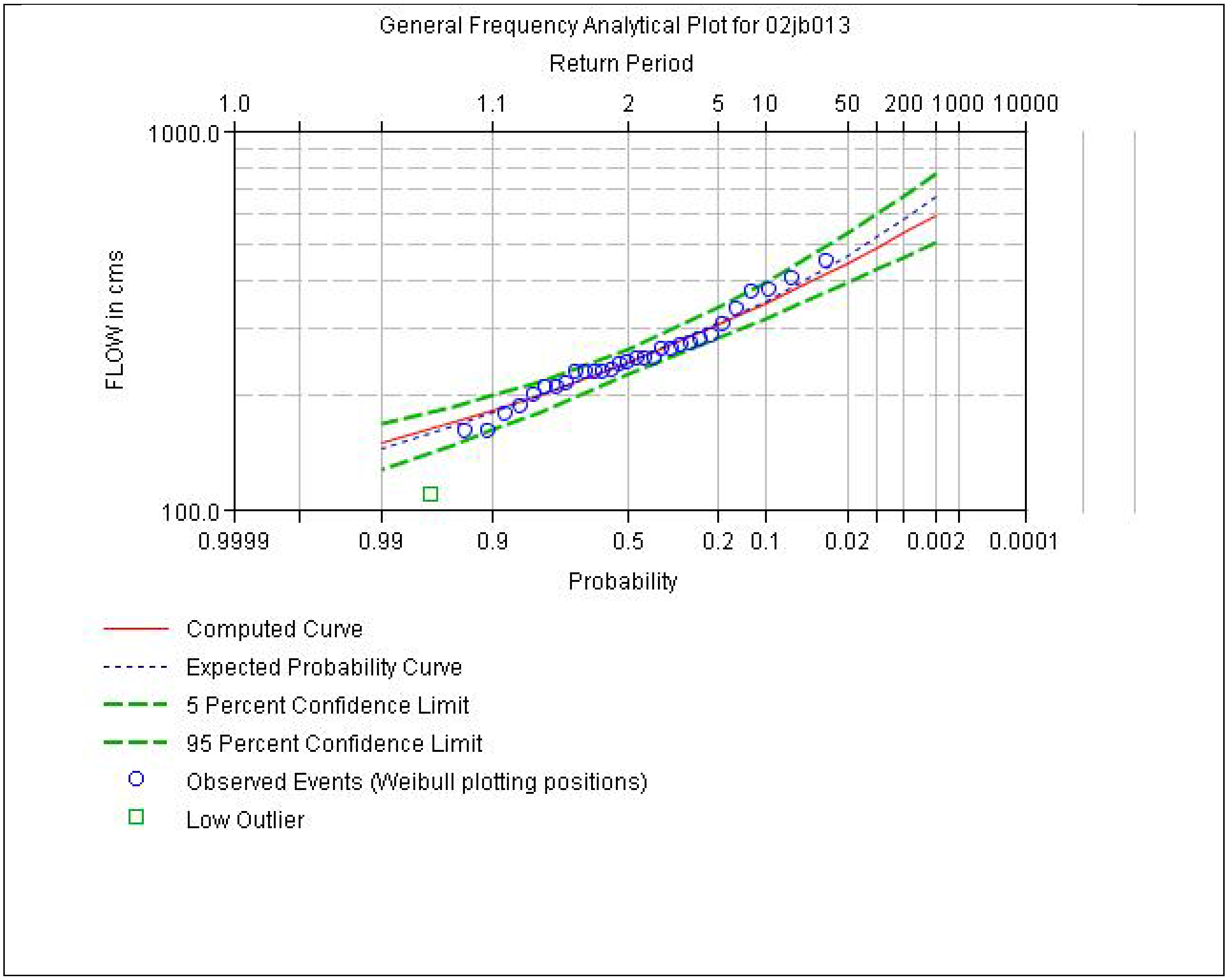
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)



General Frequency Analytical Plot for 02jb013
Return Period
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2
5
10
50
200
1000
10000
1000.0
100.0
FLOW in cms
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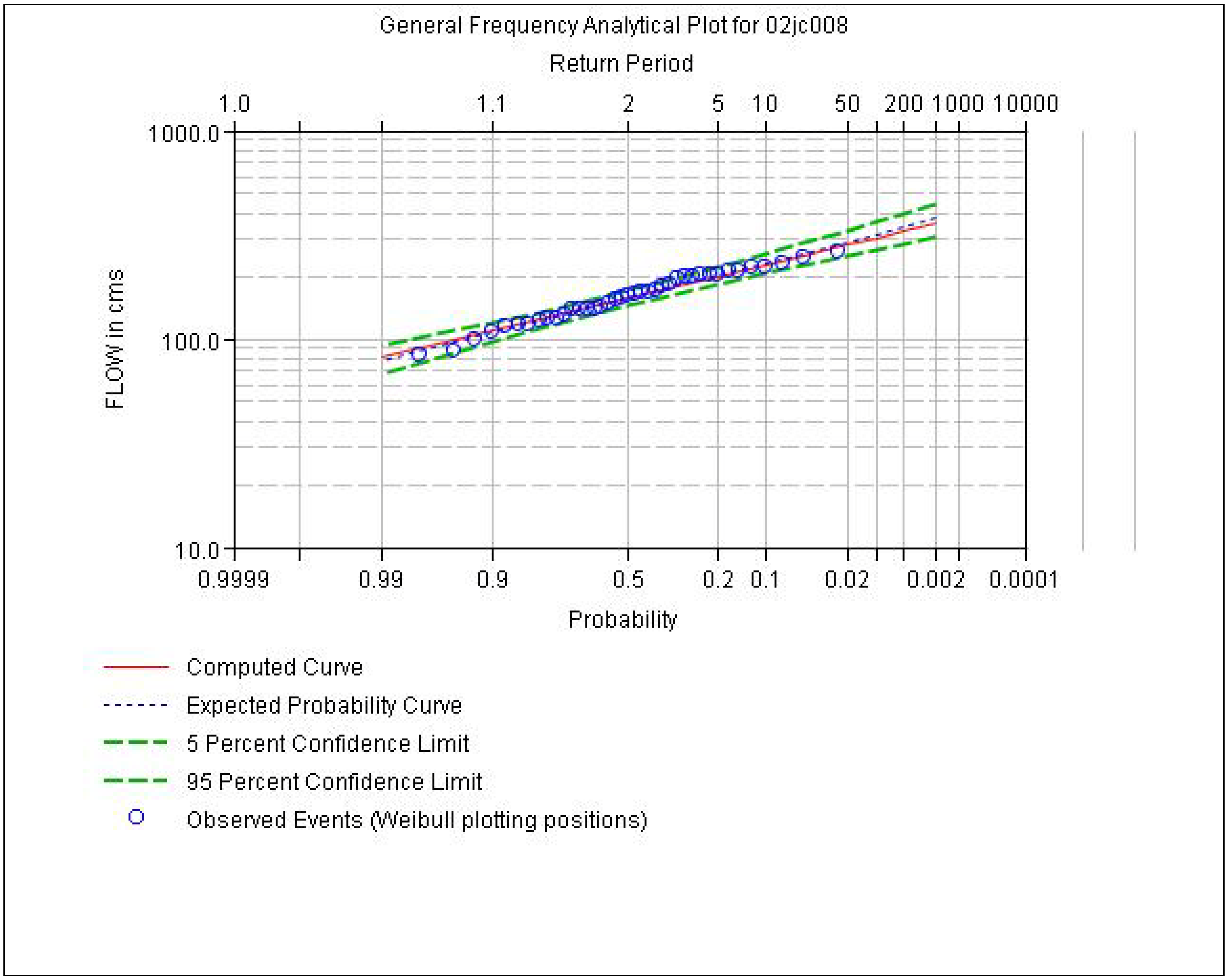
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)
Low Outlier


General Frequency Analytical Plot for 02jc008
Return Period
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1.1
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10
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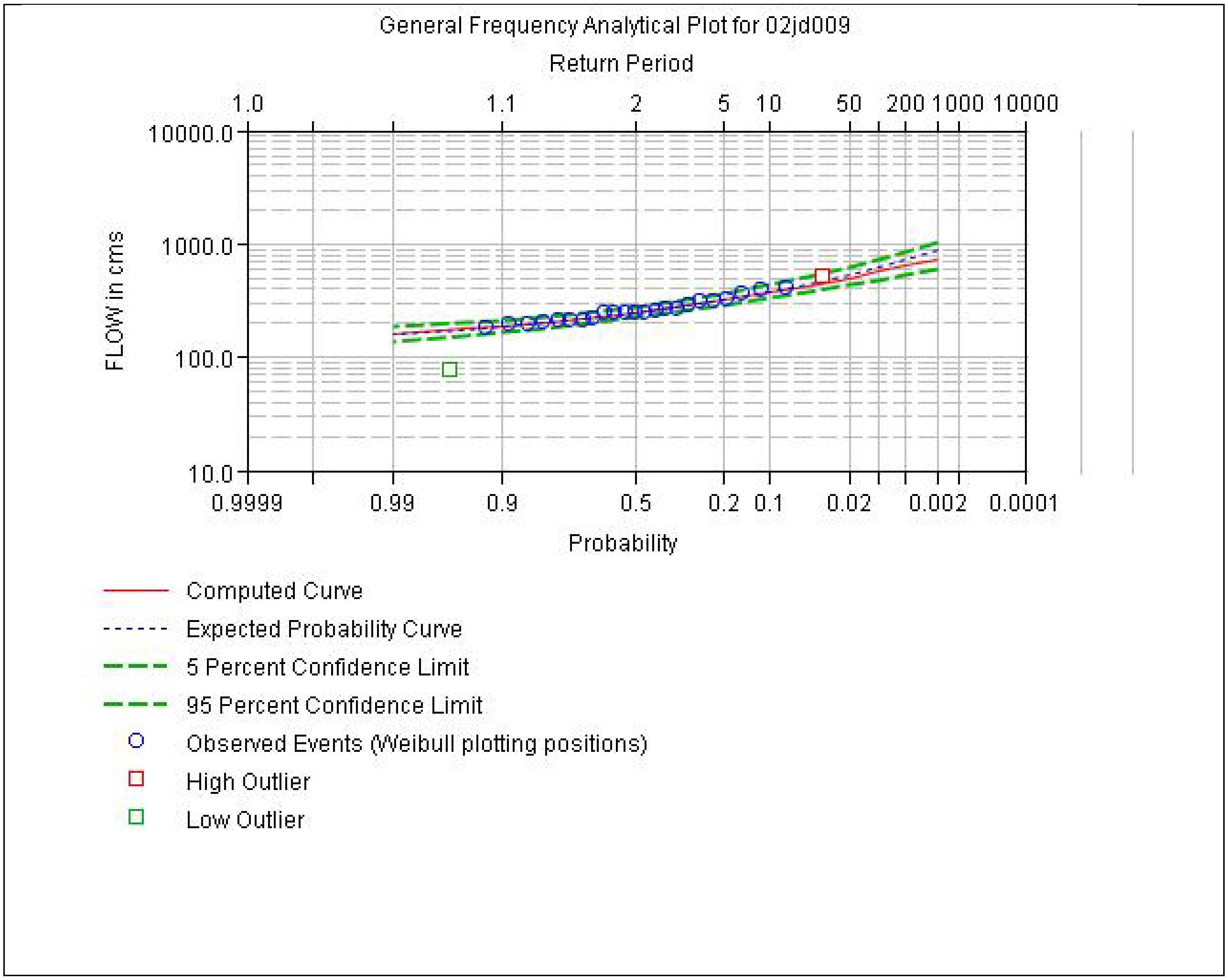
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)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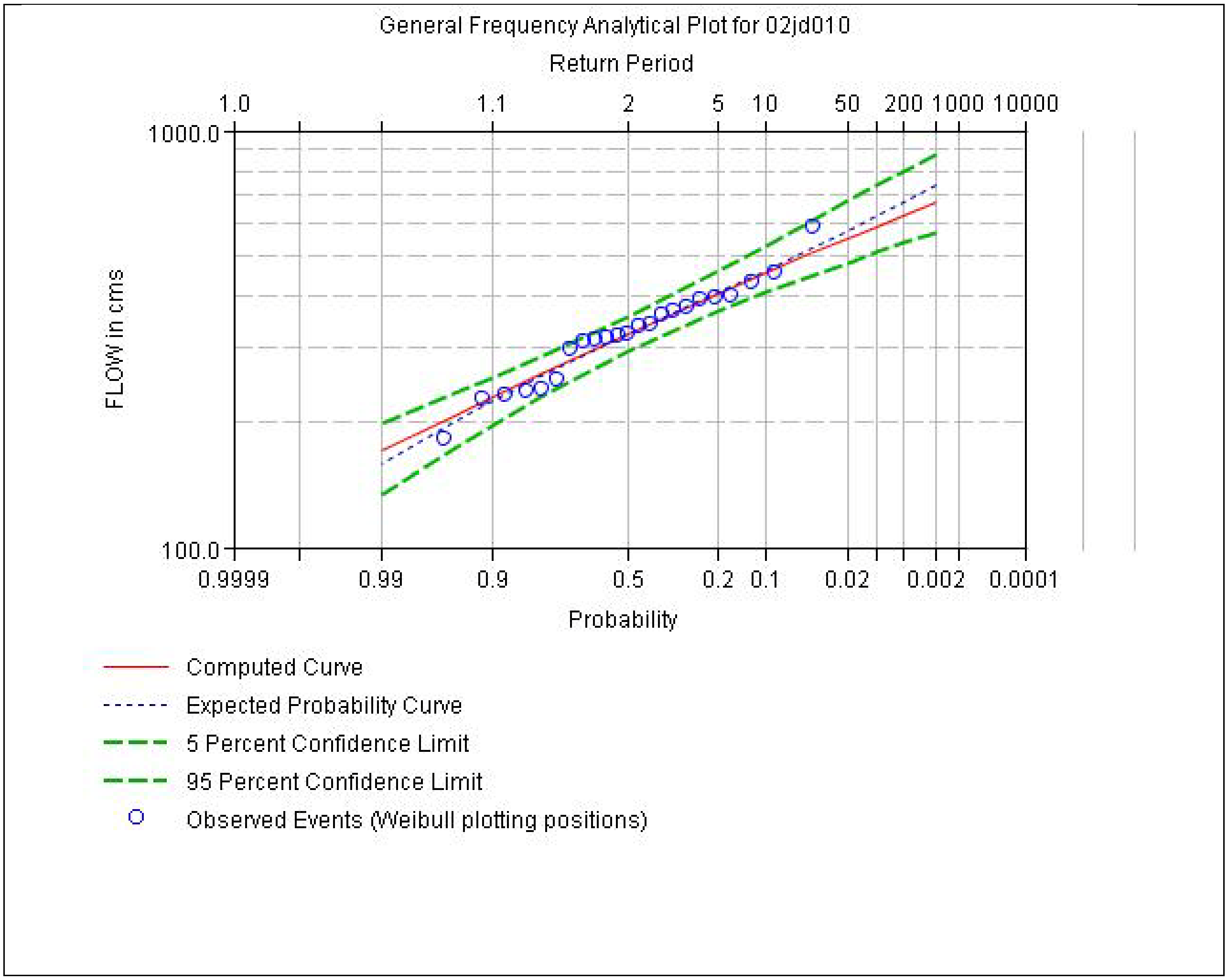
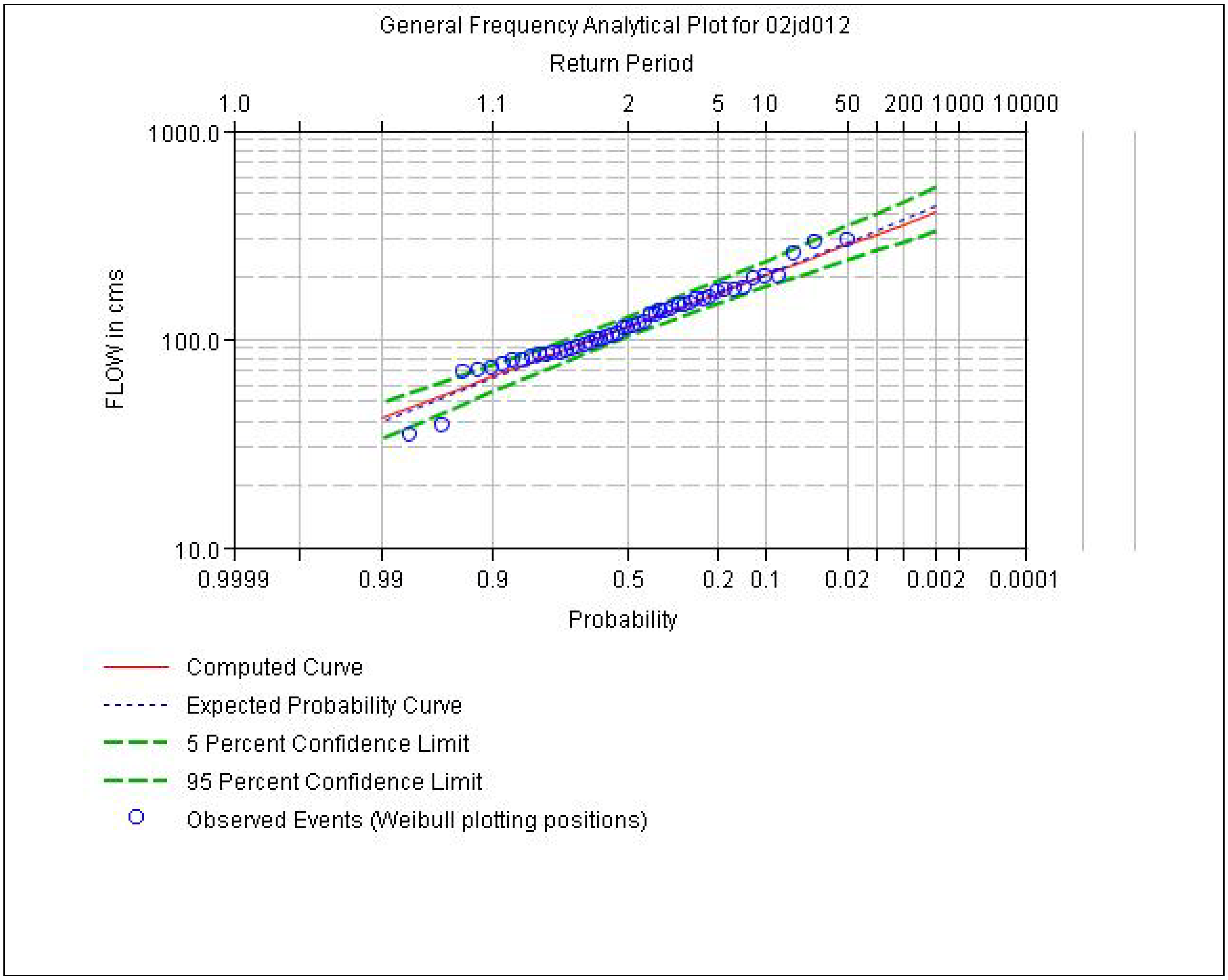
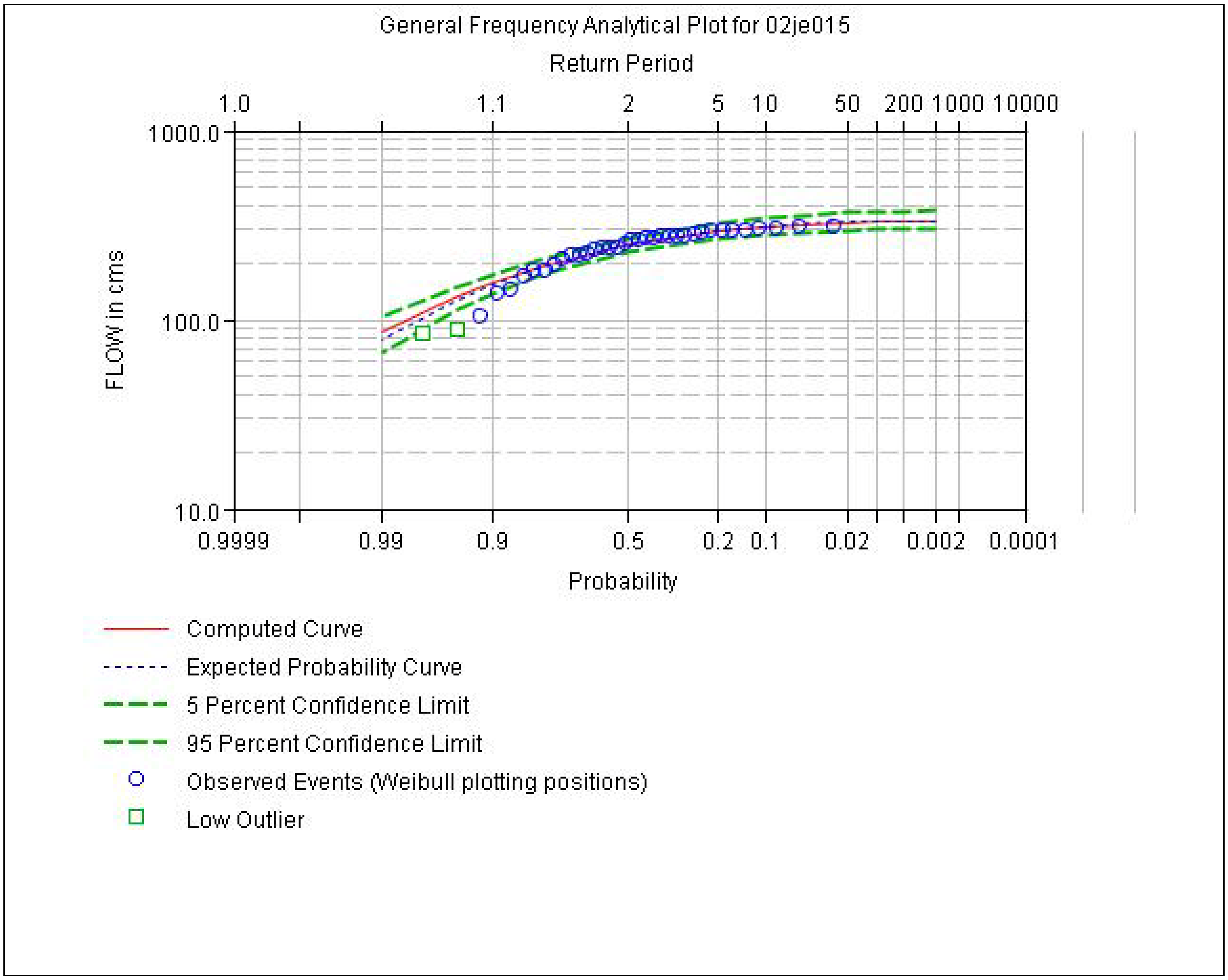
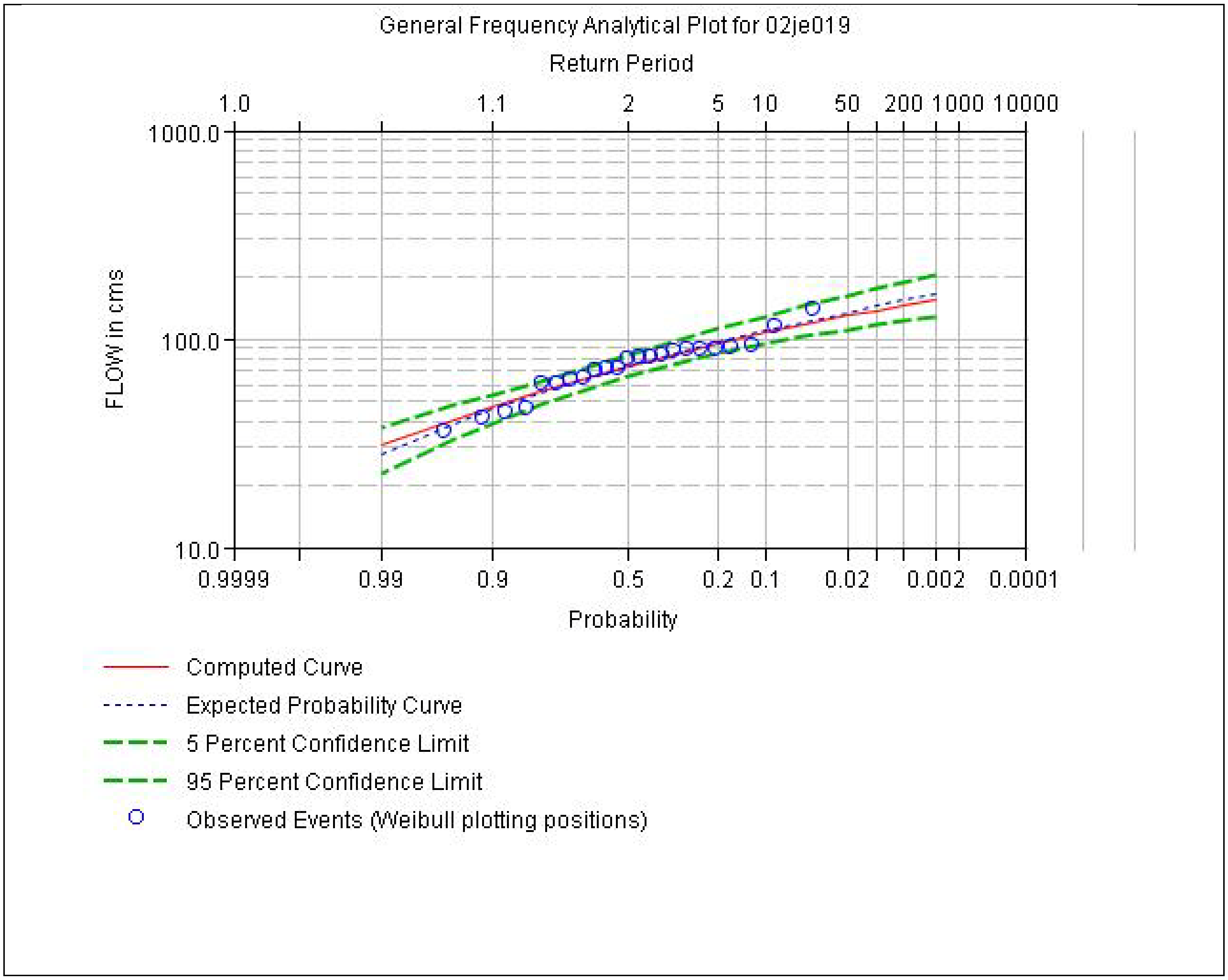
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
10000.0
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)
High Outlier
Low Outlier


General Frequency Analytical Plot for 02jd010
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)

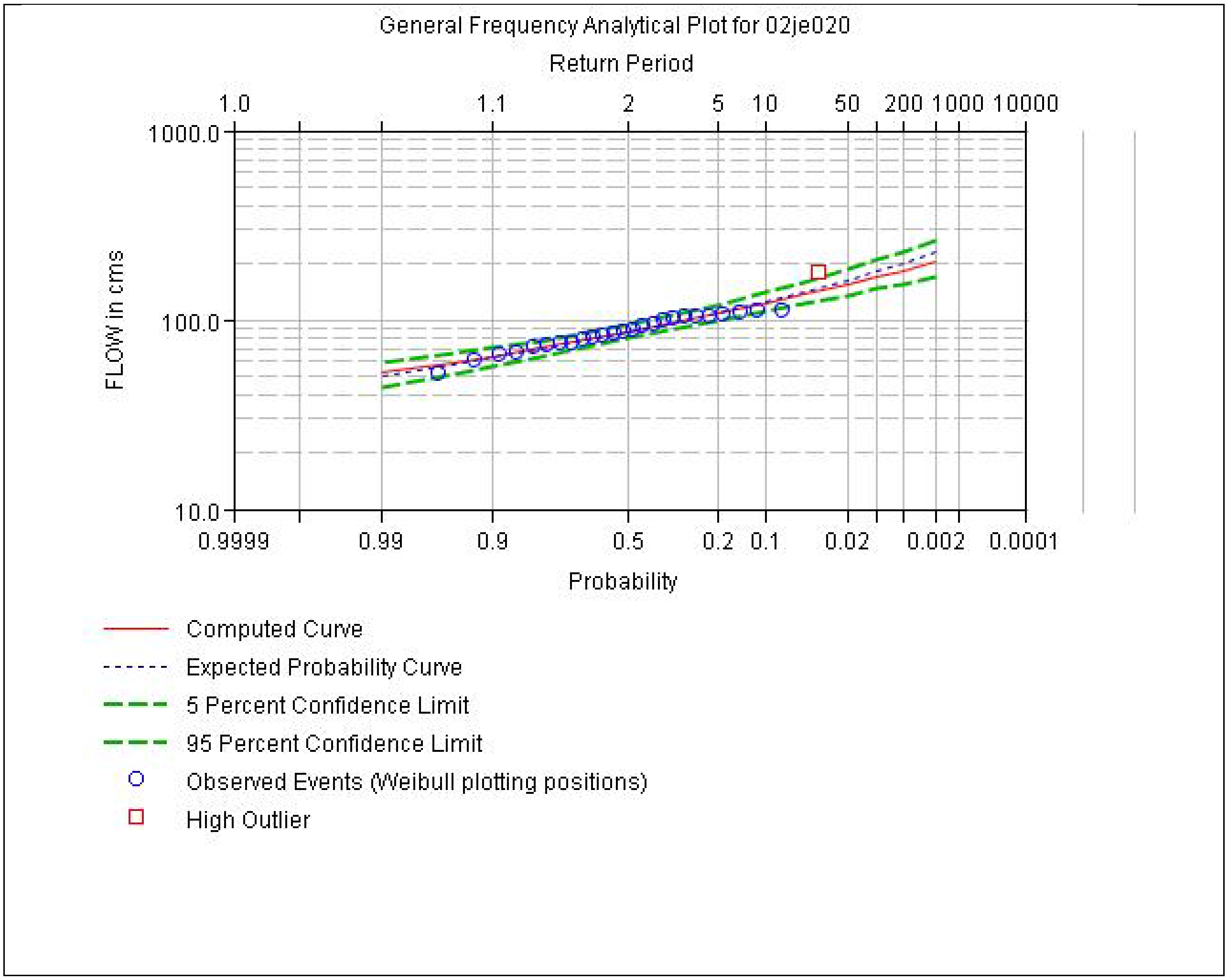

General Frequency Analytical Plot for 02jd012
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)

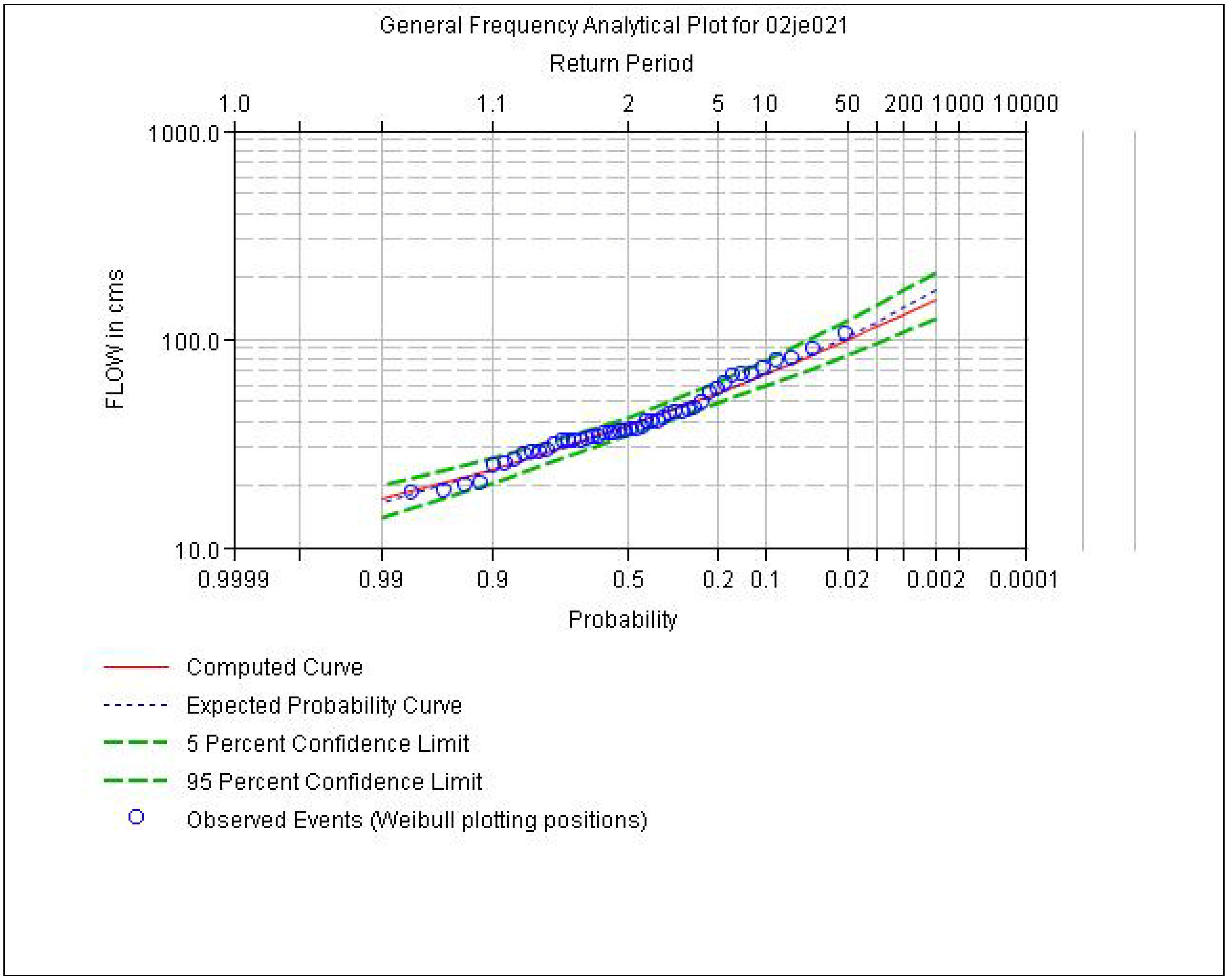


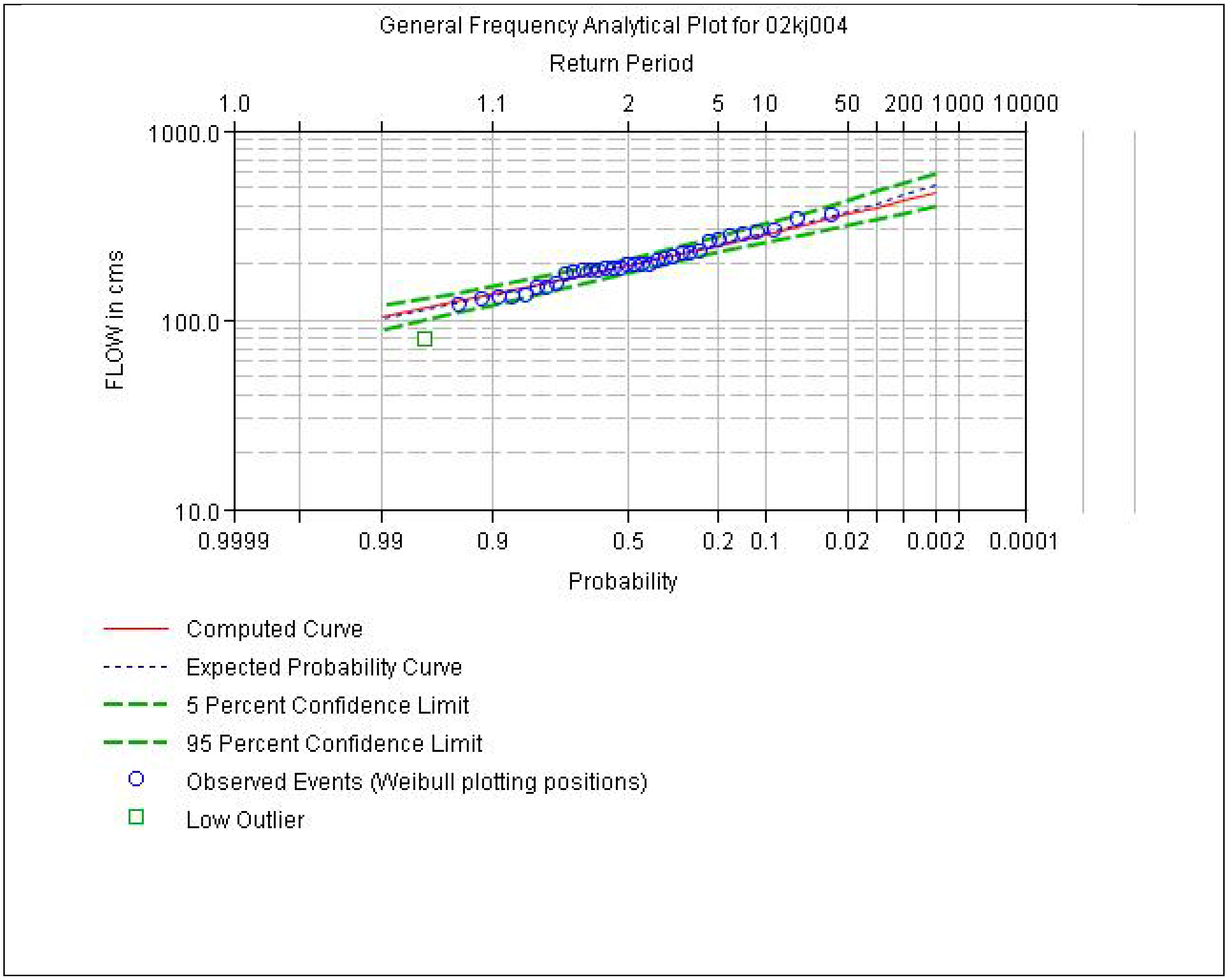
General Frequency Analytical Plot for 02je015
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)
Low Outlier

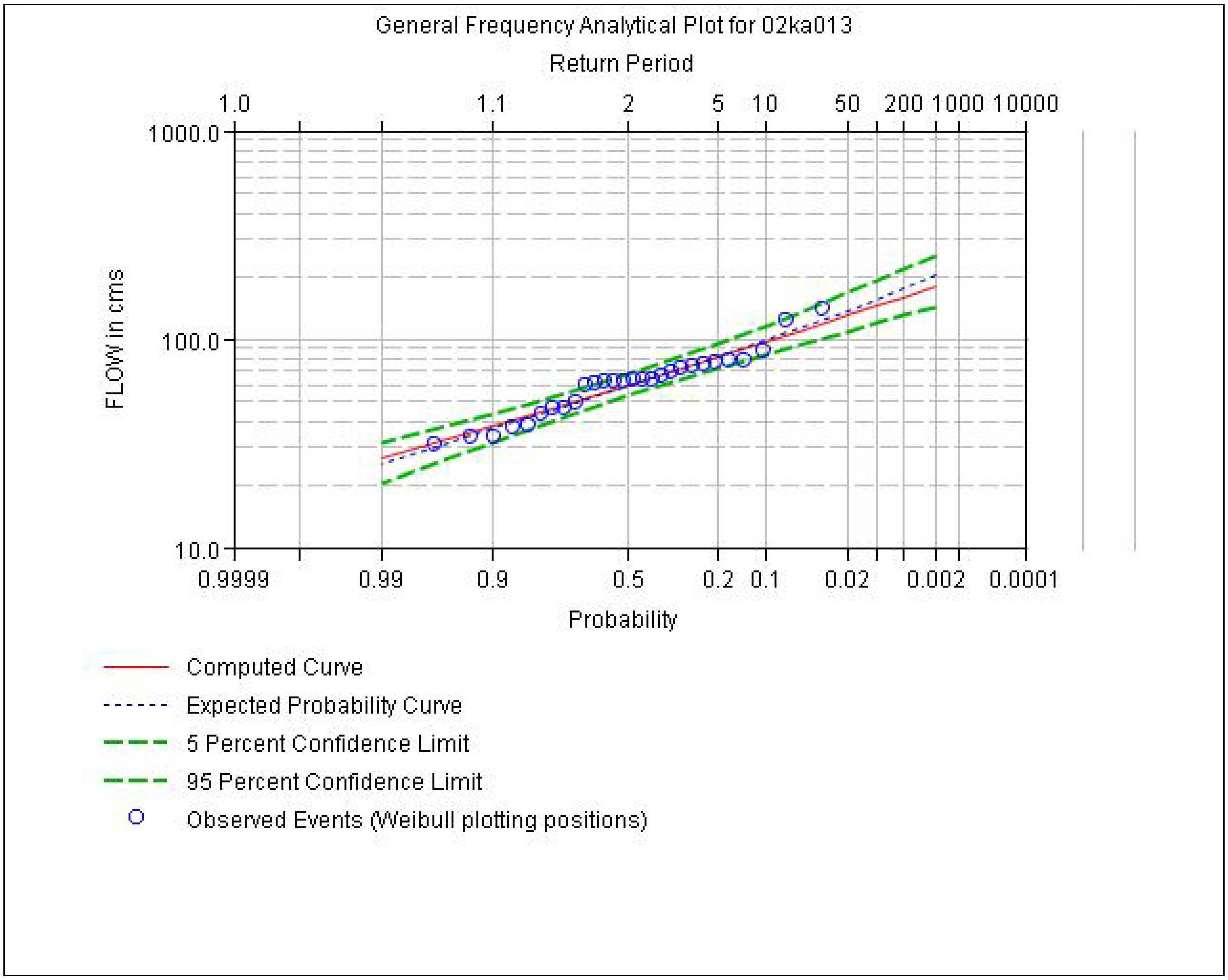


General Frequency Analytical Plot for 02je019
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)


General Frequency Analytical Plot for 02je020
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)
High Outlier


General Frequency Analytical Plot for 02je021
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)


General Frequency Analytical Plot for 02kj004
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)
Low Outlier



General Frequency Analytical Plot for 02ka013
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1000.0
100.0
10.0
FLOW in cms
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Weibull plotting positions)