Flood Vulnerability Assessment by Applying a Fuzzy Logic Method: A Case Study from Melbourne

By

Samira Rashetnia

Thesis submitted in fulfilment of the requirements for the degree of

Master of Engineering

College of Engineering and Science

Victoria University, Melbourne, Australia

August 2016

Abstract

Flood is known as the most common natural destructive phenomenon, which can cause severe physical, social and economic damages and losses in both rural and urban regions. Flood vulnerability assessment is essential to identify high risk areas and develop cost-effective flood mitigation and/or adaptation strategies, particularly for urban areas. In the recent past, vulnerability of floods has been assessed using vulnerability indicators consisting of components from various elements of flood damages, especially hydrological, social and economic components. This study presents a model based on a fuzzy rule-based system to assess the flood vulnerability of suburbs under the jurisdiction of Moreland City (MC) area in Melbourne, Australia to identify the most and the least vulnerable suburbs. The area is densely populated and consists of major waterways and creeks that increase the flood vulnerability and thus endangering the safety of people and property. Findings of the study showed that 51.6 % of the area in MC (26.21 km^2 in total) falls under very low and low flood vulnerability zones. The suburbs that fall under these 2 classes include Brunswick, Pascoe Vale and Coburg. These are the areas which have the least population density and/or have higher range of social and economic resilience (based on susceptibility indicators such as presence of broadband connection, number of low income and high income households, unemployed and low educated households). The very highly populated areas are classified into high and very high vulnerability classes, which have 4.6% and 0.3% of the total area, respectively. The suburbs that fall under these 2 vulnerable classes include Brunswick West, Gowanbrae, and Pascoe Vale South. For these parts of the study area that are vulnerable to floods, this study recommends to the relevant authorities that some range of steps need to be taken to increase the social and economic resilience in order to enhance the system's ability to cope with and recover from the negative impacts of floods.

Declaration

"I, Samira Rashetnia, declare that the Master by Research thesis entitled "Flood Vulnerability Assessment by Applying a Fuzzy Logic Method: A Case Study from Melbourne" is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature Samira Rashetnia Date Aug/2016

Acknowledgment

This thesis is especially dedicated to my supervisors and my family.

Firstly, I would like to express my sincere gratitude to my supervisors Dr. Nitin Muttil and Dr. Abdullah Yilmaz from Victoria University, for their continuous support, comments and advices. They were abundantly helpful and offered invaluable assistance all the time that I needed their opinions and help.

Secondly, I would like to acknowledge my wonderful husband Heerbod Jahanbani and my gratitude to him, who gave me accompany and a lot happiness and support through this period.

Third, thanks to my little son Heerad who was a good motivation for me with his cute smile and also, special thanks to my lovely family in Iran, particularly my parents who always encouraged me to find my potential. All the support they have provided me over the years was the greatest gift anyone has ever given me.

Finally, I would like acknowledge all the people who collaborated directly or indirectly during the development of this study. Thanks to Nalika Peiris from Moreland City Council in Melbourne and Rod Watkinson in Melbourne Water for supporting and providing necessary and valuable data for this study. Also, thanks Elizabeth Smith and other academic and administrative staff at College of Engineering and Science, Victoria University for their help and support.

Abbreviations

The following list of abbreviations are used in all through this thesis.

AMR	Annual Maximum Rainfall
AHP	Analytic Hierarchical Process
BOM	Bureau of Meteorology
BITRE	Bureau of Infrastructure, Transport and Regional Economics
DFW	Drainage system quality and number of flood protection structure Weight
EFVI	Economic Flood Vulnerability Index
FL	Fuzzy Logic
FIS	Fuzzy Inference System
FAR	Flooded Area Ratio
FVI	Flood Vulnerability Index
FFVHI	Final Flood Vulnerability Index
HFVI	Hydrological Flood Vulnerability Index
HiH	High income Households
HLD	Historical Loss Data
HCtR	Households Close to River
IPCC	Intergovernmental Panel on Climate Change
MCC	Moreland City Council

MC	Moreland City
MW	Melbourne Water
MDSD	Main Drainage System Density
MFs	Membership Functions
MDs	Membership Degrees
NBUiFA	Number of Business Units in Flooded Area
NHiFA	Number of Households in Flooded Area
NPFiFA	Number of Public Facilities in Flooded Area
NPFCtR	Number of Public Facilities Close to River
NMwHR	Number of Months with Heavy Rainfall
PD	Population Density
P0-4	People aged between 0-4
P65	People aged above 65
Pdis	People need assistance due to disability
PFA	people in Flooded Area
Pli	People with Low Income
Ple	People with Low Education
PBC	People with Broadband Connection
Pcfps	People Close to Flood Protection Structure
PAR	Permeable Area Ratio

PCA	Principal Component Analysis
PRA	Participatory Rapid Analysis
S	Slope
SFVI	Social Flood Vulnerability Index
SDSD	Sub-main Drainage System Density
UH	Unemployed Households
VC	Vulnerability Curve

Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

1.1. Introduction

Floods are known as the most common and destructive natural phenomenon (Yoon et al 2014). They can cause severe physical, social and economic damages and losses in both rural and urban areas (Masood & Takeuchi 2011; Balica et al. 2012; Balica et al. 2013; Zhang & You 2013; Albano et al. 2014). Several studies (IPCC 2007; Yilmaz 2014) reported an increase in frequency and magnitude of extreme rainfalls, which have aggravated the flood related concerns.

Global warming is one of the main reasons for the increase in frequency and magnitude of extreme rainfalls (therefore floods), since the warmer atmosphere with enhanced humidity leads to a more active hydrological cycle (Mailhot et al. 2007). Katz and Brown (1992) stated that even a small change in the mean rainfall due to global warming can cause significant changes in extreme rainfalls. Also, urbanization is another driver which increases intensity and frequency of floods. Alaghmand et al. (2010) showed that there is a direct relationship between urbanization and hydrological characteristics such as infiltration, runoff frequency and flood depth in an urban area. They stated that increased urbanization increases floods, both in frequency and magnitude. The effects of urbanization and global warming on floods will increase in future (due to more urbanization to accommodate increased population in cities and rises in greenhouse gas emissions) (IPCC 2013).

Considering the above, flood vulnerability assessment is essential to identify high risk areas and develop cost-effective flood mitigation and/or adaptation strategies. There are three primary approaches which were used to quantify (evaluate) flood vulnerability: Historical Loss Data (HLD) (Dilley et al. 2005), Vulnerability Curve (VC) (Büchele et al. 2006) and Flood Vulnerability Index (FVI) (Kumar et al. 2010; Solin 2012; Kumar & Kunte (2012); Balica et al. 2012, Zhang & You 2013; Kunte et al. 2014; Balica et al. 2013). FVI is the most commonly used approach and it is a useful tool that can assist urban planners and policy makers in prioritizing flood mitigation strategies and in increasing public awareness by providing information through highlighting hot spots for the flood risk, communities vulnerable to floods and so on (Balica et al. 2009).

The remaining sections in this chapter present a brief background to definition of flood, type of floods, frequency of floods, flood risk management and mitigation strategies. This chapter also presents the motivation and objectives of this study as well as the outline of this thesis.

1.2. What is flood?

Flood and flooding are defined as below:

A flood is defined as "a temporary condition of surface water (river, lake, sea), in which the water level and/or discharge exceeds a certain value, thereby escaping from its normal confines" (Douben 2006a; Schultz 2006).

Flooding is defined as "the spilling over or failing of the normal limits for example lake, sea or accumulation of water as a result of heavy precipitation through lack of beyond of the discharge capacity of drains, or snow melt, dams or dikes break affecting areas" (Douben & Ratnayake 2005), which are normally not submerged (Ward 1978).

1.3. Types of floods

There are in general four types of floods: coastal, river, flash and urban floods (MunichRe 2007). For this thesis, only three types of floods (namely river, flash and urban floods) were of concern and hence are explained in the following sub-sections.

1.3.1. River floods

These types of floods, which happen along the rivers, are natural events. They occur when the spring rains merge with melted snow from winter. When the basins of the river get filled fast, then the stream spills over the rivers' banks. These floods also can happen because of heavy rainfall during a continuous period of days over a large area. Hence, the river floods do not occur suddenly but develop gradually. Spreading of diseases and drinking water shortage can be counted as indirect threats of river related flooding (Douben 2006b).

1.3.2. Flash floods

These types of floods are temporary inundations of different sources such as river basins, sub catchments or some parts of a city. They usually occur in combination with thunderstorm over a small area or even intense rains in short times can cause them. In fact, when the rainfall intensity exceeds the infiltration rate, water runs off the surface. However, the ground is not soaked usually. Flash floods can take place anywhere and are good signs to predict a major river flood. The engineering structures such as dams, dikes and levees are usually constructed to protect areas against these floods. They happen without warning and cause maximum damage as huge amounts of fast-moving water is involved.

1.3.3. Urban floods

Urban flooding, which normally depends on the soil type, topographical conditions and the quality of the drainage system, is usually caused by extreme local rainfall sometimes combined with blocked drainage systems (Douben 2006b).

Urbanization is a driver which increases intensity and frequency of urban floods. Alaghmand et al. (2010) showed that there is a direct relationship between urbanization and hydrological characteristics such as infiltration, runoff frequency and flood height in urban areas. They stated that increased urbanization causes increases in floods, both their frequency and magnitude. Moreover, permeability of buildings and roads can affect urban floods, since the huge amount of rain water leads to urban runoff during heavy rainfall events, as rain cannot be absorbed into the impervious urban areas (Douben 2006b).

1.4. Flood risk management and mitigation

Flood risk is defined “as a function of flood probabilities and flood impacts” (Balica et al. 2012). Flood risk management can be defined as all those activities which can help a system to be sustainable and improve its capabilities to cope with flood events and disasters. In fact, it includes different methods to reduce the floods and mitigating flood’s harmful consequences.

Number of floods and their effects can be reduced by flood risk management and flood mitigation measures and strategies. In other words, flood management includes an extensive range of measures that help to decrease the destructive effects of floods on people, environment and the economy of any region.

Followings are some objectives of conducting flood risk management studies:

- Reducing the exposure of people, properties and environment to flood risks;
- Reducing the present level of flood damages; and
- Increasing the resilience of systems and people.

In general, methods for flood mitigation can be grouped into structural and non-structural approaches. The structural methods involve modifying the flood pattern; whereas, non-structural ones help to reduce the floods’ impacts (Douben 2006b; Andjelkovic 2001).

The structural methods consist of infrastructure development such as dams or levees, which reduce the flood risk to people and property. Non-structural methods on the other hand consist of various mitigation measures such as planning, programming, raising awareness, preparedness, and flood forecasting and warning systems.

One of the non-structural measures is the Flood Vulnerability Index (FVI) development to assess flood vulnerability of the regions. The FVI is developed considering one or more of several components such as hydrological, economic, social, environmental and political (Kumar et al. 2010; Solin 2012; Kumar & Kunte 2012; Balica et al. 2012, Zhang & You 2013; Kunte et al. 2014; Balica et al. 2013).

1.5. Motivation and objectives of the study

Moreland City (MC) is located in the inner and mid-northern parts of Melbourne. The area is mainly bordered by Moonee Pond Creek to the west and Merri Creek to the east and experiences river floods as well as urban floods. Moreover, as MC is a densely populated urban area, the major floods from the creeks and insufficient drainage network increases the risk of floods. Thus, assessing the flood vulnerability is vital for the area under the jurisdiction of Moreland City Council (MCC), which can be part of the council's flood risk management plans.

The overall objective of this study to develop a FVI for MC, which would be easily understood and used by the water authorities as well as the general public. This would create an easily understandable link between the theoretical concepts of flood vulnerability and the day-to-day decision making process. This study also aims to identify regions that are highly vulnerable to floods and those that are least vulnerable. In other words, the goal is to convert knowledge into actions by assessing the vulnerability to floods of the different suburbs of MC. Identifying the hotspots highly vulnerable to floods and raise the public awareness about such areas could save lives of people and could also reduce the economic losses due to floods.

There is an advantage of using the FVI method in that it considers not only the hydrological and economic aspects of flood damages, but also the social aspect of damage caused by floods. However, hydrologic events include many uncertainties due to their nature such as climate, limited data and imprecise modelling (Sen 2010; Bogardi et al. 2003). Moreover, there is not a clear boundary for the different vulnerability components and indicators (Yazdi & Neyshabouri 2012). Therefore, it is useful to adopt a methodology to develop and assess the vulnerability which can deal with uncertainties in development of a FVI. Thus, in order to integrate a probabilistic approach to FVI development, this study used a Fuzzy Logic (FL) based FVI which would consider the uncertainties involved in hydrology.

FL was adopted by some index studies for water quality, groundwater and flood vulnerability (e.g., Liou et al. 2004; Said et al. 2004; Ocampo-Duque et al. 2006; Muhammetoglu & Yardimic 2006; Nasiri et al. 2007; Nobre et al. 2007; Lermontov et al. 2009; Rezaei et al. 2013; Yazdi & Neyshabouri 2012). Among these studies, Yazdi and Neyshabouri (2012) assessed the flood vulnerability index for an urban watershed in Iran by applying a fuzzy rule-based method. They selected 6 indicators to map the flood vulnerability based on the availability of data and considering the fact that a system can be vulnerable to a hazardous event because of physical exposure, susceptibility and socio-economic aspects. On the other side, Balica et al. (2009), explained that the exposure, susceptibility and resilience are three main factors, which should be considered while evaluating flood vulnerability of any system (region). Exposure can be estimated from the value of goods, infrastructure, cultural heritage and people present in the flooded area. Susceptibility is mostly related to social aspects of flood damage specially awareness and preparedness of people, and resilience is the system capacity to cope with changes by modifying itself when it's exposed to flood.

In this study, a methodology was developed to use a FL based FVI to the case study area of MC. Flood vulnerable areas were identified and mapped in GIS environment, which in turn would help policy makers and other concerned authorities to develop sustainable flood management and mitigation policies.

In summary, the objectives of this study are as follows:

1- To develop a FL based FVI using data representing hydrological, social and economic components of flood vulnerability. The study used 24 indicators grouped under the above mentioned three components.

2- To apply the developed fuzzy based FVI in the areas under the jurisdiction of (MC) area in Melbourne. Such an application will identify the areas (or suburbs) that are highly vulnerable to floods.

This study will make a significant contribution to flood vulnerability assessment literature by applying an innovative methodology and presenting a simple and powerful tool in an urban area in Australia. Despite the importance of flood vulnerability assessment, to the knowledge of the author, there is no study, which attempted to develop a FL based FVI to quantify flood vulnerability of the regions, considering comprehensive indicators, which represent hydrological, social and economic effects of the floods. Also, this study significantly contributes to the study area, MC, through identification of the most flood vulnerable regions in the MC. Outcomes of the study will be useful for policy and decision makers of study area for further urban development and flood management strategies.

1.6. Overall methodology

The methodology and all its details which have been applied to develop a FVI in this study is explained in chapter 5, section 5.3. However, the overall view of the research methodology has been shown in Figure 1.1.

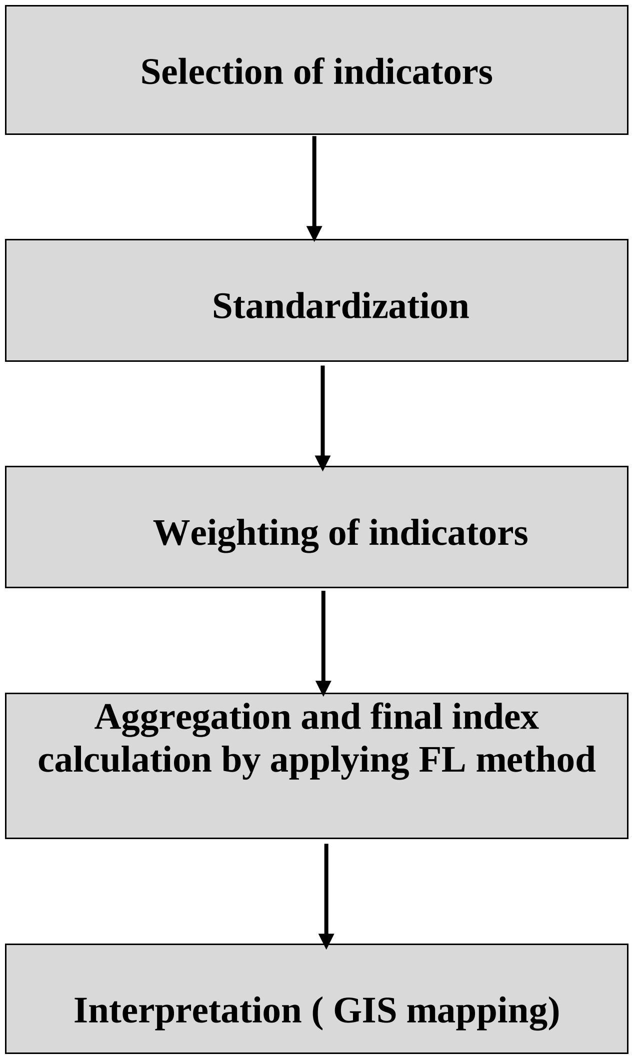


Figure 1.1. Flow chart of the study methodology

1.7. Outline of the thesis

The outline of this thesis is as follows:

1. This chapter presented the context of the present study and provided some basic definitions of terms and concepts used in this study. The motivation and objectives of this study were also presented in this chapter.

2. Chapter 2 presents a detailed literature review on flood vulnerability, including the definitions of vulnerability, vulnerability indicators and factors, as well as the fuzzy logic based approach used in hydrology.

3. Chapter 3 presents the FVI method and includes the common components used in this method. This chapter also presents in detail the five steps that need to be undertaken to develop and apply a FVI.

4. Chapter 4 explains the Fuzzy Logic (FL) approach and the steps involved in its application.

5. Chapter 5 presents the application of the FL based FVI method to the study area. The research methodology used in this study is presented in detail in this chapter. The result from the application of the developed methodology to the case study areas is also presented in this chapter.

6. Chapter 6 presents the conclusions drawn from this study. This chapter also presents the limitations of this study and the recommendations for future research.

Chapter 2
Literature Review

2.1. Introduction

As presented in Chapter 1, this study aims to demonstrate the applicability of the developed FL based FVI methodology as a useful tool to identify flood prone areas and quantify flood vulnerability (FV). This chapter explores the concept of vulnerability, expressions used in past studies to estimate flood risk, perception of FV, FV factors and finally, the FL approach in hydrology.

2.2. Conceptualizing vulnerability

Over the last two decades the concept of vulnerability has changed frequently since it's been used in different disaster studies and consequently there have been several attempts to define the term of vulnerability. Some specific definitions of vulnerability refer to climate change (IPCC 1992, 1996 and 2001), some others to environmental hazards (Blaikie et al. 1994; Klein & Nichols 1999), and also some refer to floods (McCarthy et al. 2001; Veen & Logtmeijer 2005; Connor & Hiroki 2005). Based on the literature, the various definitions of vulnerability are explained as follows:

Gabor and Griffith (1980) defined the vulnerability as the risk context and the frequency of hazardous incident. Chambers (1989) explained vulnerability "as a potential for loss" with two sides: shocks from outside exposure and the ability from the internal side which is resilience. Watts and Bohle (1993) analysed social vulnerability considering hazards and responses of societies to face and cope with resilience. Cutter (1993) and Cutter (1996) defined vulnerability as a hazard includes natural risks plus social actions and responses however, according to Coburn et al. (1994), vulnerability is defined as "the degree of loss to a given element at risk (or set elements) resulting from a given hazard at a given severity level". Klein and Nicholls (1999) explained the vulnerability as a function for the natural environment using three components: resistance, resilience and susceptibility and, Lewis (1999) described that "vulnerability is the root cause of disasters". While Mitchell (2002) explained vulnerability as a function of resistance, resilience and exposure Messner and Meyer (2006) and Merz et al. (2007) stated that it's a function of the vulnerability definition to elements at risk, exposure and susceptibility.

Kasperson et al. (2005), Adger (2006), and IPCC (2007) combined the above concept of vulnerability into a vulnerability function related to exposure, sensitivity and resilience. The International Panel of Climate Change (IPCC) defined vulnerability as the incapability degree to cope with the climate change consequences and later, IPCC (1996) defined it "as the extent to which climate change may damage or harm a system; it depends not only on a system's sensitivity but also on its ability to adapt to new climatic conditions" (Watson et al. 1996). The latest IPCC report defined vulnerability as "The propensity or predisposition to be adversely affected". It is also stated in this report that "Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC 2014).

2.3. Flood risk expressions

The procedure for managing a flood risk event is termed as the flood risk management (Plate 2002). The term of risk is defined as "the probability that a hazard will turn into a disaster" (Balica et al. 2009). Vulnerability and hazard do not define risk separately, but they are combined to estimate the risk as presented in Equation (2.1).

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \tag{2.1}$$

Where, risk is the consequence, and the hazard and vulnerability are premise and base respectively.

Also, risk can be explained as "the probability of occurrence of an event multiplied by the event consequences" (Bouma et al. 2005).

$$\text{Risk} = \text{Probability X Effect} \tag{2.2}$$

Barredo et al. (2007) used below function to evaluate the flood risk:

$$\text{Flood risk} = \text{f}(\text{Hazard}, \text{Exposure}, \text{Vulnerability}) \tag{2.3}$$

In the IPCC (2007), risk is a product of the likelihood of a hazardous condition and the consequences of that.

The latest IPCC report (IPCC 2014) used the term of risk to refer "the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services) and infrastructure”.

2.4. Perception of Flood Vulnerability

The floods have gained importance in recent years since a large number of people, ecosystems, and economic activities are negatively impacted (Balica et al. 2012). Developing countries faced by widespread poverty, high population density, and high rates of unemployment, and illiteracy make them more vulnerable. In general, every society is vulnerable to floods, based on their different conditions and cases which make them unique. To improve the quality of life of the people as well as improving policies, understanding the privileges amongst societies are very helpful.

United Nations (1982) defined the flood vulnerability “as a degree of loss to a given element at risk from a flood of given magnitude “expressed on a scale from 0 to 1. This is the definition which is applied in this study.

The concept of vulnerability was expanded by Veen and Logtmeijer (2005) to explain flood vulnerability from an economic perspective. “A system is susceptible to floods due to exposure, a perturbation, in conjunction with its ability to cope or basically adapt” (Balica et al. 2009). In order to assess flood vulnerability, flood vulnerability should be quantified first. In general, the following three primary approaches were used in the past to quantify flood vulnerability:

(i) Historical Loss Data (HLD) approach (Dilley et al. 2005)

(ii) Vulnerability Curve (VC) approach (Büchele et al. 2006)

(iii) FVI approach

In the HLD approach, loss rates from a flood hazard are calculated using historical loss data derived from previous flood events (Dilley et al. 2005). Although this method is the simplest approach to assess flood vulnerability, accuracy of the method is highly sensitive to data quality, incomplete fragility analysis and insufficient historical records. In this method, final results should be treated with caution as the loss data can be inaccurate (Downton & Pielke 2005) or often unevenly recorded (Dilley et al. 2005).

Flood Vulnerability Assessment by applying a Fuzzy Logic Method

The VC method is based on depth-damage relationship which assigns a damage percentage (for residential buildings) against various water depths during the flood event (Albano et al. 2014). The curve method is more accurate with respect to the HLD approach, since it is based on the real damage survey and loss data are often unevenly recorded (Dilley et al. 2005). However, the vulnerability curve method is very site specific; therefore generated curve for an area cannot be applicable for other regions.

Among these three quantifying methods (i.e. HLD approach, VC method and FVI), the FVI is the most widely adopted approach and is also a tool to identify the risks of flood disaster and increase the safety of infrastructure and humans (Albano et. al. 2014). In other words, the FVI is a tool that can assist urban planners and policy makers in prioritizing flood mitigation strategies and in increasing public awareness by providing information such as hotspots for the flood risk, communities vulnerable to floods and so on (Balica et al. 2009). The most important advantage of the FVI method is that it considers not only the hydrological and economic aspects of flood damage, but also the social aspect of damage caused by floods. This method is more complex than the other two approaches defined above, and it has the potential to assess flood vulnerability in a far better way than the other methods. Due to these advantages, the FVI method is the most widely adopted approach in many recent studies (Kumar et al. 2010; Solin 2012; Kumar & Kunte 2012; Balica et al. 2012, Zhang & You 2013; Kunte et al. 2014; Balica et al. 2013).

Based on the above explanation, it can be concluded that the FVI can quantify the vulnerability in the most accurate form. However, there is not a clear boundary for the different vulnerability components and indicators (Yazdi & Neyshabouri 2012). Therefore, it is useful to adopt a methodology which can deal with uncertainties in the development of a FVI.

In order to deal with uncertainties, FL was proposed by Zadeh (1965) for the first time. It is known as a powerful and flexible tool to model uncertainties and linguistic expressions of human knowledge in the form of mathematical relationships (Yazdi & Neyshabouri 2012). In fact, this theory was developed to deal with uncertainties that are not statistical in nature (Zadeh 1965). By using this theory, a wide range of real-world problems involving linguistic descriptions may be dealt effectively (Yen & Langari 1998).

2.5. Vulnerability indicators

Since a direct measurement of vulnerability is not possible, an indicator or a set of indicators should be used to quantify the condition of a system as an inherent characteristic (Balica et al. 2012). Gomez (2001) noted that indicators should focus on quantifiable and understandable small aspects of a system and give people a sense of a bigger picture. In fact, indicators are input data can be used in indicator based method to decide flood vulnerability of a region. Considering specific indicators can help to assess the systems vulnerability, which can lead to identifying actions needed to decrease the vulnerability (Balica et al. 2012).

In the indicator-based vulnerability assessment, the first step is selecting proper minimum number of indicators (Sullivan 2002). Routine practice for indicator selection is following a conceptual framework to prepare a list of them considering suitability, usefulness and recollection process (Balica et al. 2012). Selected indicators should cover actual conditions and reflect the essentials of flood disaster in any system (Li et al. 2013).

Methods which are used to select indicators of FVIs are broadly grouped into 2: quantitative methods (which are based on expert's opinions) and qualitative methods (statistical approaches). Among different qualitative methods Principal Component Analysis (PCA) has been commonly used in literature to select indicators (Ka źmierczak & Cavan 2011; Zhang & You 2013). The main quantitative methods to select indicators are Analytic Hierarchical Process (AHP), Delphi technique and Participatory Rapid Analysis (PRA). In addition, Balica et al. (2012) used a deductive approach to identify the best indicators in terms of the vulnerability conceptual frame work. As an alternative approach, Barroca et al. (2006) conducted extensive literature review on local projects to identify and finalize best indicators.

2.6. Flood vulnerability factors

Societies are vulnerable to floods based on three main factors: exposure, susceptibility and resilience, which are explained below. In this study also, it has been assumed that, the study area is vulnerable to flood due to these three factors.

2.6.1. Exposure

The values such as infrastructure, goods, cultural heritage, and mostly people are exposed to flood as they are present at the location where the floods occurred. In fact, this factor extents to humans and their properties, which are positioned in flood risk areas. Indicators for this factor can be categorized in 2 groups: first group covers the exposure of elements at risk and the second one provides the details of general specifications of the flood. In more detail, the first group covers information about the location, elevation, population density and land use. The other group supplies information about frequency of flood in floodplains or in the urban area such as slope. Messner and Meyer (2006) explained that the indicators of exposure supply certain facts about hazardous effect on the present elements at risk. In this study, exposure factor is defined similar to definition of Balica et al. (2012), which is “predisposition of a system to be disrupted by a flooding event due to its location in the inundated area”.

2.6.2. Susceptibility

Penning-Rowsell and Chatterton (1977) expressed that susceptibility is damageability of properties and materials during the flood event. In fact, this factor explains how a system can be harmed potentially and the existing abilities to diminish the level of the damage. Smit and Wandel (2006) believe that the vulnerability of any system is a function of the exposure and the susceptibility of that system to any hazardous event. Moreover, Balica et al. (2009) discussed that susceptibility is mostly related to social aspect of flood damage and the system characteristics such as awareness and preparedness of people about the risk they live with. This study assumes the susceptibility as some elements exposed in the system and effect on probabilities of being harmed when a flood event occurs. In this study, susceptibility is identified as the ingredients exposed at the time of flood hazard within the system that effect the possibility of being harmed.

2.6.3. Resilience

The term of resilience was expressed by Holling (1973) as "a measure of a system's solidity and its capability to absorb perturbation and change and still maintain the same relationships between populations and state variables". De Bruijn (2005) expressed the resilience as the system capability to resume from floods. Resilience can also be defined as the system capacity to re-achieve its balance after a reflex into a perturbation (Begon et al. 1996; Jorgensen 1992). Galderisi et al. (2005) argued that the resilience is a society or a system capacity to adapt itself to any change by resisting and modifying itself, to maintain or gain an acceptable level of structure and functioning. Pelling (2003) also explained this factor as any system or community ability to adjust to threats or mitigate the hazardous event damage. In this study, resilience or resistance is defined as the ability of a system to reduce the effect of floods.

2.7. Uncertainty in flood vulnerability

When the probabilities and extent of hazard and/or its related consequence are doubtful, uncertainty occurs due to the ambiguity of knowledge (De Bruijn 2005). The importance of uncertainties in flood risk management depends on the effects on decisions. Green (2004) explained that the decision is uncertain if the choices to be made are in doubt. Originally, uncertainty comes from vagueness in knowledge of the alternatives or their consequences or of the decision criteria.

One of the main uncertainties in flood risk management is the variability in nature (De Bruijn 2005). Also, Simonovic (1997) stated that there are different sources of uncertainties in terms of flood risk assessment originate from human knowledge and natural variability. The uncertainty of knowledge is coming from limited ability to model the real world events and phenomena with mathematical models. The flood risk uncertainty is mainly because of spatial and temporal variability in urban stormwater elements and variables such as precipitation, drainage area size, shape and orientation; ground cover and soil type; slope of terrain; vegetation; roughness; porosity;

storage potential (wetlands, ponds, reservoir etc.); characteristics of drainage system, etc. (Ahmad & Simonovic 2013).

The use of a FVI can help in modelling various scenarios to reduce the uncertainty. Balica et al. (2012) mention that this function cannot reduce the uncertainty essentially; however it can be a useful tool to assist the decision makers for decisions that increase the mitigation and adaptation to flood risk. It helps them to identify hotspots, where for instance, specific actions can be prioritised and can take place to raise the public awareness.

2.8. Fuzzy logic approach in hydrology

Water resources and hydrology mostly involve a system of principals, methods and concepts to deal with modes of reasoning which are approximate rather than exact. In fact, hydrology involves uncertainties due to factors such as climate, limited data and imprecise modelling capabilities (Bogardi et al. 2003). In order to integrate a probabilistic approach, FL allows researchers to consider the treatment of vagueness in hydrology (Zadeh 1965). Fuzzy rule-based modelling can be considered as an extension of FL. This type of modelling has a high potential in some cases when a causal relationship is well established but is difficult to calculate under real life conditions and scarce data situations (Sen 2001, 2010).

The fuzzy rule-based modelling has been used in different hydrology areas such as: classification of spatial hydro meteorological events (e.g., Bardossy & Duckstein 1995); climatic modelling of flooding (Bogardi et al. 1995); modelling of groundwater flow and transport (e.g., Bardossy & Disse 1993; Dou et al. 1997b, 1999); modelling regional-scale nitrate leaching using available soil and cultivation data (e.g., Bardossy et al. 2003; Haberlandt et al. 2002); forecasting pollutants transport in surface waters (e.g., Di Natale et al. 2000); water quality, groundwater, water resource and flood vulnerability (e.g., Esogbue et al. 1992; Chang & Chen 1996; Bender & Simonivic 2000; Mujumdar & Subbarao 2004; Labadie 2004; Liou et al. 2004; Said et al. 2004; Akter & Simonivic 2005; Ocampo-Duque et al. 2006; Muhammetoglu & Yardimic 2006; Nasiri et al. 2007; Nobre et al. 2007; Lermontov et al. 2008; Fu 2008; Niksokhan et al. 2009; Kerachian et al. 2010; Yazdi & Neyshabouri 2012; Rezaei et al. 2013).

Among above studies, Yazdi and Neyshabouri (2012) assessed the flood vulnerability index for an urban watershed in Iran by applying a fuzzy rule-based method. They selected 6 indicators to map the flood vulnerability based on the availability of data and considering the fact that a system can be vulnerable to a hazardous event because of physical exposure, susceptibility and socio-economic aspects. The present study uses 24 indicators from three components (social, economic and hydrological) and therefore provides a more comprehensive and detailed fuzzy based FVI in comparison to Yazdi and Neyshabouri (2012).

2.9. Summary

It can be highlighted based on the literature review that FVI is a powerful tool since it considers not only the hydrological aspects of flood damages, but also the social and economic aspects of damage caused by floods. Literature review showed that there is no worldwide accepted methodology in constructing a FVI. Hydrologic events include many uncertainties due to their nature such as climate, limited data and imprecise modelling (Sen 2010; Bogardi et al. 2003). Moreover, there is not a clear boundary for the different vulnerability components and indicators (Yazdi & Neyshabouri 2012). Therefore, FL is a suitable approach for FVI development. Therefore, FL based FVI was developed in this study, and developed FVI considered hydrological, economic and social components of floods comprehensively in addition to FL based FVI studies in the literature.

Chapter 3

Flood Vulnerability Index Method

3.1. Introduction

Human population have always been vulnerable to floods, which are increasing in frequency and magnitude due to the climate variability. Flood is also known as the most common natural destructive phenomenon (Yoon et al. 2014) causing severe physical, social and economic losses in rural and urban regions (Masood & Takeuchi, 2011; Balica et al. 2012; Zhang & You 2013; Balica et al. 2013; Albano et al. 2014). Since the number of people who are exposed to the adverse effects of hazardous flood events are increasing, the assessment of flood impacts have gained more importance in recent years. Flood studies and protection policies have been combined with technical and social aspects in flood prone areas (Balica et al. 2013).

In a restricted sense, Flood Risk Management (FRM) is managing procedure of an existing flood risk condition however, in a general sense it's a planning process which reduces the flood risk in a system (Plate 2002). FRM will bring a new holistic view on flood management and policy and a FVI can play a key role in the area of risk assessment as well as making comparisons across different urban and rural flooded areas.

This chapter presents the structure of a FVI including the commonly used components, the general steps used in the development of a FVI as well as various issues and challenges in its development.

3.2. General structure of a FVI

The general structure of a FVI is shown in Figure 3.1. As can be seen from this figure, FVIs have, in general, three components, namely hydrological (physical), social and economic. It should be noted that not all studies have used all three components. Hydrological component represents the climatic and hydro-geo-morphological characteristics of a region, whereas social and economic components are related to people (e.g. gender, age, and disabilities), infrastructure and assets of a region. Details of these components are discussed in the following section.

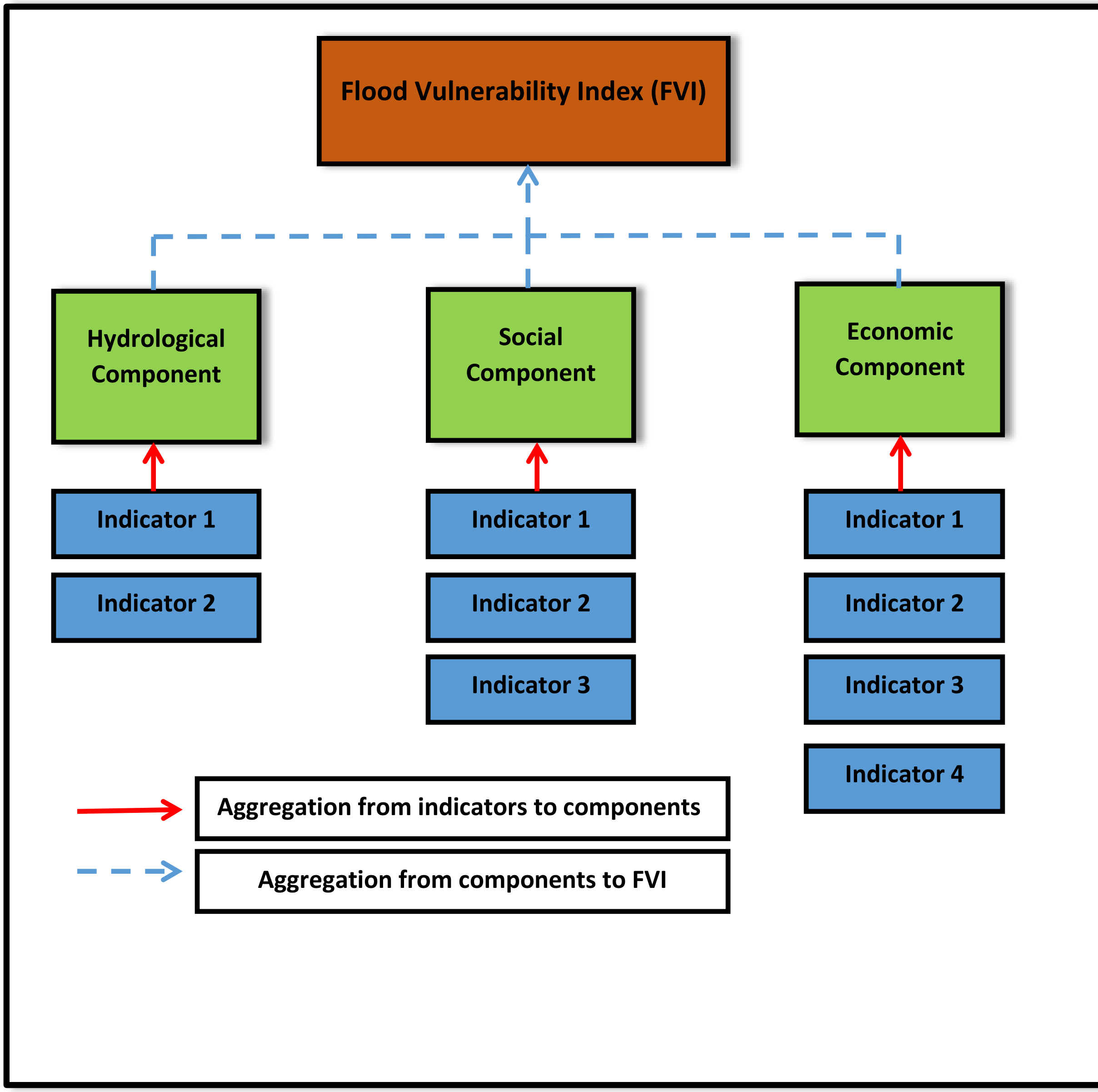


Figure 3.1. General Structure of a FVI

3.3. Components of a FVI

As explained earlier, the general structure of a FVI includes different components (i.e. hydrological (physical), social and economic). As the direct measure of flood vulnerability is not possible, all components (i.e. hydrological, social and economic) use set of indicators. These indicators can be decided by variables, which characterize the flood vulnerability of a region (Solín 2012). McLaughlin and Cooper (2010) explained that using all available data to create an index were popular in the initial FVI development studies. For instance, Dal Cin and Simeoni (1989) stated that using more indicators (variables) can result in more accurate results. However, this is not necessarily true since the indicators, that represent the associated component (i.e. hydrological, social or economic) best, should be selected in FVI development. Moreover, some of the indicators, which are showing high correlation, can be eliminated in index development (Balica et al. 2009).

Hydrological component or physical component comprises geo-morphological and hydro-climatic condition of a region using physical indicators. This component is related to the predisposition of infrastructure to be damaged by floods. Also, explains how the physical condition can influence the vulnerability of a certain region to floods. Some common indicators of this component are daily water stage, annual peak flow, rainfall intensity and distribution, topography, runoff, slope, geological conditions, soil type, drainage network, flood water depth.

Social component explains how lives of population which belongs to a system are affected due to the flood events. In other words, this component considers the indicators directly related to human beings. They can measure variables explaining the context, skills, knowledge, capacity, beliefs, households, organizations and communities in a system. In other words, social indicators are typically used to evaluate current conditions or achievements of social goals in terms of human health, education, housing and social equity issues. Population is the most significant and common indicator of social component of a FVI (Kubal et al. 2009). In population, elderly people and children are more vulnerable to floods, therefore age of the people should also be considered as indicator in social component of a FVI (Meyer et al. 2009).

Indicators, which represent direct and indirect flood damages on residential buildings, infrastructures, industrial facilities, transport system, and commercial facilities, can be categorized in economic component (Ahmad & Simonovic 2013). The regions, which are developed economically, are more able being fast recovery from losses and cope with flood because of insurance, social safety nets and welfare policies (Zhang & You 2013).

3.4. Steps in Developing a FVI

There are in general five steps undertaken for the development of a FVI, which are as follows:

i) Selection of indicators

ii) Standardization

iii) Weighting of indicators

iv) Aggregation to form FVI

v) Interpretation

Figure 3.2 presents the common methods used in each of the above five steps, which are discussed in detail in the following sub-sections.

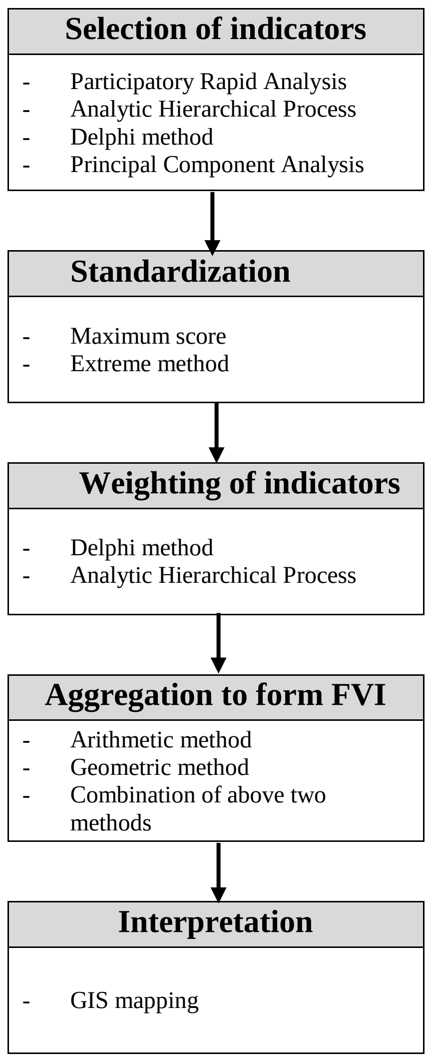


Figure 3.2. Steps used in the development of a FVI and common methods used in each step

3.4.1. Selection of indicators

The first step of FVI development is the selection of appropriate indicators. Standard practice (Peduzzi et al. 2001; Pratt et al. 2004; Adger & Vincent 2005; Guillaumont 2008) is preparing a list of indicators considering factors such as suitability, having a conceptual framework or a clear definition, accessibility of data, their usefulness and ease of recollection. Selected indicators should cover actual conditions and reflect the essentials of flood disaster (Li et al. 2013).
Methods which are used to select indicators of FVIs can be broadly grouped into 2 groups: quantitative methods (which are based on expert's opinions) and qualitative methods (statistical approaches).

Among different qualitative methods Principal Component Analysis (PCA) has been commonly used in some studies to select indicators (Ka´zmierczak & Cavan 2011; Zhang & You 2013). The main quantitative methods to select indicators are Analytic Hierarchical Process (AHP), Delphi technique and Participatory Rapid Analysis (PRA).

PCA is a statistical way to convert a set of related variables by linear transformation in to another group of unrelated variables and present descending order based on the variance. In other word, PCA method is used to reduce the complexity of multidimensional data or avoiding double-counting of inter-correlated indicators .This method is applied in some studies to finalize the best indicators (Ka´zmierczak & Cavan 2011; Zhang & You, 2013; Lujala et al. 2014).

Analytic Hierarchical Process (AHP) approach (Saaty 1986) can be considered as a mathematical core of Multi Criteria Decision-Making or Multi Criteria Analysis (MCA) tool which uses pair wise comparison matrices to create a scale of preference from a set of variables (Dai et al. 2001).

Delphi technique is a method to get expert's opinion by using series of questionnaires without congregate the experts at agreed place and time (Delbecq Ven & Gustafon 1975). By using this method, experts can assess, modify and present their opinions and feedbacks about the related issue (Wang et al. 2011; Kienberger 2012).

Participatory Rapid Analysis (PRA) is a form of quick appraisals of rural and environmental conditions, developed between 1970s and 1980s, to conventional sample surveys (Younus & Harvey 2013). In this method, the analysis is open-ended which usually performs by groups of people through comparison. Participating local people in research and planning increase their effectiveness as well as saving time and money (Cornwall & Jewkes 1995). Younus and Harvey (2013) identified 45 indicators for their research through the PRA sessions in a community level in their study. In Delphi technique experts are the only participants involve in a project to get opinion while in PRA local people and communities with an extensive experience in related issue can be involved. In addition to commonly used indicator selection methods in literature (as explained above), Balica et al. (2012) used a deductive approach to identify the best indicators in terms of the vulnerability conceptual frame work. As another approach, Barroca et al. (2006) conducted extensive literature review on local projects to identify and finalize best indicators. In this study, indicators are selected based on availability of data and MCC experts' opinion.

3.4.2. Standardization

Considering the fact that the actual data have different measurement scales and, some of the indicators have different relationship and effectiveness on flood vulnerability (some positive and some negative), indicators should be standardized from their original values to the value ranging from 0 to 1 to eliminate the impact of different scales and dimensions on the final index (Wang et al. 2011). The standardization has to be done individually for all indicators (Fedeski and Gwilliam. 2007).

There are different methods for standardization such as standard score, maximum score, extreme method (Featuring scaling), and coefficient of variation. Featuring Scaling and the maximum score are the most common methods (Equation (3.1) and (3.2)) (Wang et al. 2011; Zhang and You 2013):

$$V_{is} = \frac{X_i - \mathrm{X}_{imin}}{X_{imax} - X_{imin}} \tag{3.1}$$

where V_{is} is a standardized value, $X_i$is the i_{th} value, X_{imax} is the maximum value, and X_{imin} is the minimum value for the indicator i.

Solin (2012) used maximum score approach to standardize indicators using the following equation:

$$X'_i = \frac{\mathrm{X}_i}{X_i^{max}} \tag{3.2}$$

where X'_i is standardized score, X_i is criterion score, and X_i^{max} is the maximum criterion score. In this study standardization is done using the second equation.

3.4.3. Weighting

After the selection of indicators and standardization, the next step is to assign suitable weights to the selected indicators. At this step, a weighting score is individually assigned to each indicator. Weighting the indicators enables to take into account the relevant effects of each of them in vulnerability level. For weighting process, one of the most important issues is to adopt worst-case approach, if there is more than one probability to rank a specific indicator (Del Rio and Gracia, 2009).

Weighting can be carried out in two different ways: equal and unequal weighting. In the equal weighting, indicators have the same (equal) importance on the final index, whereas some of the indicators have greater or lesser degree of importance on the final index in unequal weighting. The most common unequal weighting methods in the literature to assign the weights are Delphi and AHP methods.

As mentioned above, the Delphi method involves getting expert's opinion by using a series of questionnaires without congregating the experts at an agreed place and time. This application includes the design of some questioners, selection of key experts (respondents), distribution and collection of the completed questionnaires and data analysis (Wang et al. 2011).

The AHP is a structural methodology for analysing and organizing complex decisions based on mathematics and psychology. This approach gains the public or expert's opinion to assign the weights to indicators performing a pair wise comparison matrices and calculating the eigenvectors for the matrices. In fact, this method compares factors in pairs to judge which of them is preferred (Zou et al. 2012; Fedeski and Gwilliam 2007).

The other methods, which were used in few studies for weighting assignment, are simple additive weighting (SAW) (Scheuer et al. 2010; Kubal et al. 2009), the weighted matrix index value (Younus and Harvey 2013) and the optimization model (Li et al. 2013; Huang et al. 2012).

In this study, indicators are weighted equally except the susceptibility indicator (i.e., drainage system quality and number of flood protection structure (DFW)) of economic component. For this indicator, considering existing flood protection structures and the quality of drainage system in each suburb, the good, medium or poor conditions are assumed and arbitrary weights are assigned to each suburb. The drainage system quality has been assessed based on the number of hotspots which are reported for the drainage system in each suburb (Moreland Flood Management Plan, 2013). The arbitrary weights for DFW indicator are 0.25, 0.5 and 0.75, which represent poor, medium and good conditions for each suburb.

3.4.4. Aggregation and final index calculation

Once suitable weights for all indicators are decided, aggregation process takes place. The two common methods for aggregation are arithmetic (additive) or geometric (multiplicative). Also, combination of these two basic methods (i.e. additive and multiplicative) can be applied for aggregation.

The arithmetic method is applied through the summation of weighted indicator (and components) values (as shown in Equation 3.3), whereas geometric method is used by multiplying weighted indicator (and component) values (Equation 3.4).

$$I = \sum_{j=1}^{N} W_i C_i \tag{3.3}$$

$$I = \prod_{i=1}^{n} {C_i}^{W_i} \tag{3.4}$$

where I represents the aggregated index, n is the number of indicators to be aggregated, C_i is the component of indicator i and W_i is the weight of indicator i. Aggregation can be done in three ways: (1) from indicators to components (2) from components to final index and (3) from indicators to final index (without aggregating indicators to components). In this study, the final vulnerability index has been calculated based on arithmetic aggregation with equal weights for each component. In fact, aggregation has been done from components to create the final index by summing up amounts for each components and dividing by 3.

3.4.5. Interpretation

The final step of FVI development is to define an interpretation criterion to evaluate final index values. Some studies (Fedeski & Gwilliam 2007; Kumar et al. 2010) evaluated the final index based on three classes: low, moderate and high vulnerability, whereas some other studies (Balica et al. 2013; Rawat et al. 2012; Wang et al. 2011) defined a more detailed classification as very low, low, moderate, high and very high vulnerability. The common range for classifying the final index in the literature is from 0 (very low vulnerability) to 1 (high and very high vulnerability) (Solin 2012; Balica et al. 2013). Some other common ranges used in the literature are mentioned in Table 3.1 based on Hegde and Reju (2007), Ologunorisa (2004), Rao et al. (2008) and Kumar et al. (2010).

Table 3.1. Common interpretation criteria ranges for the final FVI

Author(s) (year)	Range	Level of Vulnerability
Hegde and Reju (2007)	> 1.5 1.5-3.2 > 4.2	Low Medium High
Kumar et al. (2010)	2.1-4.7 4.7-9.5 > 9.5	Low Medium High
Rao et al. (2008)	15-26 27-36 37-46 47-57	Low Moderate High Very High
Ologunorisa (2004)	>100 100-600 > 600	Low Medium High

3.5. Summary

The structure of FVIs, consists of three components, in general, which are hydrological, social and economic as explained earlier. However, some components such as politico-administrative and environmental were rarely used in literature (Meyer et al. 2009; Balica et al. 2012). It is mostly a challenge to find reliable socio-economic data in particular for developing countries. On the other hand, hydrological indicators, which represent hydro-climatic aspect of a region, can be easily measured and to be quantified to evaluate the flood risk in a true scale (Ologunorisa 2004). Therefore, majority of FVIs in many studies consider hydrological component.

One of the major weaknesses of indicator based method is related to accuracy of data. Data for indicators must be exported from reliable sources (Balica et al. 2009). In addition to accuracy of data, sufficient number of indicators should be used in components for better representation. This will result in more reliable final indices.

Chapter 4
Fuzzy Logic Method

4.1. Introduction

As discussed in earlier chapters, there is not a clear boundary for the different vulnerability components and indicators. Therefore, it is useful to adopt a methodology which can deal with uncertainties in development of a Flood Vulnerability Index (FVI). For this purpose, this chapter presents the FL method which has been applied to develop the FVI for the study area. The chapter also illustrates the different components of FL method, namely fuzzy sets, fuzzy membership degrees, fuzzy logic rules (IF…THEN rules), fuzzification and defuzzification steps as well as the fuzzy inference engine and its two common methods (Mamadani and Sugeno).

4.2. What is Fuzzy Logic?

The concept of FL or fuzzy set theory was proposed by Zadeh for the first time (Zadeh 1965). It is known as a powerful and flexible tool to model uncertainties and linguistic expressions of human knowledge in the form of mathematical relationships (Yazdi and Neyshabouri 2012). In fact, this theory was developed to deal with uncertainties that are not statistical in nature and by using fuzzy sets, a wide range of real-world problems involving linguistic descriptions may be dealt effectively (Zadeh 1997).

Hydrological phenomena are complicated for precise descriptions and hence approximate reasoning or fuzzying must be introduced to gain reasonable models. Most of the available and traditional tools which are being used for modelling, reasoning, and computing are deterministic and crisp in nature and these crisp (classical) models, ignore fuzzy human knowledge in mathematical methods. In hydrological events, however, it is needed to develop a model which can formulate human knowledge in a systematic way to be able to integrate it with other source of information such as linguistic information (Sen 2010; Zimmermann 2010).

4.3. Basic concepts of Fuzzy Logic

This study uses fuzzy inference which is a primary application of FL. The main approach of fuzzy inference is taking input variables through a mechanism which is comprised of parallel IF-THEN rules and fuzzy logical operations, and then reaches the output space. The IF-THEN rules are expressed directly by human words, and each of the word is regarded as a fuzzy set. All of these fuzzy sets are required to be defined by membership functions before they are used to build IF-THEN rules. In this section, basic FL concepts such as fuzzy sets and their properties, membership functions, fuzzy logical rules, IF-THEN rules and fuzzification are presented.

4.3.1. Fuzzy sets (FS)

Fuzzy sets are introduced by Zadeh (1965) as a mathematical method to explain the vagueness in linguistics, which can be considered as a generalization of classical set theory that is known as crisp set theory. The main difference between crisp and fuzzy sets is that the crisp sets always have unique Membership Functions (MFs) however, every fuzzy set has infinite MFs which provide the maximum ability to adjust its utility based on any condition (Ahmad & Simonovic 2011; Afshar et al. 2011). To understand the fuzzy sets, first, it's important to understand the crisp (deterministic) sets. The traditional logic assigns a Membership Degree (MD) of 1 to each item as a member of a set and 0 to the non-members.

In hydrology field, basic concepts can be generalized by replacing a crisp set as a target under the concept of fuzzy sets. In fact, by adopting the FS theory, a linguistic variable can be converted to the mathematical form of a FS. A set of linguistic variables (A) can be normalized as (Zimmermann 2010):

$$A=\{X_1, \mu A(x) | x \in X\} \quad 0 \leq \mu A(x) = 1 \qquad (1)$$

where, x_1 belongs to X (a range of possible values) and is an element of fuzzy set A, and the value of $\mu A(x)$ shows the membership grade of x_1 in fuzzy set A (specifying to what degree x_1 belongs to the fuzzy set A). In this study, fuzzy sets are defined in 3 sets of low (0-0.3), medium (0.3-0.6) and high (0.6-1) ranges for each indicator considering the range of available data.

4.3.2. Membership functions

Membership Functions (MFs) or Membership Degrees (MDs) are the fuzzy sets that can be expressed by mathematical expressions by considering the normality and convexity properties. Fuzzy sets can be defined in terms of these MDs and map a domain of interest (each point in the input space) to the interval [0, 1] and generally, these fuzzy sets can be in different forms such as triangular, trapezoidal, bell and Gaussian (Lermontov et al. 2008). The simplest MD has a triangular shape and is a function of a support vector x which depends on three (a, b and c) scalar parameters, however, the trapezoidal MD is a function of a support vector x which depends on four scalar parameters (a, b, c and d). The mathematical expression of triangular and trapezoidal MDs as the most common ones are shown is shown in Figure 4.1.

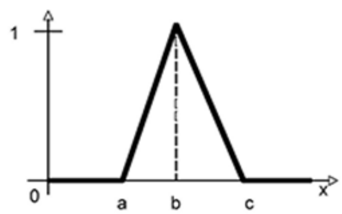
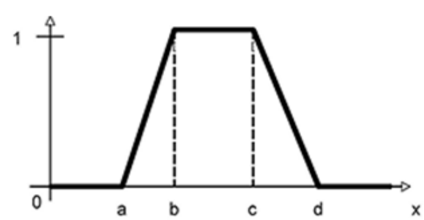
	Shape	Function
Triangular		$\mu(x)=\begin{cases} 0, \& x \le a \\ \frac{x-a}{b-a}, \& a \le x \le b \\ \frac{c-x}{c-b}, \& b \le x \le c \\ 0, \& c \le x \end{cases}$
Trapezoidal		$\mu(x)=\begin{cases} 0, \& x \le a \\ \frac{x-a}{b-a}, \& a \le x \le b \\ 1, \& b \le x \le c \\ \frac{d-x}{d-c}, \& c \le x \le d \\ 0, \& d \le x \end{cases}$

Figure 4.1. Triangular and trapezoidal MDs (Sen 2010)

In this study, the shapes of MDs are selected as a mix of triangular and trapezoidal based on the literature and expert knowledge.

4.3.3. Fuzzy logical rules

Any hydrologic event has a generating mechanism including a set of relationships between input and output variables and can be expressed by different methodologies such as mathematic, statistic and stochastic processes in which all of them have rational and logical foundations. All these methodologies are based on the Classical Logic (CL) and it is important to have a mathematical formulation for them. Also, it is necessary to have a set of assumptions, simplification statements and parameters in a CL. Expanding a model construction from CL to FL needs detailed logical relationships among input and outputs based on fuzzy sets without limited assumptions and parameters (Sen 2010). To generate a mechanism for a hydrologic event, it is needed to express a set of rules as a fundamental requirement. Therefore, a rule base is a collection of all possible rules in which any of them explains some part of the behaviour of the hydrological event. There are many methods to establish the rule base such as mechanical, personal logic inspirations, and expert views on the event prior to rule base establishment. However, it is important to fuzzify all input and output linguistic variables (Lermontov et al. 2008; Kohonen 2001; Chen & Mynett 2004). The fuzzification establishes a bigger generality and efficient ability to model a real world problem. In other words, FL helps to gain robustness and lower solution cost.

4.3.4. Fuzzification

One of the purposes of modelling is to map input variables to output variables in a way that the output variables show the minimum error. It is not compulsory to have a database for FL modelling in the beginning. The first stage of FL modelling is that of identifying input and output linguistic variables and then breaking them down to the formal fuzzy subsets. Following points are important in fuzzification:

- There may be many input variables whereas there is a single output variable. In fact, it is Multiple-Input-Single-Output modelling (MISO).
- It has been advised that the number of fuzzy sets should be taken at least three because it can pick the nonlinearity in the variations in the hydrologic phenomenon behaviour.

- With regards to fuzzy set shapes, they must be determined and it is advised to depend on triangular and trapezoidal MDs initially to establish the model.
- The most right and left sides of MFs must reach to MDs equal to 1, in any fuzzification procedure.

For any successful modelling study, it is important to decompose linguistic variables in a qualitative way by considering the above points (Zadeh 1997; Seising 2007; Sen 2010).

4.3.5. "IF…THEN…" Rules

A grammatical sequence of words in any language is a sentence (Sen 2010). Sentences should express a meaning by connecting different conditions to each other. Scientific sentences have two parts which are referred to as premise. The premise also, has two parts: the antecedent and the consequent. The input conditions are explained in the antecedent part and the input condition are implied in consequent portion. In most of the cases the premises has "IF…THEN…" format. In our case, an example can be expressed as below:

"IF the number of disabled people are in the low range (fuzzy set), THEN the vulnerability is low."

The above sentence defines the relationships among the inputs, outputs and fuzzy sets. In general, IF…THEN rules can be written in the following way:

IF A is a THEN C is c.

IF B is b THEN C is c.

where a, b, and c are the linguistic terms for the subsets expressed for sets A, B, and C, respectively.

In this study, input variables are fuzzified into 3 fuzzy sets (as, 'Low', 'Medium', and 'Large'). For each component and for 9, 8 and 7 inputs, the number of all possible rules are 19683, 6561 and 2178 rules, respectively. However, the human mind cannot handle this kind of high amount calculation (Chau 2006; Zadeh 1973). Therefore, to reduce possible imprecision, in each component, indicators of social, economic and hydrological components were clustered into different groups, and the Fuzzy Inference Systems (FISs) and rules were created for each group. Then, outputs of grouped FISs were re-grouped, and final FIS were created for each component.

4.4. Fuzzy inference system

Structure of a fuzzy system is based on numerical estimation. The FIS of a fuzzy expert system, uses a collection of MDs and rules, instead of mathematical statement, and provide approximate reasoning about data. Each expert system has 2 main functions. One is problem solving by using different domain-specific knowledge and the second one is the user interaction function (Adriaenssens et al. 2004). In general, an expert system which is a user-interactive set up, as shown in Figure 4.2, has three major parts:

1) Knowledge base: this section includes the specific knowledge and facts about the application domain plus the rules that describe relations.

2) Inference engine: this part uses the available knowledge to perform reasoning to gain answers for user's questions.

3) User Interface: this section enable the user to communicate with the system and give an insight into the user in terms of problem solving process through the inference.

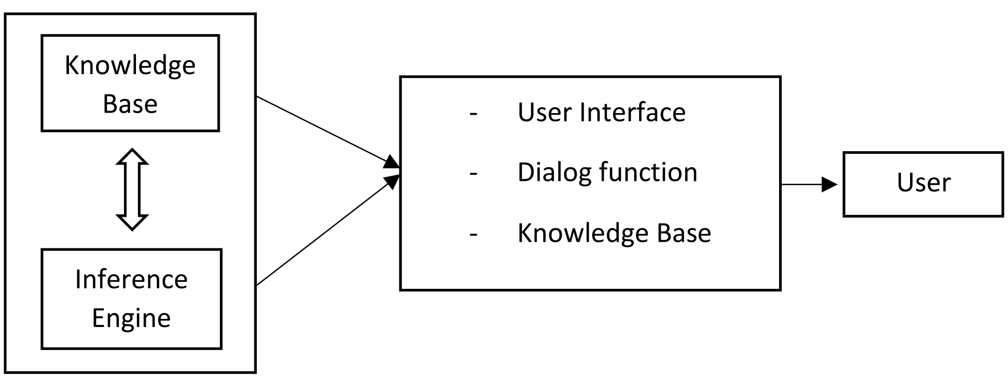


Figure 4.2. Structure of a user-interactive fuzzy expert system (Sen 2010)

The general steps of any FIS application in practice are also shown in Figure 4.3.

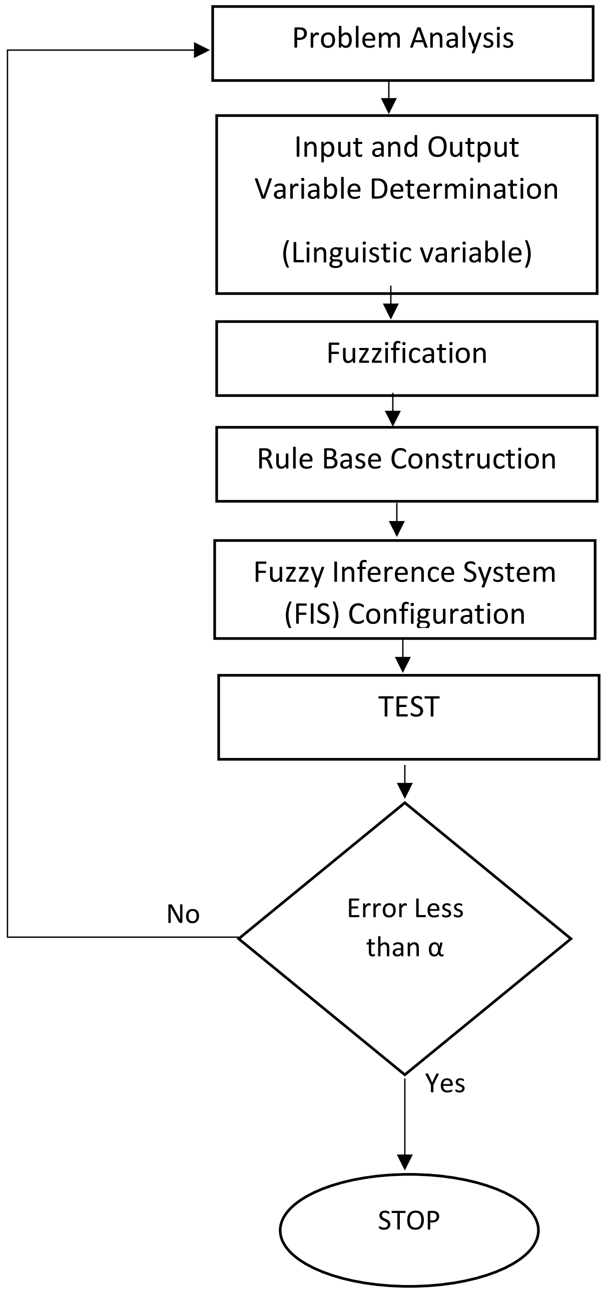


Figure 4.3. General steps in a fuzzy inference system application (Sen 2010)

In summary, the first step is to take inputs in and express the degree to which they belong to each of the fuzzy sets through the membership functions. Then and after fuzzifying inputs, the membership degrees for the premise is computed for each rule and is applied to the concluding part of each rule. The results are assigned to each output variable for each rule in one fuzzy subset. In next step, all the fuzzy subsets will be aggregated to form a single fuzzy subset for each output.

Finally, in defuzzification step, the fuzzy output set will be converted to a crisp number by using the different defuzzification methods (Gharibie et al. 2011; Raju et al. 2011). There are two common fuzzy inference methods. The first one is Mamadani, which is presented by Mamadani (1975) to control a steam engine and boiler combination. The other fuzzy inference system is the Sugeno, which was proposed by Sugeno (1985) also known as Takagi-Sugeno type (Sen 2010; Raju et al. 2011).

4.4.1. Mamadani FIS

Mamadani FIS was presented by Mamadani (1975) to control a steam engine and boiler combination. This FIS is completely fuzzy in input, output and rule base and so, the estimations are fuzzy sets which are not formal but in various shapes without any MD equal to 1. This FIS system helps the user to include unavoidable imprecision in the available data. Mamadani FIS is the genuine process of mapping based on the given set of input variables to an output using a set of fuzzy rules with fuzzy inputs and outputs. The general steps below are necessary for the successful application of a Mamadani (Jang et al. 1997; Sen 2010).

1) Fuzzification of inputs: The first step is to take inputs in and express the degree to which they belong to each of the fuzzy sets through the membership functions.

2) Inference: After fuzzifying inputs, the membership degrees for the premise is computed for each rule and is applied to the concluding part of each rule. The results are assigned to each output variable for each rule in one fuzzy subset.

3) Composition: At this stage, all the fuzzy subsets will be aggregated to form a single fuzzy subset for each output.

4) Defuzzification: The fuzzy output set will be converted to a crisp number by using the different defuzzification methods.

Figure 4.4 shows the Mamadani FIS graphically. The Mamadani FIS is employed in this study.

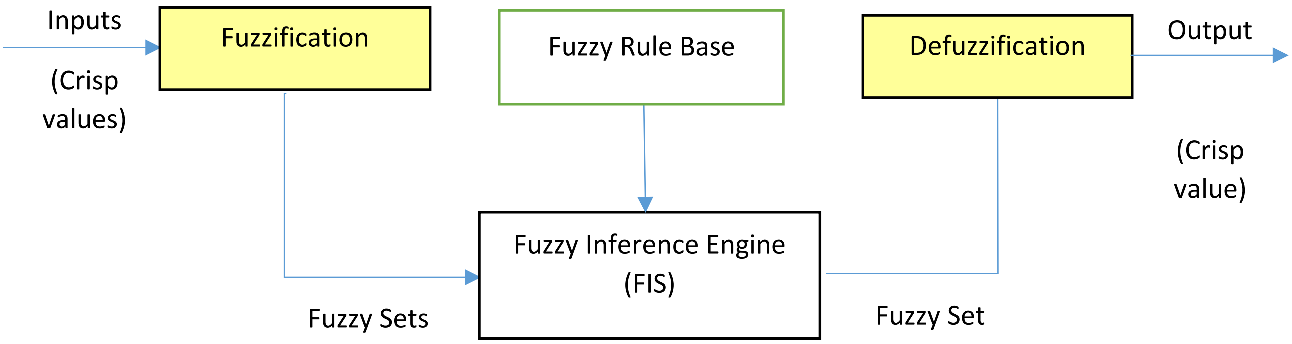


Figure 4.4. Mamadani FIS System (Yazdi and Neyshabouri 2012)

4.4.2. Sugeno FIS

The second fuzzy inference system is the Sugeno, which was proposed by Sugeno (1985) also known as Takagi-Sugeno type (Takagi and Sugeno 1985). They presented a systematic method to generate fuzzy rules, based on a given set of input-output data. The Takagi & Sugeno fuzzy inference system contains an inference system that the fuzzy rule conclusion comprises a weighted linear combination of a crisp inputs. This system is good for approximating a large class of non-linear systems. In Sugeno FIS, each rule has a crisp value as an output therefore, the final overall output will be produced as a weighted average and no need to pass a time-consuming defuzzification process as Mamadani FIS requires. In general the difference between these two systems are the definition of the consequent parameters (Rezaei et al. 2013; Sen 2001). Figure 4.5 shows the schematic view of Sugeno FIS system.

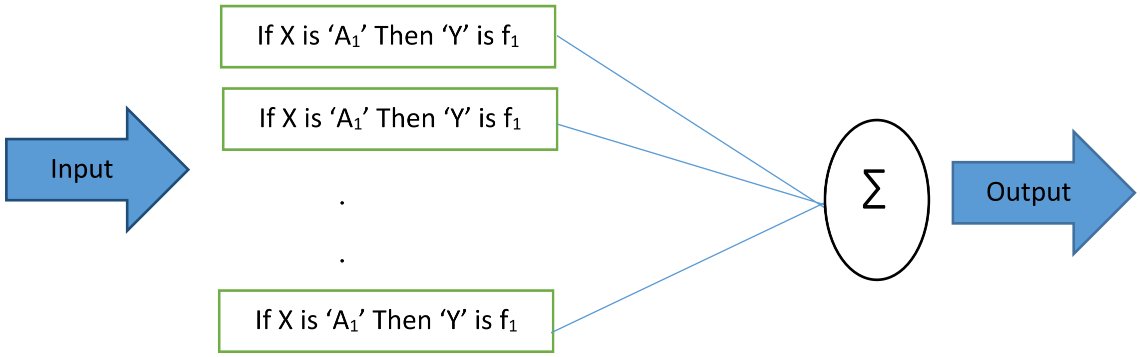


Figure 4.5. Sugeno FIS system (Takagi and Sugeno 1985)

4.4.3. Defuzzification

The reverse process of fuzzification is defuzzification. In fact, it converts the confidences in fuzzy sets which are expressed in words into real numbers. This step is necessary especially when the output needs to be expressed as a crisp number by the user. In other words, the final step of this approximate reasoning algorithm is choosing a crisp number as the output variable.

4.5. Summary

FL is known as a powerful and flexible tool to model uncertainties and linguistic expressions of human knowledge in the form of mathematical relation (Yazdi and Neyshabouri 2012). This theory was developed to deal with uncertainties that are not statistical in nature (Zadeh 1965) and by using the theory a wide range of real-world problems involving linguistic descriptions may be dealt effectively (Yen and Langari 1998). The fuzzy sets involve the subjective uncertainties and ambiguities of judgments in vulnerability assessment, therefore it is a very helpful approach in flood vulnerability index development. This method has grown in the field of water resources management successfully during last decades. Development of a Fuzzy Logic (FL) based FVI is one of the objectives of the present study by choosing proper fuzzy sets, membership functions and generating suitable IF…THEN rules.

Chapter 5

Application of FL Method to the Study Area

5.1. Introduction

The FVI method and FL approach as well as their advantages were discussed in chapters 3 and 4 respectively. A combination of the methods is applied to the study area by selecting 24 indicators of three vulnerability factors in the region. This chapter presents the steps of the methodology which has been applied in the study area and discusses the following sections: data collection and selection of indicators, indicator standardization and weighting, calculation of FVIs through application of FIS, aggregation of FVIs, and interpretation of the FFVIs. Finally, results are provided for each of the social, economic and hydrological components in GIS maps and the most and the least vulnerable suburbs are identified.

5.2. Study area

Moreland City (MC) covers an area of 50.9 km^2 and is located in the inner and mid-northern parts of Melbourne. The area consists of 12 suburbs (355 grids) including Gowanbrae, Glenroy, Fawkner, Hadfield, Oak Park, Pascoe Vale, Pascoe vale South, Coburg North, Coburg, Brunswick West, Brunswick East and Brunswick. MC is mainly bordered by Moonee Pond Creek to the west and Merri Creek to the east. According to the available census data, the residential population of the MC is 155,087 as in June, 2011 (Id community 2016). Figure 5.1 shows the location and suburbs of MC. In general, MC experiences two types of floods:

1) Riverine flooding which happens when the water overtops the bank in the creek or river
2) Overland flooding which happens when the capacity of the local drainage network is not able to carry the excess stormwater flow

Considering the fact that this area has a high density of population and there have been major floods from waterways and drainage network from 1963 to 2011 (Moreland Flood Management Plan, 2013), MC was chosen as the case study area to identify flood risk and vulnerability.

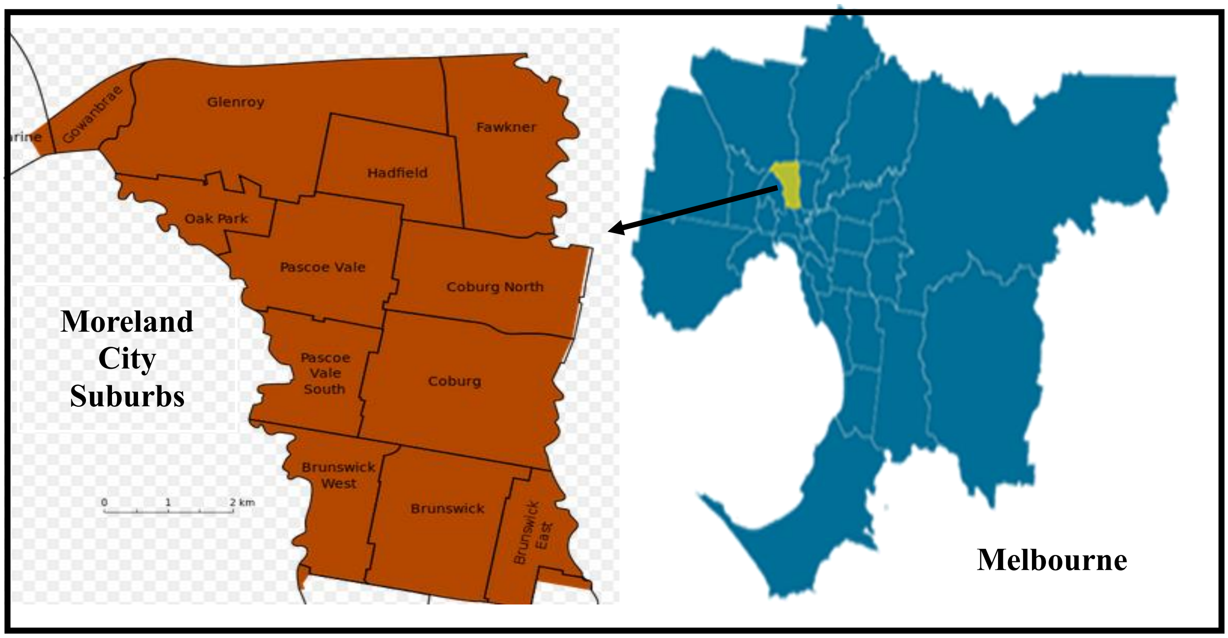


Figure 5.1. Location and suburbs of MC

5.3. Research Methodology

General steps of the research methodology are consists of five steps as shown below:

1. Data collection and selection of indicators
2. Standardization and weighting of indicators
3. Calculation of FVIs through application of FIS
4. Aggregation of FVIs
5. Interpretation of the FFVIs

5.3.1. Data collection and selection of indicators

The required data for this project can be categorized into three groups (under hydrological, social and economic components) as shown in Table 5.1. Required data are collected from Bureau of

Meteorology (BOM), Melbourne Water and the MCC. The items which are listed in the table are used to select proper indicators which are aggregated to define components. Indicators are selected in this study based on availability of data and MCC experts' opinion through some technical meetings and chats. Selected indicators for this study are listed in Table 5.2. These are the data which are collected separately for each grid in each suburb for the entire study area.

Table 5. 1 Data collected for each of the three components

Hydrological	- Rainfall - Permeable/ Non permeable areas - Drainage network length/Density - Digital Elevation Model (DEM) - Land use - Natural water way - Flood extent - Flood protection structures
Social	- Population density - Age - Percentage of disable people - Income levels - Education levels - Broadband Connection
Economic	- Business units in flooded area or close to river - Public facilities close to river or in flooded area - Unemployment - Drainage system quality

Table 5. 2. List of selected indicators

Component	Exposure	Susceptibility	Resilience
Social	Population density (PD)	Number of low income people (Pli)	Number of people with broadband connection (PBC)
	Number of people aged between 0-4 (P0-4)		
	Number of people aged above 65 (P65)		
	Number of people need assistance due to disability(Pdis)	Low education level (Number of people under Grade 11 degree) (Ple)	Number of people close to the flood protection structure (Pcfps)
	Number of people in flooded area (PFA)		
Economic	Number of business units in flooded area (NBUiFA)	Number of unemployed households (UH)	Drainage system quality and number of flood protection structure (DFW)
	Number of households in flooded area (NHiFA)		
	Number of public facilities in flooded area (NPFiFA)	Number of high income households (HiH)	
	Number of Households Close to River (HCtR)		
	Number of public facilities close to river (NPFCtR)		
Hydrological	Flooded Area Ratio (FAR)	Slope (S)	Main drainage system density (MDSD)
	Annual Maximum Rainfall (AMR)		
	Number of months with heavy rainfall (NMwHR)	Permeable area ratio (PAR)	Sub-main drainage system density (SDSD)

5.3.2. Indicator standardization and weighting

Indicators were standardized for each grid through division of the indicator value of a single grid by the maximum value of the same indicator in the grids of the suburb as explained before in the thesis. As an example the standardised amounts for all 53 grids of the Glenroy for the number of people between 0-4 (P0-4) is calculated by dividing each grid amount by the maximum reported amount in Glenroy which is 45.

$$\mathrm{Sp} = \frac{\mathrm{I_i}}{\mathrm{Max\ I_i}} \tag{5.1}$$

where, I_i is the original value of the indicator in ith grid and the Max I_i is the maximum amounts in each suburb.

After selection of indicators and standardization, the next step is to assign suitable weights to the selected indicators. Details of weighting in this study is explained in Chapter 3.

5.3.3. Calculation of FVIs applying (FIS) system

As can be seen from Table 5.2 there are 9, 8 and 7 indicators selected for social, economic and hydrological components respectively. For each input (indicator), three fuzzy sets were defined showing low, medium and high ranges. The shapes of fuzzy sets are considered trapezoidal for the first and last ranges and triangular for the medium range based on the expert opinion and the literature review. In this study the first fuzzy inference or the Mamadani type is applied for the inference engine as the all input, output and rule base are fuzzy and there were not a certain answer for vulnerability. Construction of FIS and computation are conducted in the fuzzy toolbox of MATLAB (2014).Figure 5.2 shows the fuzzy sets and membership functions selected for the inputs variables.

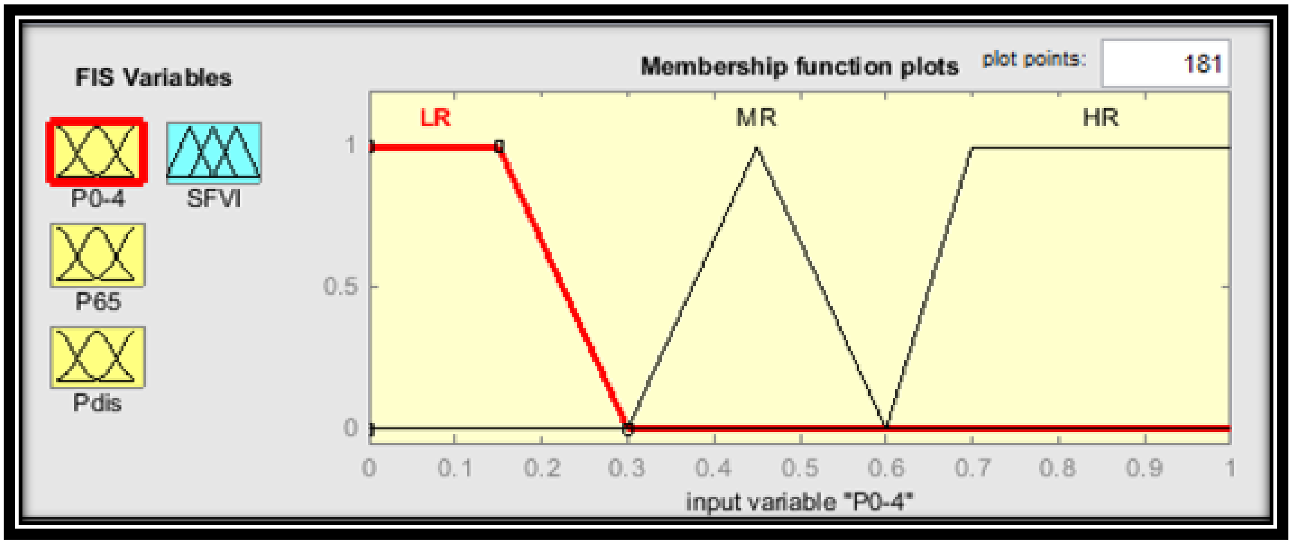


Figure 5.2. Membership shapes and fuzzy sets

After adding the inputs and membership functions in fuzzy toolbox, rules must be constructed. As the input variables are fuzzified into 3 fuzzy sets (‘Low’ ‘Medium’ ‘High’), for 9, 8, and 7 input variables there are 3^7=2187, 3^8= 6561, 3^9= 19683 rules theoretically. It is very difficult to handle this kind of high amount of data, therefore, to reduce possible imprecision, indicators of social, economic and hydrological components were clustered into groups, and the FIS and rules were created for each group. Then, outputs of grouped FISs were re-grouped, and final FIS were created for each component. Table 5.3 shows the grouped indicators, and number of FIS for each component.

Table 5. 3. The FIS groups for social, economic and hydrological components

Component	FIS1	FIS2	FIS3	FIS4	FIS Final
Social	(P0-4) (P65) (Pdis)	(PD) (PFA)	(Ple) (Pli)	(Pcfps) (PBC)	FIS1 FIS2 FIS3 FIS4
Economic	(NBUiFA) (NHiFA) (NPFiFA)	(HCtR) (NPFCtR)	(UH) (HiH)	(DFW)	FIS1 FIS2 FIS3 FIS4
Hydrological	(FAR) (AMR) (S) (PAR)	(MDSD) (SDSD) (NMwHR)	_	_	FIS1 FIS2

For the FISs with 3 inputs and 3 fuzzy sets, there are 27 rules and for the FISs with 2 and 4 inputs and 3 fuzzy sets, there are 8 and 81 rules respectively. The Figure 5.3 shows the schematic diagram of the FISs development for social component.

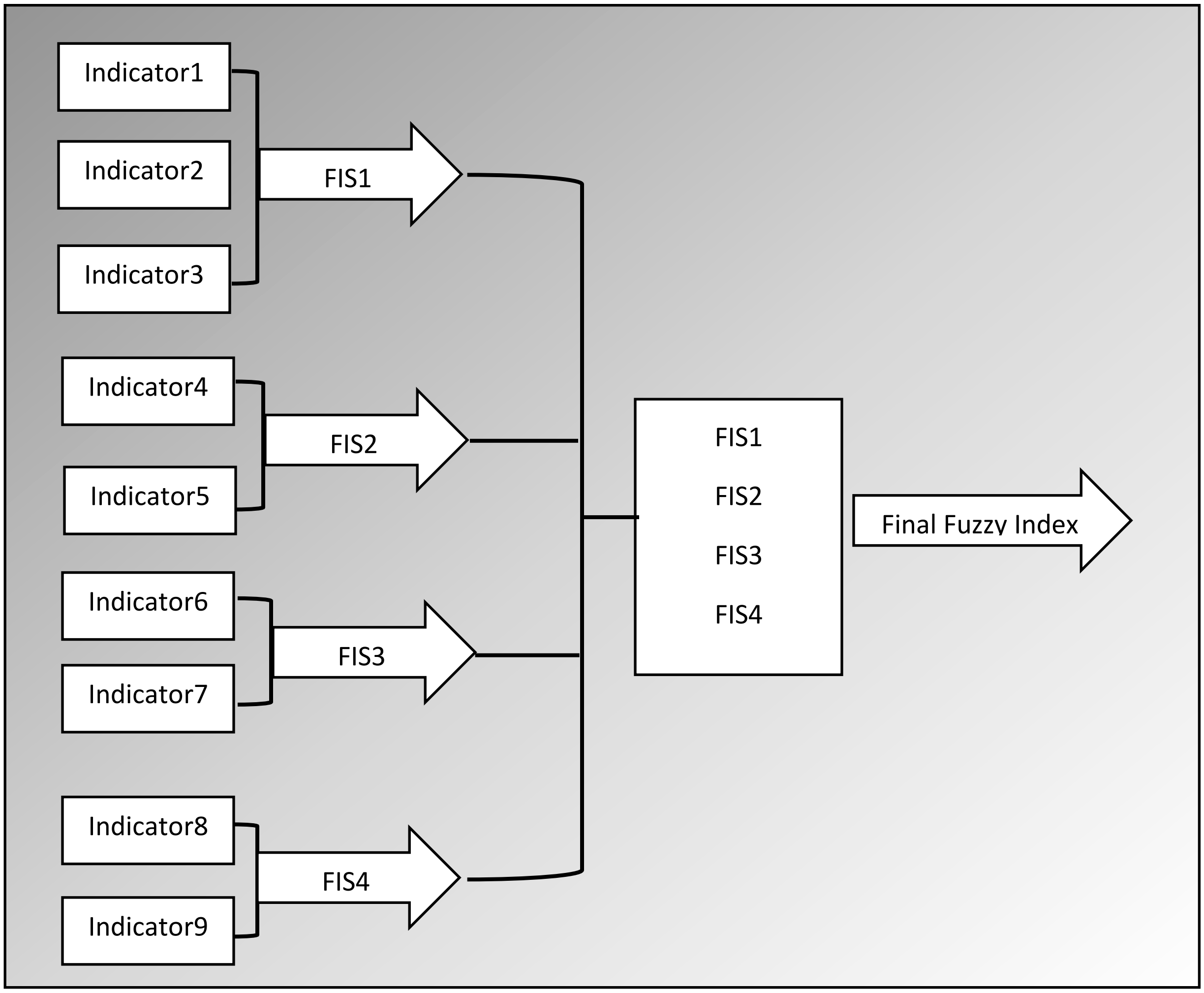


Figure 5.3. Schematic diagram of the FISs development for social component.

5.3.3.1. Output of Final FISs

The output range of the FIS, which is a value in [0, 1], is the vulnerability index for each component separately. The output of the final FIS for social component gives the Social Flood Vulnerability Index (SFVI), whereas output of the final FIS for economic and hydrological components give the Economic Flood Vulnerability Index (EFVI) and Hydrological Flood Vulnerability Index (HFVI) respectively. The output of final FIS is divided to 9 classes for social and economic components and to 5 classes for hydrological component which are shown in Figures 5.4 and 5.5 respectively. These classes are used for the FVI interpretation in GIS environment.

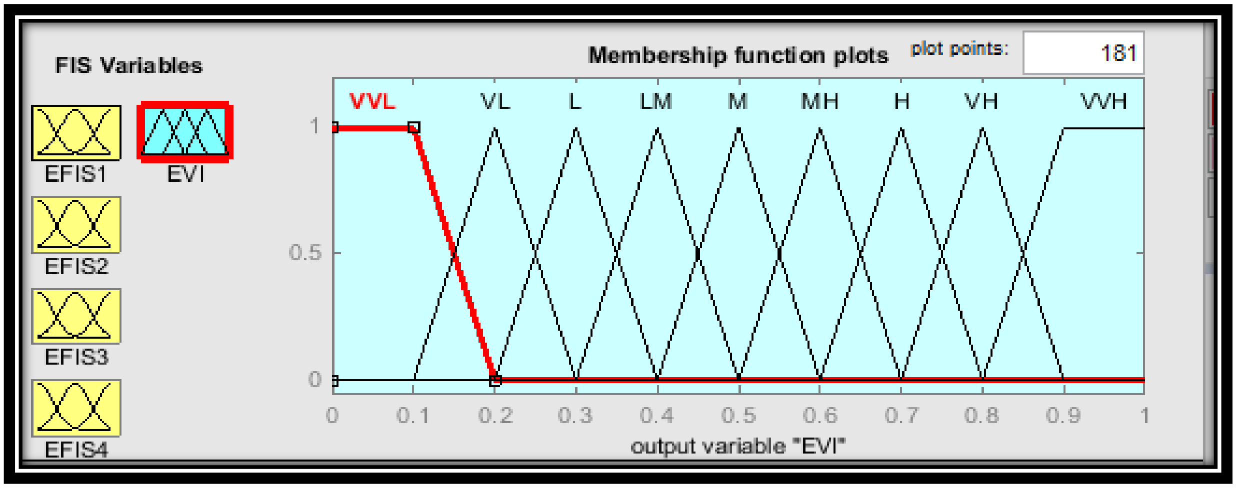


Figure 5.4. Economic Vulnerability Index (EVI) output classes

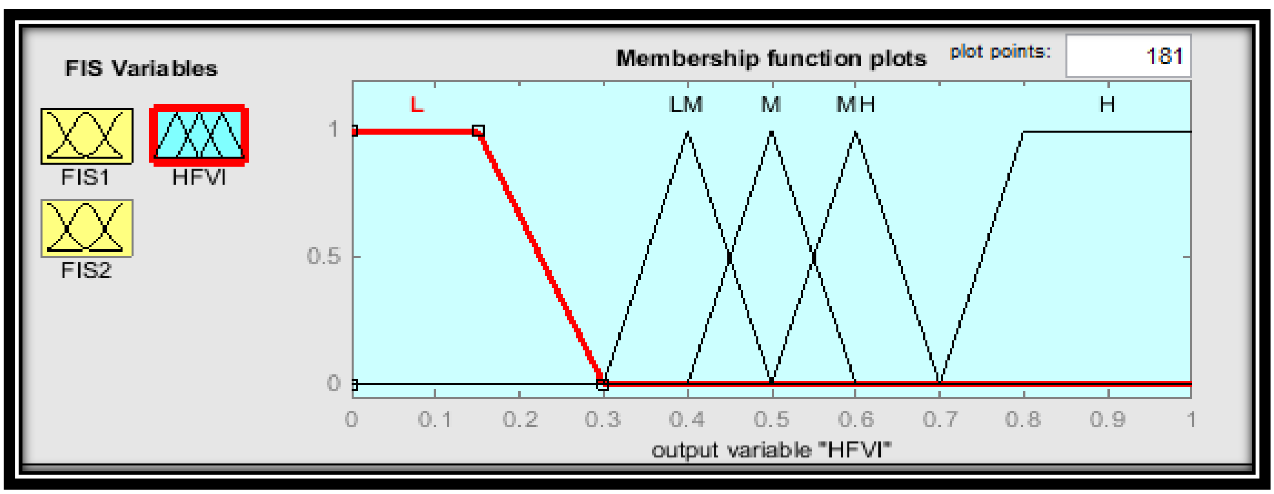


Figure 5.5. Hydrological Flood Vulnerability Index (HFVI) output classes

The labels shown in these figures are the linguistic variables which meanings as below:

VVL: extremely non-vulnerable, VL: very non-vulnerable, L: non-vulnerable, LM: relatively non-vulnerable, M: medium vulnerable, MH: relatively vulnerable, H: vulnerable, VH: very vulnerable and VVH: extremely vulnerable.

SFVI, EFVI and HFVI were calculated for each grid of each suburb, and SFVI, EFVI and HFVI are later aggregated to calculate the final index again for each grid in each suburb.

5.3.4. Aggregation of FVIs

After calculation of FVI for all three components (SFVI, EFVI and HFVI), final aggregation process takes place to calculate final aggregated FVI. The two common methods for aggregation are arithmetic (additive) and geometric (multiplicative). Also, combination of these two basic methods (i.e. additive and multiplicative) can be applied for aggregation.

In this study, the final vulnerability index has been calculated based on arithmetic aggregation through equal weight for each component as can be seen in Equation 5.2.

$$\mathrm{FFVI} = \frac{\mathrm{HFVI} + \mathrm{EFVI} + \mathrm{SFVI}}{3} \qquad (5.2)$$

In Equation 5.2 FFVI represents the final flood vulnerability index, whereas HFVI, EFVI and SFVI are hydrological, economic and social vulnerability indexes respectively.

5.3.5. Interpretation of the FFVIs

The final step of FVI development is to define an interpretation criterion to evaluate final index values. To create the final map for the Final Flood Vulnerability Index (FFVI) in GIS environment, the interpretation index range was defined from 0 to 1 based on 5 vulnerability classes for each component shown in Table 5.4. High index values correspond to high vulnerability, whereas low index values correspond to low vulnerability.

Table 5. 4. Vulnerability classes

Class Number	Range	Vulnerability
Class 1	0-0.2	Very Low Vulnerable
Class 2	0.2-0.4	Low Vulnerable
Class 3	0.4-0.6	Medium Vulnerable
Class 4	0.6-0.8	High Vulnerable
Class 5	0.8-1	Very High Vulnerable

5.4. Results

The results for each of the three components are presented in the following sub-sections.

5.4.1. Results for HFVIs

As mentioned earlier, MC was represented by 355 grids. Out of these 355 grids, 7 grids represent unoccupied land, and number of people living in these unoccupied grids is zero. Therefore, FVI values of these grids are zero. The area of grids with zero FVI value is 4.54 km^2, which is 9% of the total area.

According to the analysis of flood vulnerability considering hydrological component, the five vulnerability classes discussed in the previous section; 1, 2, 3, 4 and 5 cover 14%, 5%, 43%, 37% and 1 % of the total area, respectively. The low and very low vulnerable classes (Classes 1 and 2) with an area of 9.77 km^2 cover 77 grids in the study area and these grids are the ones which have low slope, low percentage of permeable area, low percentage of flooded area, smaller area to receive the maximum rainfall. On the other hand, these grids have the high density of sub main and main drainage system. 140 grids fall under medium vulnerability class (Class 3) with an area of 21.98 km^2. Remaining 19.18 km^2 of land (139 grids) is under high vulnerability classes (Classes 4 and 5) mainly due to low drainage system density. Figure 5.6 shows the HFVI classes for the MC suburbs.

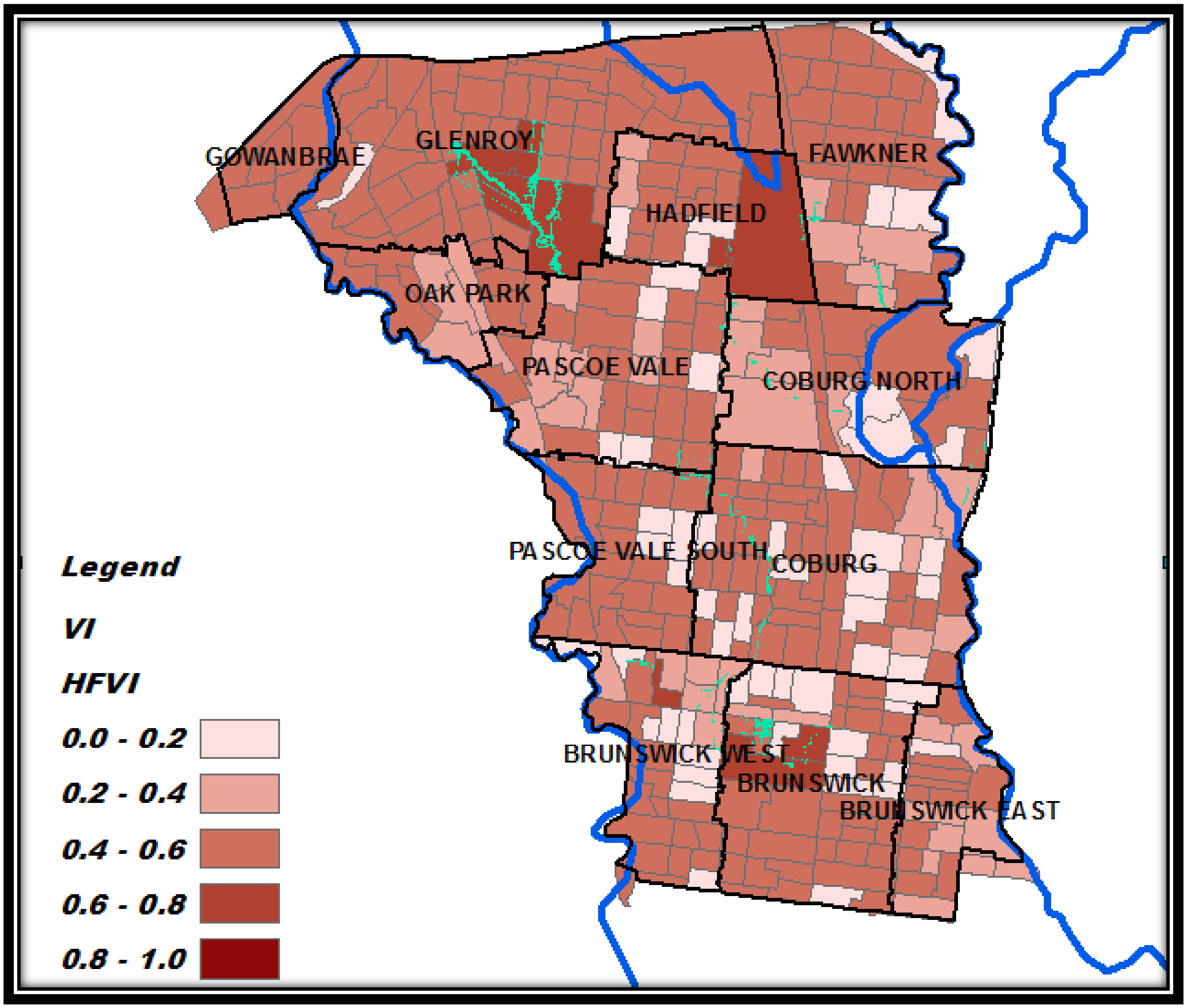


Figure 5.6. HFVI in MC Area

Figure 5.7 presents the HFVI values for each suburb in MC. Based on the provided results and from hydrological point of view, Pascoe Vale South, Coburg, Brunswick, Brunswick East, Brunswick West, Coburg North, Fawkner, Hadfield, Gowanbrae, Oak Park, Pascoe Vale and Glenroy are ranked from the most vulnerable suburbs to the least vulnerable ones. It should be noted that the number of grids which fall within very high and high vulnerability levels (Classes 4 and 5) divided by the total number of grids in each suburb to find the percentage for ranking suburbs in terms of vulnerability (for all three components).

It was observed that the most vulnerable suburbs have the low density of main and submain drainage systems in most of their grids. The two resilience indicators (SDSD and MDSD), influenced the vulnerability level, as they help the system to reach back to the normal condition after a heavy rainfall in a high density range. In summary, the high percentage of drainage system density causes the lower vulnerability level. The susceptibility indicators, slope and permeable area ratio, affected the level of vulnerability as the high percentage of permeable area ratio and the steeper slope cause higher vulnerability values in each grid. All suburbs have the same condition considering the annual maximum rainfall and the number of months with heavy rainfall; however, slope, the permeable ratio and FAR are the elements that affected vulnerability significantly in each grid (and each suburb). Pascoe Vale South, Coburg, Brunswick, Brunswick east, Brunswick West and Coburg North have the largest number of vulnerable grids. Glenroy has a high percentage of flooded area; however, the total number of grids that have very high and high vulnerable values in Glenroy is lesser than the other suburbs when compared to the total number of grids at the suburb scale. Pascoe Vale, Oak Park and Gowanbrae suburbs have fewer number of vulnerable grids in the high and very high vulnerable classes.

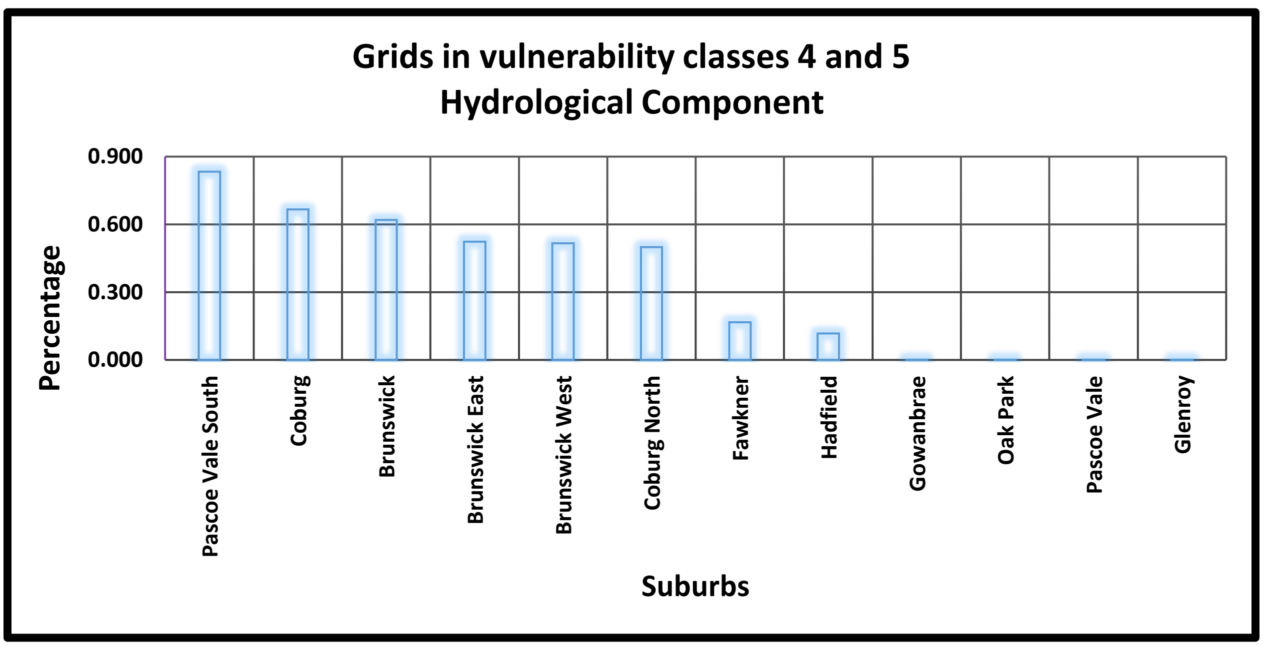


Figure 5.7. HFVI – Most and the least vulnerable suburbs

5.4.2. Results for SFVIs

According to the results of FVIs for social component, the very high vulnerability zone (Class 5) covers 25 grids (an area of 3.9 km^2), mainly located in the flood prone areas defined by Melbourne Water or because of being close to the creeks or rivers. These grids are mostly highest populated areas with lowest range of broadband connection or the highest range of elderly people, disable people and children in the age group of 0-4. Class 5 grids cover 8% of the total area. The total number of grids with very low (Class 1) and low vulnerability (Class 2) zones are 96, which corresponds to 22% (an area of 11.12 km^2) of the total area. Class 1 and 2 grids are located very close to flood protection structures (such as levees and embankment), or have large number of people with broadband connections (which is important for people to be alerted by authorities such as Bureau of Meteorology when flood events occur), and less population density. There are 15.3 km^2 land within medium vulnerability zone (Class 3), which corresponds to 30% of the total area. Class 3 zone consists of grids with a medium range of population density, broadband connection or located distant from flood extent areas. The remaining 16.05 km^2 land corresponding to 31% of the total area is in high vulnerability zone (Class 4). Figure 5.8 shows the SFVI classes for each grid in study area.

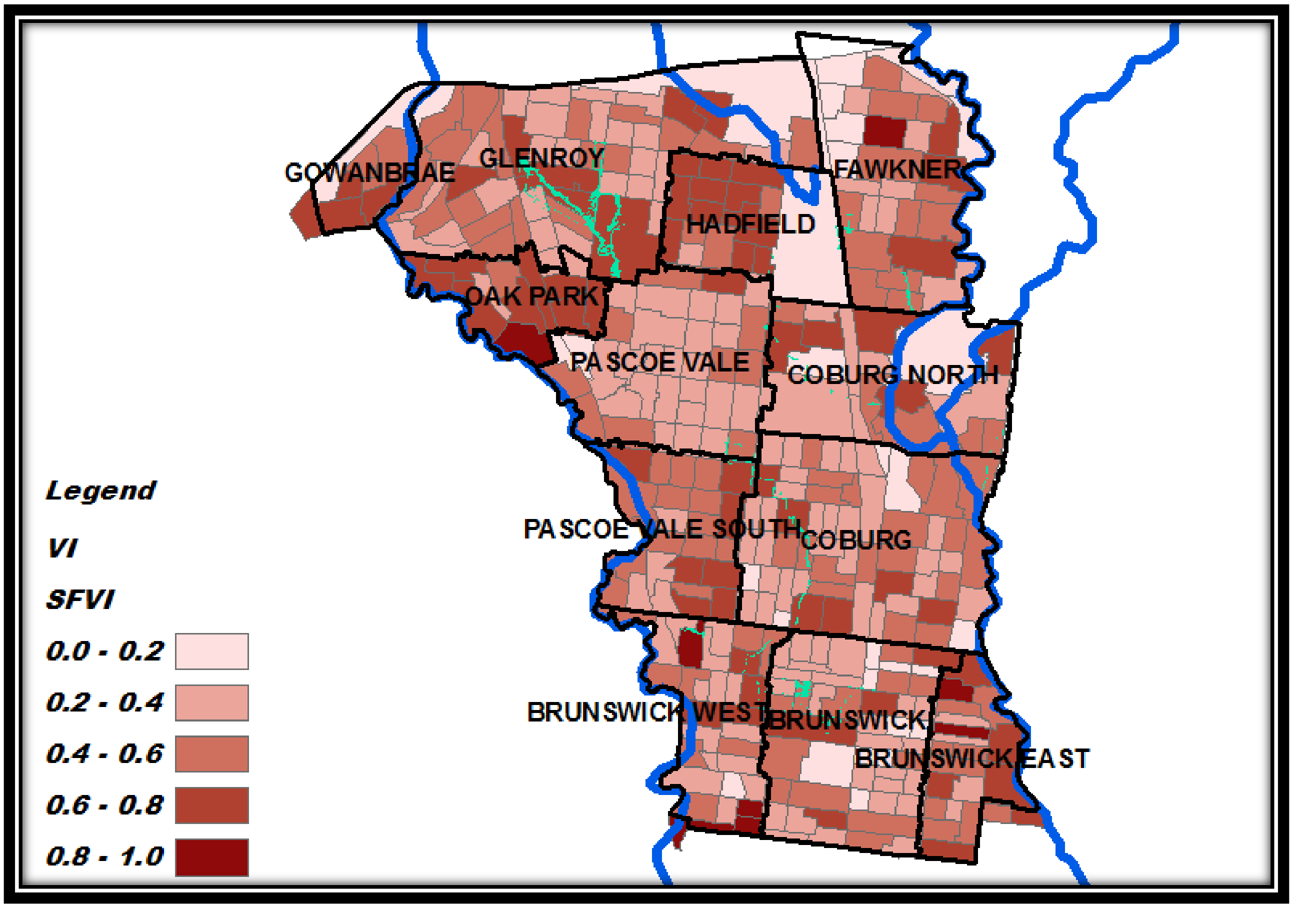


Figure 5.8. SFVI in MC Area

According to the SFVI analysis, it can be stated that suburbs of Hadfield, Oak Park, Pascoe Vale South, Brunswick East, Gowanbrae, Brunswick West, Fawkner, Coburg North, Glenroy, Coburg, Pascoe Vale and Brunswick are ranked from the most to the least vulnerable suburbs respectively (Figure 5.9).

The high range of exposure indicators ((PD), (P0-4), (P65), (Pdis) and (PFA)) affected the level of vulnerability as they increase the number of people who are exposed to flood. Therefore, provided results showed a higher vulnerability level for the grids (and the suburbs) which their ranges of disabled people, young or old people are higher in comparison to the other grids. Moreover, in those grids, population density is high and/or the number of people who are living in flood prone areas is high, thus making the level of vulnerability as high or very high. The resilience indicators (PBC and Pcfps) increase the system ability to cope and adapt with the hazardous condition, so, in the study, the grids (and suburbs) which have the higher range of people close to flood protection structure and/or broadband connections, are the least vulnerable to flood (Brunswick and Pascoe Vale). In summary, the suburbs which have less number of vulnerable grids considering the 9 selected indicators are classified in low and medium vulnerability classes which mean that they have a higher or medium range of resilience and the susceptibility indicator values. Hadfield, Oak Park, Pascoe Vale South, Brunswick East, Gowanbrae have higher number of vulnerable grids when compared to the other suburbs.

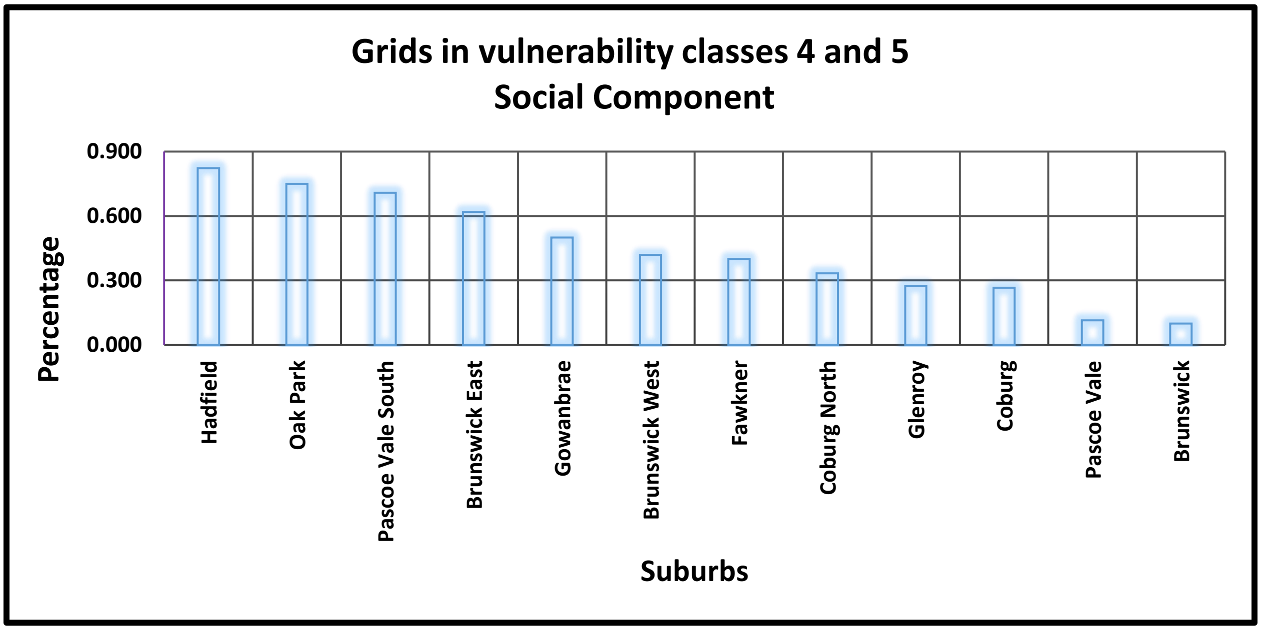


Figure 5.9. SFVI – Most and the least vulnerable suburbs

5.4.3. Results for EFVIs

The analysis of flood vulnerability for economic component showed that 187 grids are in the vulnerability classes 1 and 2 (an area of 24.66 km^2 which corresponds to 48.5% of the total area). In comparison with the other grids, these are the ones which have the lower or zero number of business units or public facilities in flooded area, or closer to the rivers. Also, these grids have a low range of unemployed people, higher range of high income people, and better drainage system. For the medium vulnerability class, there is an area of 20.09 km^2 (137 grids), which covers 39.5%

of the total area. These grids have a low range of business units, public facilities in flooded area or close to river, however, their range of high income people is high or medium. They also have a medium drainage system quality. The remaining 6.24 km^2 corresponding to 12% of the total area falls under high level of vulnerability. This level of vulnerability consists of 32 grids with a high range of unemployed people, low number of high income households and low drainage system quality as well as high range of business units and public facilities in flooded area or close to river.

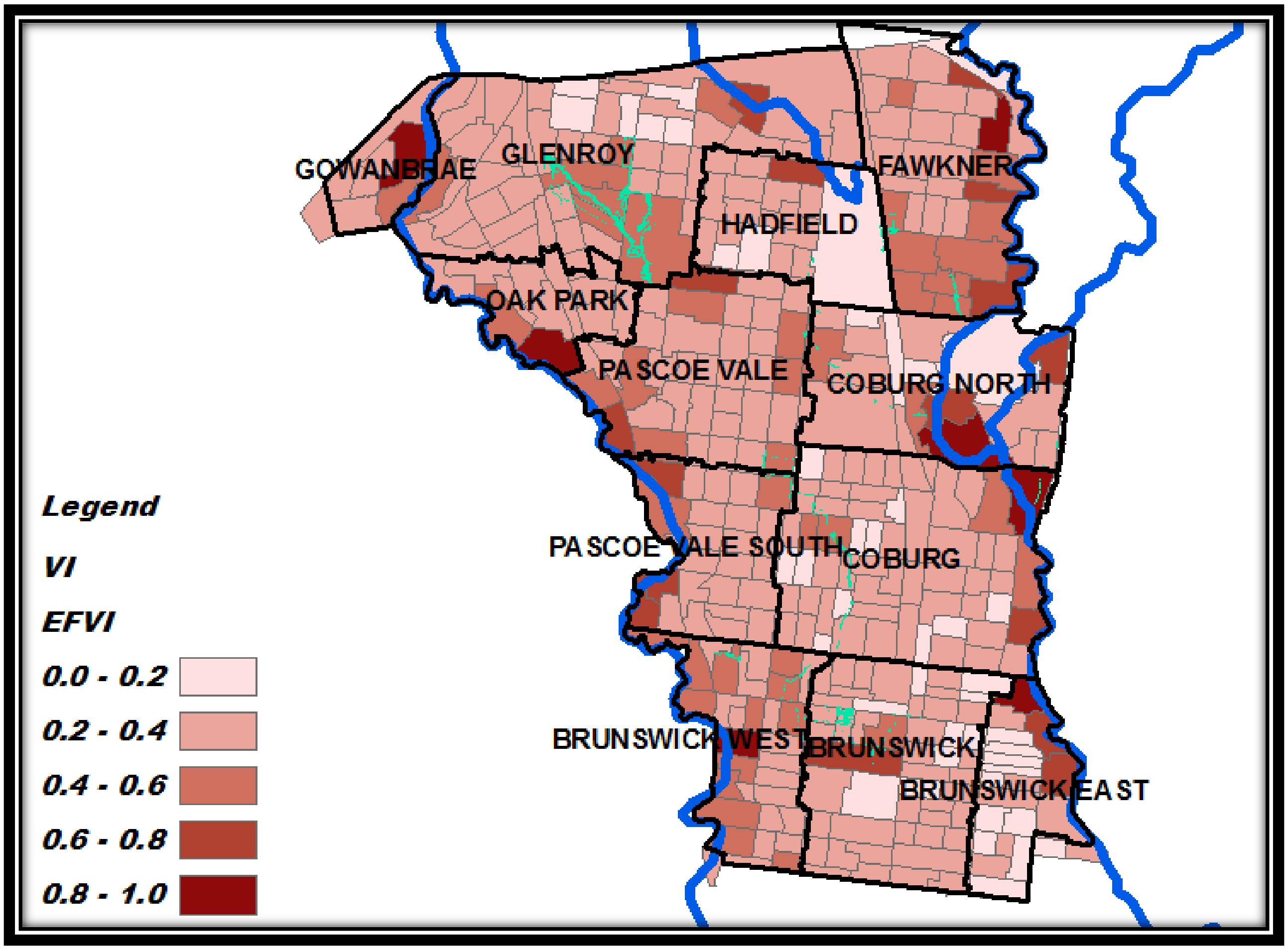


Figure 5.10. EFVI in MC Area

From the economic point of view, Gowanbrae, Pascoe Vale South, Fawkner, Coburg North, Brunswick West, Brunswick East, Oak Park, Pascoe Vale, Hadfield, Coburg, Glenroy and Brunswick are ranked from the most to the least vulnerable suburbs in the study area (Figure 5.10).

Based on these results, the number of business units or/and the number of public facilities or/and the number of households which are adjusted/close to the main creeks or are located in flooded area affected the vulnerability values from the economic point of view. The higher numbers of these units mean higher vulnerability level. The indicators which are from the susceptibility factor (UH and HiH) impacted the vulnerability values in each grid as the higher number of people with high income have more capability to cope with the flood event, and are able to be recovered faster when compared with the other people. Also, the higher number of UH leads to increase in the level of vulnerability in each grid as more support is needed after a flood event to return back to the normal condition. The most effective indicator on the level of vulnerability in each grid was the resilience indicator, which helped to reduce the vulnerability level and make the system more flexible to recover after flood events. In this study, for the economic component, resilience factor is the drainage system quality in each suburb considering the fact that any existing flood protection structure (DFW) would increase resilience and hence a suitable weight has been assigned to each suburb for the EFVI analysis (Section 5.3.2).

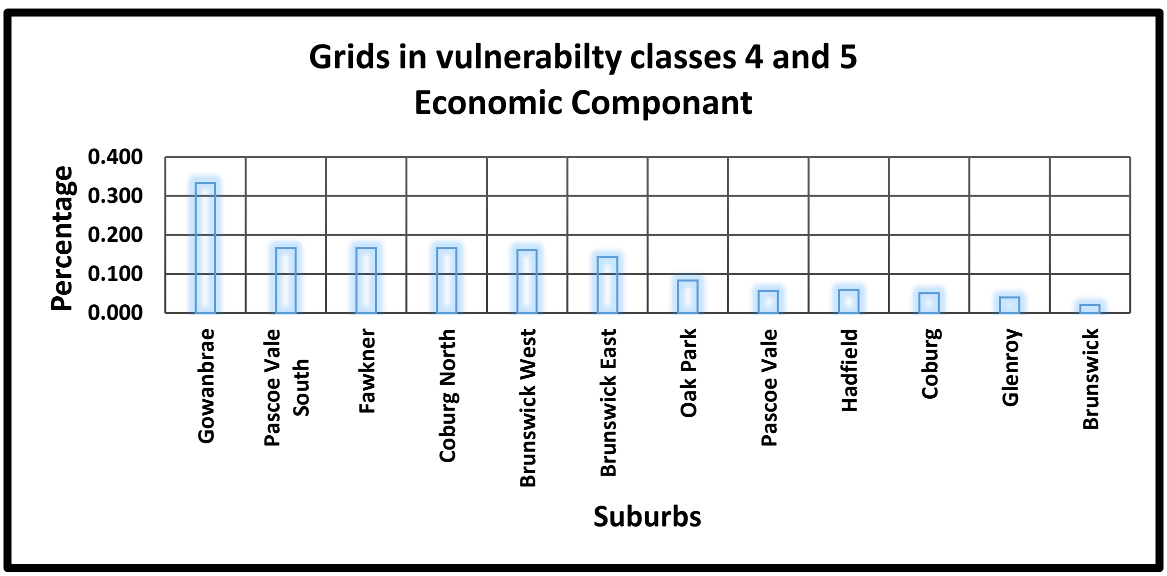


Figure 5.11. EFVI – Most and the least vulnerable suburbs

5.4.4. Results for final FVI

As explained in the Section 5.3.4 SFVI, EFVI and HFVI were aggregated and final FVIs (FFVI) were calculated for each grid in the study area. Figure 5.12 shows the FFVIs for each grid. According to the analysis of the FFVIs, 51.6% (corresponding to 26.21 km^2 land area) of the study area is under very low and low vulnerability zones (Classes 1 and 2). It was also found that the very high and high-vulnerable zones (Classes 4 and 5) are 4.6 % and 0.3 % of the total area respectively. Moreover, medium-vulnerable areas (Class 3) cover 43.5 % (22.17 km^2) of the total area.

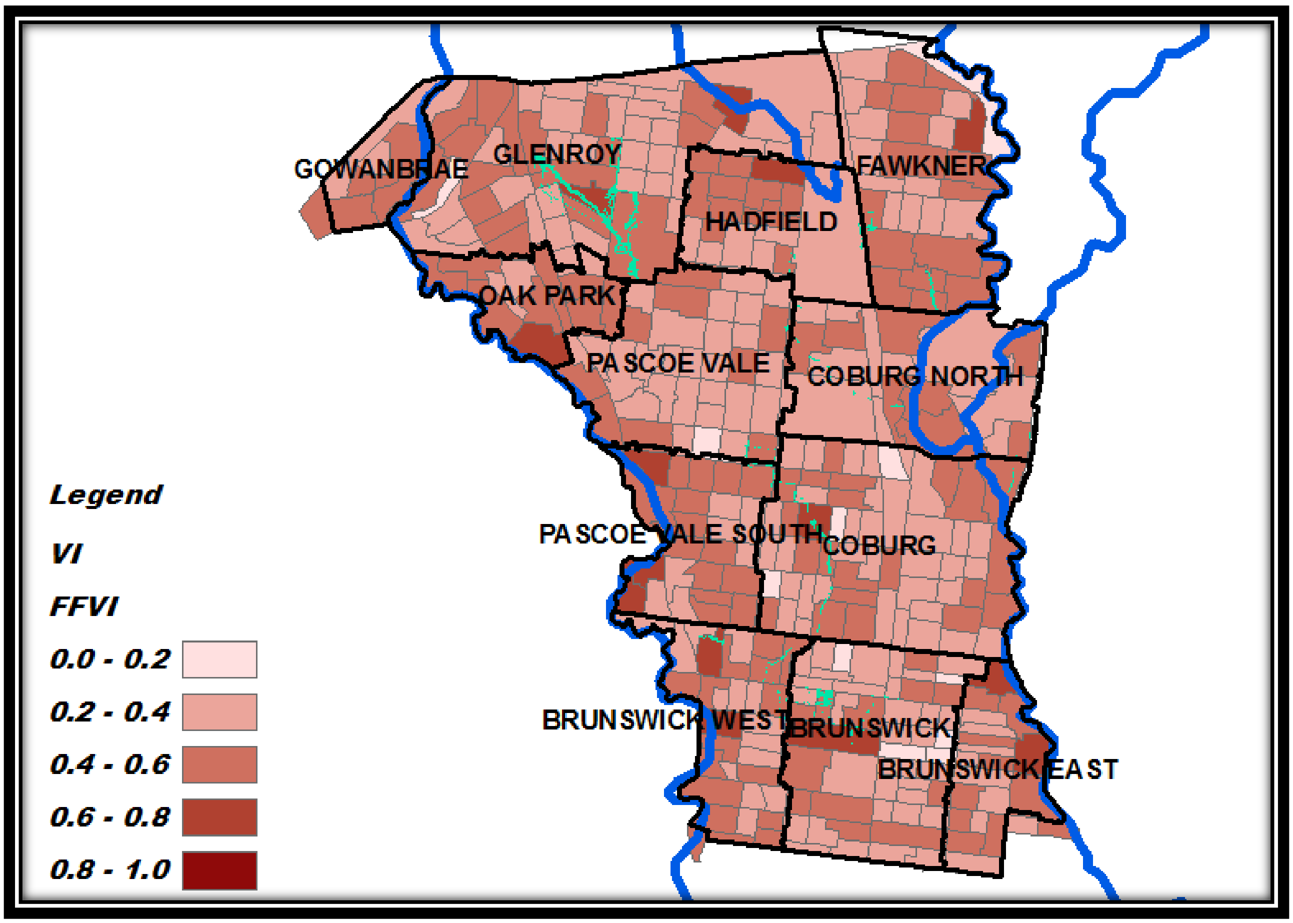


Figure 5.12. FFVIs in MC Area

Final results indicate that Pascoe Vale South, Gowanbrae, Brunswick West, Fawkner, Oak Park, Coburg North, Glenroy, Brunswick East, Hadfield, Coburg, Pascoe Vale, Brunswick are the suburbs from the most to the least vulnerable suburbs respectively (Figure 5.13).

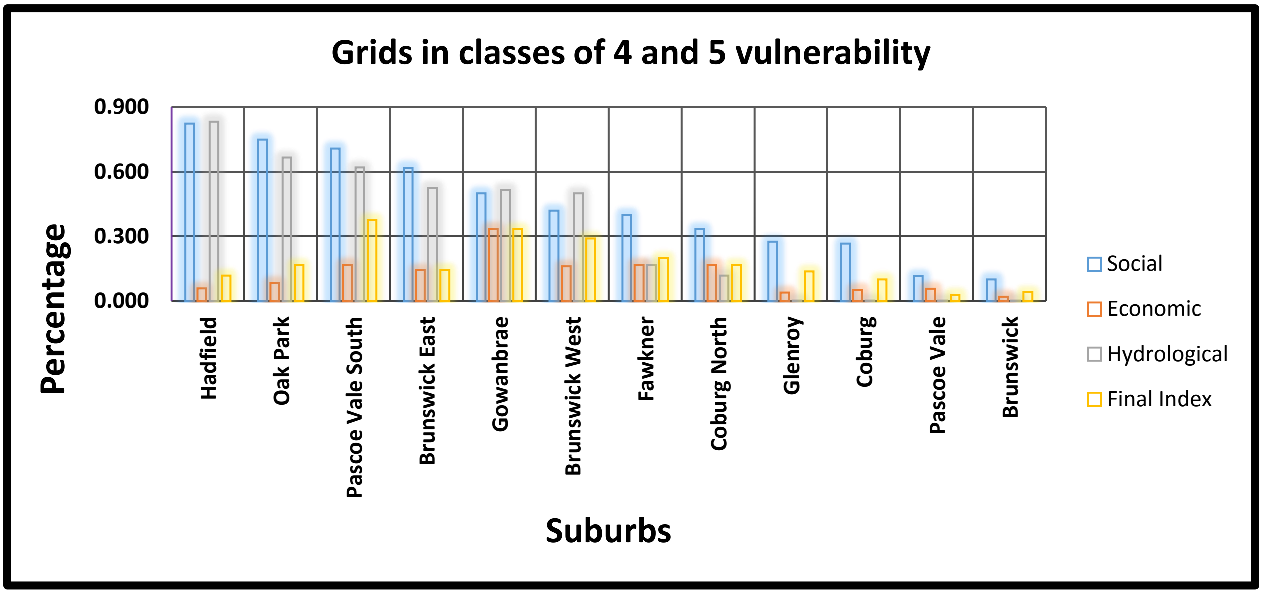


Figure 5.13. FFVI- Very high and high vulnerable classes

5.5. Summary

Flood vulnerability of MC was assessed through developed fuzzy logic based FVI considering social, economic and hydrological aspects in this chapter. Social, economic and hydrological flood vulnerability indices were developed separately, and then aggregated to have Final Flood Vulnerability Index (FFVI). Through the analysis of different components the most and the less vulnerable suburbs are highlighted considering the highest percentage of the area under vulnerability classes 4 and 5. FFVI analysis showed that Pascoe Vale South, Gowanbrae and Brunswick West are the most vulnerable suburbs to flood, whereas Brunswick and Pascoe Vale are found as the less flood vulnerable suburbs.

Chapter 6
Summary and Conclusions

6.1. Summary

This chapter presents the overall outcomes of the study. The final results of the analyses were presented in Chapter 5 and discussed for the social, hydrological and economic components through the use of GIS maps. Suburbs are ranked from the most to the least vulnerable ones from the social, economic, and hydrological point of view. In the GIS maps, the most and the least vulnerable suburbs (grids) are highlighted and classified into different levels of vulnerability (5 classes). In this section, a brief summary of the study is presented. This is followed by the conclusions. The limitation of this study and some recommendations for future study are also presented in this chapter.

In summary, seven indicators are used to determine the Hydrological Flood Vulnerability Index (HFVI) values. Indicators are selected based on the availability of data and Moreland City Council experts' opinion. Selected indicators for hydrological component were Flooded Area Ratio (FAR), Annual Maximum Rainfall (AMR), Number of Months with Heavy Rainfall (NMwHR), Slope (S), Permeable Area Ratio (PAR), Main Drainage System Density (MDSD), and Sub-main Drainage System Density (SDSD). Indicators of FAR, AMR and NMwHR belong to the exposure factor, whereas S and PAR belong to susceptibility, and MDSD and SDSD to the resilience factor.

In total, 9 indicators were used in the social component (5, 2, and 2 indicators belonging to the exposure, susceptibility and resilience factors respectively). The selected indicators were population density (PD), number of people aged between 0-4 (P0-4), number of people aged above 65 (P65), number of people need assistance due to disability (Pdis), number of people in flooded area (PFA), number of low income households (Pli), low education level (number of people under Grade 11 degree) (Ple), number of people with broadband connection (PBC), and number of people close to the flood protection structures (Pcfps).

Eight indicators were used to assess the Economic Flood Vulnerability Index (EFVI) in this study. The selected indicators were number of business units in flooded area (NBUiFA), number of households in flooded area (NHiFA), number of public facilities in flooded area (NPFiFA), number of households close to river (HCtR), number of public facilities close to river (NPFCtR), number of unemployed households (UH), number of high income households (HiH) and drainage system quality and number of flood protection structure (DFW). The first five belonged to the exposure factor, “UH” and “HiH” belonged to susceptibility and (DFW) expressed the resilience factor for the system.

This thesis intended to provide an approach to assess the flood vulnerability of an urban area as a part of flood risk assessment, consisting of a conceptual methodology by identifying indicators, factors of vulnerability, components of the system, and applying a fuzzy logic based method which addresses the vagueness and uncertainties arising from natural variability. Using this approach, this study contributed to the flood vulnerability assessment, as well as flood mitigation and flood risk management in study area.

6.2. Conclusions

Assessment of flood vulnerability of regions are vital as global warming and increased urbanization have been causing more intense and frequent flood events. It has been reported by several studies that flood related disasters will increase almost everywhere in the world in the future. Despite the importance of flood vulnerability assessment, there are relatively limited number of flood vulnerability assessment studies. This thesis has attempted to contribute to the flood protection of the local communities through development of a new FVI. The advantages of the FVI approach are as below:

- FVI provides a systematic and easy method to understand and present the flood vulnerability using a single number to characterize high or low vulnerability.
- FVI contributes to the decision-making process by identifying the flood prone areas.
- The FVI method is a powerful tool for policy makers to prioritise investments and make the decision-making process more transparent. Having a better understanding of high flood vulnerability areas will assist the water authorities and the policy makers towards better flood management.

6.2.1. FL approach for vulnerability assessment

Vulnerability to floods is a function of system's characteristics, namely exposure, susceptibility and resilience. Quantification of these elements is not an easy task. There is no clear boundary for the different vulnerability components and indicators (Yazdi and Neyshabouri 2012) and moreover, hydrologic events include many uncertainties due to their nature such as uncertain climate, limited data and imprecise modelling tools (Sen 2010; Bogardi et al. 2003). Towards integrating a probabilistic based approach, Fuzzy Logic (FL) allows researchers to account for the uncertainties discussed above.

In this study, a FL based FVI was used to assess the flood vulnerability of an urban area. To do so, 24 indicators from three social, hydrological and economic components were selected as the input for fuzzy toolbox in MATLAB (2014). Then through construction of a rule based database in the form of IF…THEN statements, the inputs were mapped to the output vulnerability index to calculate the vulnerability of flood prone areas.

The FL based FVI is a reliable tool in an urban region for the purpose of flood prone area identification. The fuzzy approach has clearly outperformed the deterministic crisp index based method as it involves the subjective uncertainties and ambiguities of judgments in vulnerability assessment.

Developed FL based FVI is specific to the study area, MC. Since different regions have different hydrological, social and economic conditions, the FVI developed in this study should be modified for different regions before using for flood vulnerability assessment. However, methodology of this study is generic, so the FL based FVI development steps can be applied for different regions by simply modifying the hydrological, social and economic indicators.

6.2.2. Hydrological Component

From the hydrological point of view based on the provided results (Figure 5.7), suburbs of the MC are ranked from the most vulnerable to the least vulnerable ones listed as follow: Pascoe Vale South, Coburg, Brunswick, Brunswick East, Brunswick West, Coburg North, Fawkner, Hadfield, Gowanbrae, Oak Park, Pascoe Vale and Glenroy. In Pascoe Vale South, Coburg and Brunswick, which are the most flood vulnerable suburbs, 60 % or more of the grids are classified in very high and high vulnerability levels (Classes 4 and 5). However, in least vulnerable suburbs, which are Glenroy, Pascoe Vale, Oak Park, Hadfield, Fawkner and Gowanbrae, only 30 % or less of the grids are in very high and high vulnerable zones. In Brunswick East, Brunswick West, and Coburg North 30 % to 60 % of grids are located in the vulnerability classes 4 and 5.

6.2.3. Social Component

According to the SFVI analysis (Figure 5.9), Hadfield, Oak Park, Pascoe Vale South, Brunswick East, Gowanbrae, Brunswick West, Fawkner, Coburg North, Glenroy, Coburg, Pascoe Vale and Brunswick are ranked from most to the least vulnerable suburbs.

In the most vulnerable suburbs, which are Hadfield, Oak Park, Pascoe Vale South and Brunswick East, 60 % or more of the grids are classified in very high and high vulnerable levels (Classes 4 and 5). While in the least vulnerable suburbs (Glenroy, Coburg, Pascoe Vale and Brunswick) 30 % or less of the grids fall under very high and high vulnerable zones. Gowanbrae, Brunswick West, Fawkner and Coburg North are classified in a medium level of vulnerability from the social point of view as their classes 4 and 5 grids are between 30 to 60%.

6.2.4. Economic Component

From the economic point of view and based on the provided results (in Figure 5.10), Gowanbrae, Pascoe Vale South, Fawkner , Coburg North, Brunswick West, Brunswick East, Oak Park, Pascoe

Vale, Hadfield, Coburg, Glenroy and Brunswick are ranked from most to the least flood vulnerable suburbs in the study area.

In Gowanbrae, which is the most vulnerable suburb, more than 30% of grids are classified in very high and high vulnerable classes (Classes 4 and 5) but in Glenroy, Coburg, Pascoe Vale, Hadfield, Oak Park and Brunswick less than 10% of the grids are in very high and high vulnerable zones. These are the least flood vulnerable suburbs. Pascoe Vale South, Fawkner, Coburg North, Brunswick East and Brunswick West are in a medium class of flood vulnerability as the percentage of their grids, classified in classes 4 and 5 of vulnerability is between 10 to 20%.

6.2.5. Final FVI

After analysing the flood vulnerability index for each component, the last step of the methodology was aggregating HFVI, SFVI and EFVI to obtain the Final Flood Vulnerability Index (FFVI) for each suburb in the study area. As explained earlier in Section 5.6, there are three common methods for aggregation; arithmetic (additive), geometric (multiplicative) and a combination of these two basic methods (i.e. additive and multiplicative). In this study, the FFVIs were calculated by using arithmetic method (Equation 5.2).

According to the FFVIs, suburbs are ranked from the most to the least flood vulnerable zones (Figure 5.13) as follow: Pascoe Vale South, Gowanbrae, Brunswick West, Fawkner, Oak Park, Coburg North, Glenroy, Brunswick East, Hadfield, Coburg, Pascoe Vale and Brunswick. In summary, in Pascoe Vale South and Gowanbrae more than 30% of grids are classified in high and very high vulnerability classes (Classes 4 and 5) so, in compare with other suburbs they are the most vulnerable suburbs.

6.3. Limitations of this study

An initial step for the vulnerability index assessment is to collect proper and reliable data to select the most suitable indicator for each component. In this study, indicators were selected based on the availability of data from the MCC and the web site recommended by MCC (http://profile.id.com.au/moreland). More accurate data would provide more reliable and accurate final flood vulnerability index values. More detailed data would lead more accurate flood vulnerability assessment. For example, for the economic component, the flood insurance data for each household was not available. Also for the social component, the number of child cares and family day care centres in each suburb was also not available. The availability of these could significantly improve the reliability of the FVI results.

It should be noted that to achieve a better understanding of the flood prone areas, there is a need to update the currently developed GIS maps based on most current data for the study area.

6.4. Recommendations for future study

It is possible to improve currently developed FVI by considering more components such as ecological and/or environmental component. This will provide more comprehensive understanding of flood hazard zones, and it will be a very useful contribution to develop accurate and reliable flood mitigation strategies in the study area.

It would be interesting to assess the future flood vulnerability by FVIs considering climate change scenarios and future social projections. Most major urban cities in the world are expected to experience consequences of global warming in the form of more extreme rainfalls. Moreover, urban areas are expanding day-by-day, and social profile of the cities are changing rapidly. Therefore, a future flood vulnerability predictions would provide significant contribution to the literature and study area.

References

Albano, R, Sole, A, Sdao, F, Giosa, L, Cantisani, A & Pascale, S 2014, ‘ A systemic approach to evaluate the flood vulnerability for an urban study case in southern Italy’, *Journal of Water Resource and Protection*, vol. 6, No. 4, pp. 351–362.

Ahmad, SS & Simonovic, SP 2013, ‘Spatial and temporal analysis of urban flood risk assessment’, *Urban Water Journal,* vol. 10, No. 1, pp. 26–49.

Afshar, A, Mariño, MA, Saadatpour, M & Afshar, A 2011, ‘Fuzzy TOPSIS multi-criteria decision analysis applied to Karun Reservoirs System’, *Water Resources Management*, vol. 25, No. 2, pp. 545–563.

Alaghmand, S, Abdullah, R, Abustan, I & Vosoogh, B 2010. ‘GIS-based river flood hazard mapping in urban area (A case study in Kayu Ara River Basin, Malaysia)’, *International Journal of Engineering and Technology*, vol. 2, No. 6, pp. 488–500.

Adger, NW 2006, Vulnerability, Global Environmental Change 16, pp. 268-281.

Adger, WN & Vincent, K 2005, ‘Uncertainty in adaptive capacity’, *Geoscience*, Vol. 337, No. 4, pp. 399–410.

Akter, T & Simonovic, SP 2005, ‘Aggregation of fuzzy views of a large number of stakeholders for multi-objective flood management decision-making’, *Journal of Environmental Management*, vol. 7, No. 2, pp. 133–134.

Adriaenssens, V, De Baets, B, Goethals, PLM & De Pauw, N 2004, ‘Fuzzy rule-based models for decision support in ecosystem management’, *The Science of Total Environment* vol. 319, no. 1, pp. 1-12.

Andjelkovic, I 2001, ‘International hydrological program guidelines on non-structural measures in urban flood management’, IHVP, *Technical Documents in Hydrology,* No. 50, UNESCO, Paris.

Balica, S, Dinh, Q, Popescu, I, VO, TQ & Pham, DQ 2013, ‘Flood impact in the Mekong Delta, Vietnam’, *Journal of Maps,* vol. 10, No. 2, pp. 257–268.

Balica, SF, Wright, NG & Meulen, F 2012, ‘A flood vulnerability index for coastal cities and its use in assessing climate change impacts’, *Natural Hazards,* vol. 64, No. 1, pp. 73–105.

Balica, SF, Douben, N & Wright, NG 2009, 'Flood vulnerability indices at varying spatial scales', *Water Science and Technology Journal*, vol. 60, No. 10, pp. 2571–80.

Bureau of Infrastructure, Transport and Regional Economics (BITRE) (2008). About Australia's Regions. BITRE, Canberra.

Barredo, JI, de Roo, A & Lavalle, C 2007, 'Flood risk mapping at European scale', *Water Science and Technology*, vol. 56, No. 4, pp. 11–17.

Barroca, B, Bernardara, P, Mouchel, JM & Hubert, G 2006, 'Indicators for identification of urban flooding vulnerability', *Natural Hazards and Earth System Science*, vol. 6, no. 4, pp. 553–561.

Büchele, B, Kreibich, H, Kron, A, Thieken, A, Ihringer, J, Oberle, P, Merz, B & Nestmann, F 2006, 'Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks', *Natural Hazards and Earth System Science*, vol. 6, No. 4, pp. 485–503.

Bouma, JJ, François, D & Troch, P 2005, 'Risk assessment and water management', *Environmental Modelling & Software*, vol. 20, No. 2, pp. 141–151.

Bardossy, A, Haberlandt, U & Krysanova, V 2003, 'Automatic fuzzy-rule assessment and its application to the modelling of nitrogen leaching for large regions', *Soft Computing*, vol. 7, No. 6, pp. 370-385.

Bogardi, I, Bardossy, A, Duckstein, L & Pongracz, R 2003, Fuzzy logic in hydrology and water resources. In: Fuzzy logic in geology, (eds: Demicco, RV, & Kiler, GJ), New York, USA.

Bender, MJ & Simonovic, SP 2000, 'A fuzzy compromise approach to water resources systems planning under uncertainty', *Fuzzy Sets and Systems*, vol. 115, No. 1, pp. 35–44.

Begon, M, Harper, JL & Townsend, CR 1996, Ecology, From Individuals to Ecosystems, Blackwell Science Ltd., Oxford, UK.

Bogardi, I, reitel, R & Nachtnebel, P 1995, Fuzzy rule-based estimation of flood probabilities under climatic fluctuation, in: Hamies, YY, Moser, DA & Stakhiv, E Z (ed), Risk-based Decision-making in Water Resources VII, Proceedings, pp. 61-79. ASCE, Reston, VA.

Bardossy, A & Duckstein, L 1995, Fuzzy rule-based modelling with applications to geophysical biological and engineering systems, CRC Press, Boca Raton, New York, London, Tokyo.

Blaikie, P, Cannon, T, Davis, I & Wisner, B 1994, At risk—Natural Hazards, People's Vulnerability and Disasters, 2nd ed., London.

Bardossy, A & Disse, M 1993, 'Fuzzy rule based models for infiltration', *Water Resource Research, vol*. 29, No. 2, pp. 373-382.

Chau, K 2006, 'A review on integration of artificial intelligence into water quality modelling', *Marine Pollution Bulletin*, vol. 52, No. 7, pp. 726–733.

Connor, RF & Hiroki, K 2005, 'Development of a method for assessing flood vulnerability', *Water Science and Technology*, vol. 51, No. 5, pp. 61–67.

Chen, Q & Mynett, AE 2004, 'A robust fuzzy logic approach to modelling algae biomass', *Journal of Hydraulic Research*, vol. 42, No. 3, pp. 303–309.

Cutter, SL 1996, Vulnerability to environmental hazards, Progress in Human Geography, London.

Chang, NB & Chen, HW 1996, 'The application of Genetic algorithm and nonlinear fuzzy programming for water pollution Control in a River Basin', lEEE Xplore, pp. 224-229.

Cornwall, A & Jewkes, R 1995, 'What is participatory research', *Social Science Medicine Journal*, vol. 41, No. 12, pp. 1667–1676.

Coburn, AW, Spencer, JS & Pomoni, A 1994, training manual: vulnerability and risk assessment, 2nd ed., Oast House: UNDP Disaster Management Training Programme.

Cutter, SL 1993, living with risk: the geography of technological hazards, London.

Chambers, R 1989, Vulnerability: how the poor cope, IDS Bulletin, vol. 20, No. 2, pp. 1-7.

Ward, R 1978, Floods: a geographical perspective (Focal problems in geography Series), The Macmillan Press LTD.

Del Rio, L & Gracia, FJ 2009, 'Erosion risk assessment of active coastal cliffs in temperate environments', *Geomorphology*, vol. 112, No. 1, pp. 82–95.

Douben, N 2006a, 'Characteristics of river floods and flooding: a global overview 1985 – 2003', *Irrigation and Drainage*, vol. 55, No. 1, pp. S9 –S21.

Douben, N 2006b, Flood management, UNESCO-IHE, Lecture Notes.

De Bruijn, KM 2005, 'Resilience indicators for flood risk management systems of lowland rivers', *International Journal of River Basin Management*, vol. 2, No. 3, pp. 199-210.

Dilley, M, Chen, RS, Deichmann, U 2005, Natural disaster hotspots: a global risk analysis, The World Bank, Hazard Management Unit, Washington, DC.

Downton, MW & Pielke, RA 2005, 'How accurate are disaster loss data? The case of U.S. flood damage', *Natural Hazards*, vol. 35, No. 2, pp. 211–228.

Douben, N & Ratnayake, RMW, 2005, Characteristic data on river floods and flooding: facts and figures. In: J, van Alphen, E, van Beek & M, Taal (ed.): Floods, from Defence to Management. Taylor & Francis Group: London, pp 11-27.

Dai, FC, Lee, CF & Zhang, XH 2001, 'GIS-based geo-environmental evaluation for urban land-use planning : a case study', *Engineering Geology*, vol. 61, No. 4, pp. 257-271.

Di Natale, M, Duckstein, L & Pasanisi, A 2000, forecasting pollutants transport in river by a fuzzy rule-based model, presented in: Workshop on Fuzzy Logic and Applications, Mons Institute of Technology, Belgium.

Dou, C, Woldt, W, Bogardi, I & Dahab, M 1999, 'Fuzzy rule-based approach to describe solute transport in the unsaturated zone', *Journal of Hydrology*, vol. 220, No. 1, pp. 74-85.

Dou, C, Woldt, W, Bogardi, I & Dahab, M 1997b, 'Numerical solute transport simulation using fuzzy sets approach', *Journal of contamination Hydrology*, vol. 27, No. 1, pp. 107-126.

Dal Cin R & Simeoni U 1989, 'Coastal zoning and vulnerability: application to the Middle Adriatic (Italy)', *Coastal Zone*, vol. 89, No. 3, pp. 98–110.

Delbecq, AL, Van d Ven, AH & Gustafon, DH 1975, Group techniques for program planning: A guide to nominal group and Delphi processes, Glenview, Illinois.

Esogbue, AO, Theologidu, M & Guo, K 1992, 'On the application of fuzzy sets theory to the optimal flood control problem arising in water resources systems', *Fuzzy Sets and Systems*, vol. 48, No. (2), pp.155–172.

Fu, G 2008, 'A fuzzy optimization method for multicriteria decision making: an application to reservoir flood control operation', *Expert Systems with Applications*, vol. 34, No. 1, pp 145–149.

Fedeski, M & Gwilliam, J 2007, 'Urban sustainability in the presence of flood and geological hazards: The development of a GIS-based vulnerability and risk assessment methodology', *Landscape and Urban Planning Journal*, vol. 83, No. 1, pp. 50–61.

Gharibi, H, Mahvi, AH, Nabizadeh, R, Arabalibeik, H, Yunesian, M & Sowlat, MH 2012, 'a novel approach in water quality assessment based on fuzzy logic', *Journal of Environmental Management*, vol. 112, pp.87–95.

Guillaumont, P 2008, an economic vulnerability Index : Its design and use for international development policy, WIDER research paper, UNUWIDER, VOL November 2008/99.

Galderisi, A, Ceudech, A, Pistucci, M 2005, Integrated vulnerability assessment: the relevance "to" and "of" urban planning in proceedings (CD format) of the 1st ARMONIA project Conference "Multi-hazards: Challenges for risk assessment, mapping and management", Barcelona, 5-6, December 2005.

Green, C 2004, the evaluation of vulnerability to flooding, Disaster Prevention and Management, Emerald Group Publishing Limited, vol. 13, pp. 323-329.

Gomez, G 2001, Combating Desertification in Mediterranean Europe: Linking Science with Stakeholders, Contract EVK2-CT-2001-00109, King's College, London.

Gabor, T & and Griffith, TK 1980, 'The assessment of community vulnerability to acute hazardous material incidents', *Journal of Hazardous Materials*, vol. 8, pp. 323-22.

Huang, D, Zhang, R, Huo, Z, Mao, FEY & Zheng, W 2012, 'An assessment of multidimensional flood vulnerability at the provincial scale in China based on the DEA method', *Natural Hazards*, vol. 4, No. 2, pp. 1575–1586.

Hegde, AV & Reju, VR 2007, 'Development of coastal vulnerability index for Mangalore', *Journal of Coastal Research*, vol. 23, No. 5, pp. 1106–1112.

Haberlandt, U, Krysanova, V & Bardossy, A 2002, 'Assessment of nitrogen leaching from arable land in large river basins', Part II: regionalization using fuzzy rule based modelling, *Ecological Modelling*, vol. 150, No. 3, pp. 277-294.

Holling CS 1973, 'resilience and stability of ecological systems', Annual review of Ecology and Systematics, vol. 4, pp. 1–23.

IPCC 2014, 'Intergovernmental Panel on Climate Change', Fifth assessment report of the intergovernmental panel on climate change.

IPCC, 2013, Contribution of working group I to the fifth assessment report of the Intergovernmental panel on climate change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC 2007, 'Intergovernmental Panel on Climate Change', Forth assessment report: Climate Change 2007.

IPCC 2001, 'Intergovernmental Panel on Climate Change', the scientific basis, Cambridge, Cambridge University Press.

IPCC 1996, 'Intergovernmental Panel on Climate Change', Second Assessment Climate Change.

IPCC 1992, 'Intergovernmental Panel on Climate Change', First Assessment WMO/UNEP, Overview and policymakers summaries.

Id the population expert, Melbourne 2011, (http://profile.id.com.au/moreland).

Jang, JSR, Sun, CT & Mizutani, E 1997, neuro-fuzzy and soft computing; a computational approach to learning and machine intelligence, Prentice Hall, New jersey.

Jorgensen, SE 1992, integration of ecosystem theories: a pattern, Kluwer Academic Publishers Dordrecht, the Netherlands.

Kunte, PD, Jauhari, N, Mehrotra, U, Kotha, M, Hursthouse, AS & Gagnon, AS 2014, 'Multi-hazards coastal vulnerability assessment of Goa, India, using geospatial techniques', *Ocean & Coastal Management*, vol. 95, pp. 264–281.

Kienberger, S 2012, 'Spatial modelling of social and economic vulnerability to floods at the district level in Búzi, Mozambique', Natural Hazards, vol. 64, No. 3, pp. 2001–209.

Kumar, AA & Kunte, PD 2012, 'Coastal vulnerability assessment for Chennai, east coast of India using geospatial techniques', Natural Hazards, vol. 64, No. 1, pp. 853–872.

Ka źmierczak, A & Cavan, G 2011, 'Surface water flooding risk to urban communities: analysis of vulnerability, hazard and exposure', *Landscape and Urban Planning*, vol. 103, No. 2, pp. 185–197.

Kerachian, R, Fallahnia, M, Bazargan-Lari, MR, Mansoori, A & Sedghi, H 2010, 'A fuzzy game theoretic approach for groundwater resources management: application of Rubinstein Bargaining Theory', *Resources, Conservation and Recycling*, vol. 54, No. 10, pp. 673–682.

Kumar, TS, Mahendra, RS, Nayak, S, Radhakrishnan, K & Sahu, KC 2010, 'Coastal vulnerability assessment for Orissa State, East Coast of India', *Journal of Coastal Research*, vol. 26, No. 3, pp. 523–534.

Kubal, C, Haase, D, Meyer, V & Scheuer, S 2009, 'Integrated urban flood risk assessment – adapting a multicriteria approach to a city', *Natural Hazards and Earth System Science*, vol. 9, No. 6, pp. 1881–1895.

Kasperson, JX, Kasperson RE, Turner BL, Hsieh W & Schiller A 2005, vulnerability to global environmental change. In: Kasoerson JX, Kasperson RE (ed.). The social contours of risk, Earthscan, London, 245-285.

Kohonen, T 2001, self-organizing maps. Springer, Berlin, Heidelberg, (Third Extended Edition 2001).

Klein, RJT & Nicholls, RJ 1999, 'Assessment of coastal vulnerability to climate change', AMBIO, vol. 28, No. 2, pp. 182-187.

Katz, RW & Brown, BG 1992, 'Extreme events in a changing climate: variability is more important than averages', *Climatic Change*, vol. 21, No. 3, pp. 289-302.

Lujala, P, Lein, H & Rosvoldaune, R 2014, 'Quantifying vulnerability to flooding induced by climate change: The case of Verdal, Norway', *Journal of Geography*, vol. 68, No. 1, pp. 34–49.

Li, CH, Li, N, Wu, LC & Hu, AJ 2013, ' A relative vulnerability estimation of flood disaster using data envelopment analysis in the Dongting Lake region of Hunan', *Natural Hazards and Earth System Science*, vol. 13, No. 7, pp. 1723–1734.

Lermontov, A, Yokoyama, L, Lermontov, M & Machado, MAS 2009, 'River quality analysis using fuzzy water quality index: Ribeira do Iguape river watershed, Brazil', *Ecological Indicators*, vol. 9, No. 6, pp. 1188-1197.

Labadie, JW 2004, 'Optimal operation of multi-reservoir systems: state-of-the-art review', *Journal of Water Resources Planning and Management*, ASCE, vol. 130, No. 2, pp. 93–111.

Liou, S, Lo, S & Wang, S 2004, 'A generalized water quality index for Taiwan', *Environmental Monitoring and Assessment*, vol. 96, No. 1, pp. 35–52.

Lewis, J 1999, Development in disaster- prone places, intermediate technology London.

Melbourne Water, Moreland City Council & Victoria State Emergency Service 2013, Moreland Flood Management Plan.

Masood, M & Takeuchi, K 2011, ‘ Assessment of flood hazard, vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model’, *Natural Hazards*, vol. 61, No. 2, pp. 757–770.

McLaughlin, S & Cooper, JAG 2010, ‘A multi-scale coastal vulnerability index: A tool for coastal managers’, *Environmental Hazards*, vol. 9, No. 3, pp. 1–16.

Meyer, V, Scheuer, S & Haase, D 2009, ‘A multicriteria approach for flood risk mapping exemplified at the Mulde River, Germany’, *Natural Hazards*, vol. 48, No. 1, pp. 17–39.

Mailhot, A, Duchesne, S, Caya, D & Talbot, G 2007, ‘Assessment of future change in intensity–duration–frequency (IDF) curves for Southern Quebec using the Canadian Regional Climate Model (CRCM)’, *Journal of Hydrology*, vol. 347, No. 1-2, pp. 197–210.

Merz, B, Thieken, AH & Gocht, M 2007, ‘Flood risk mapping at the local scale: concepts and challenges’, *Flood risk management in Europe*, vol. 25, pp. 231–251.

MunichRe 2007, flooding and insurance, Report on the 128th year of business, I of January to 31 December 2007, Munich Reinsurance Company.

Messner, F & Meyer, V 2006, ‘Flood damages, vulnerability and risk perception-challenges for flood damage research’, *Flood risk management: Hazards, vulnerability and mitigation measures*, vol. 67. pp. 149–167.

Muhammetoglu, A & Yardimci, A 2006, ‘A fuzzy logic approach to assess groundwater pollution levels below agricultural fields’, *Environmental Monitoring and Assessment*, vol. 118 No. 1, pp. 337–54.

Mujumdar, P & Subbarao, VV 2004, ‘Fuzzy waste load allocation model: simulation-optimization approach’, *Journal of Computing in Civil Engineering*, ASCE, vol. 18, No. 2, pp. 120–131.

Mitchell, J 2002, ‘Urban disasters as indicators of global environmental change: assessing functional varieties of vulnerability’, presented at the Symposium on Disaster Reduction and Global Environmental Change, Federal Foreign Office, Berlin, Germany, 20-21 June 2002.

McCarthy, JJ, Canziani, OF, Leary, NA, Dokken, DJ & White, KS (ed.) 2001, Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge.

Niksokhan, MH, Kerachian, R & Amin, P 2009, 'A stochastic conflict resolution model for trading pollutant discharge permits in river systems', *Environmental Monitoring and Assessment*, vol. 154, pp. 219–232.

Nasiri, F, Maqsood, I, Huang, G & Fuller, N 2007, 'Water quality index: a fuzzy river pollution decision support expert system', *Water Resource Planning and Management*, vol. 133, No. 2, pp. 95–105.

Nobre, RCM, Rotunno Filho, OC, Mansur, WJ, Nobre, MMM & Cosenza, CAN 2007, 'Groundwater vulnerability and risk mapping using GIS, modelling and a fuzzy logic tool', *Journal of Contaminant Hydrology*, vol. 94, No. 3, pp. 277–292.

Ocampo-Duque, W, Ferre´-Huguet, N, Domingo, JL & Schuhmacher, M 2006, 'Assessing water quality in rivers with fuzzy inference systems: a case study', *Environmental International*, vol. 32, No. 6, pp. 733–742.

Ologunorisa, TE 2004, 'An assessment of flood vulnerability zones in the Niger Delta, Nigeria', *International Journal of Environmental Studies*, vol. 61, No. 1, pp. 31–38.

Pratt C, Kaly U, Mitchell J 2004, how to use the environmental vulnerability index, UNEP/SOPAC South Pacific Applied Geo-science Commission, SOPAC Technical Report 383.

Pelling, M 2003, the vulnerability of cities; 'Natural disaster and social resilience', *Earthscan Publications*, UK & USA.

Plate, E J 2002, 'Flood risk and flood management', *Journal of Hydrology*, vol. 267, No. 1, pp. 2–11.

Peduzzi, P, Dao, H, Herold, C, Rochette, D & Sanahuja, H 2001, feasibility study report—on global risk and vulnerability index—trends per year (GRAVITY), United Nations development program emergency response division UNDP/ERD, Geneva, Switzerland.

Penning-Rowsell, EC & Chatterton, JB 1977, the benefits of flood alleviation: A Manual of Assessment Techniques (The Blue manual), Gower technical Press, Aldershot, UK.

Rezaei, F, Safavi, HR & Ahmadi, A 2013, 'Groundwater vulnerability assessment using fuzzy logic: a case study in the Zayandehrood aquifers, Iran', *Environmental Management*, vol. 51, No. 1, pp. 267–77.

Rawat, PK, Pant, CC, Tiwari, PC, Pant, PD & Sharma, AK 2012, 'Spatial variability assessment of river-line floods and flash floods in Himalaya: A case study using GIS', *Disaster Prevention and Management: An International Journal*, vol. 21, No. 2, pp. 135-159.

Raju, GSVP, Sumalatha, V, Ramani, K & Lakshmi, KV 2011, 'Solving uncertainty problems using ANFIS', *International Journal of Computer Applications*, vol. 29, No.11.

Rao, KN, Subraelu, P, Rao, TV, Malini, BH, Ratheesh, R, Bhattacharya, S., … Subraelu, KNRP 2008, 'sea-level rise and coastal vulnerability: An assessment rise and coastal vulnerability : remote of Andhra Pradesh coast, India through sensing and GIS', *Journal of Coastal Conservation*, vol. 12, No. 4, pp. 195–207.

Solin, Ľ 2012, 'Spatial variability in the flood vulnerability of urban areas in the headwater basins of Slovakia', *Journal of Flood Risk Management*, vol. 5, No. 4, pp. 303–320.

Scheuer, S, Haase, D & Meyer, V 2010,'Exploring multicriteria flood vulnerability by integrating economic, social and ecological dimensions of flood risk and coping capacity: from a starting point view towards an end point view of vulnerability', *Natural Hazards*, vol. 58, No. 2, pp. 731–751.

Sen, Z 2010, Fuzzy logic and hydrological modelling, London, Taylor & Francis.

Seising, R 2007, 'Fuzzification of systems: the genesis of fuzzy set theory and its initial applications - developments up to the 1970s', *Studies in Fuzziness and soft computing*, vol. 216, Springer, Berline.

Smit, B & Wandel, J 2006, 'Adaptation, capacity and vulnerability', *Global Environment Change*, vol. 16, No. 3, pp. 282–292.

Schultz, B 2006, ‘Flood management under rapid urbanisation and industrialisation in flood-prone areas: a need for serious consideration’, *Irrigation and Drainage*, Supplement: Integrated Flood Management, vol. 55, No. S1, pp. S3-S8.

Said, A, Stevens, D & Selke, G 2004, ‘An innovative index for evaluating water quality in streams’ *Environmental Assessment*, vol. 34, No. 3, pp. 406–414.

Sullivan, C 2002, ‘Calculating a water poverty index’, *World Development*, vol. 30, No. 7, pp. 1195–1210.

Sen, Z 2001, Fuzzy logic and foundation, Bilge Kultur Sanat Publisher, Istanbul, Turkey.

Simonovic, SP 1997, risk in sustainable water resources management. In: D. Rosbjerg, N. Boutayeb, A. Gustard, Z.W. Kundzewicz, P.F. Rasmussen, (ed.), Sustainability of water resources under increasing uncertainty, IAHS Publications, No. 240, pp. 3–17.

Saaty, TL 1986, ‘Axiomatic foundations of the analytic hierarchy process, *Management Science*, vol. 32, No. 7, pp. 841–855.

Takagi, T & Sugeno, M 1985, fuzzy identification of systems and its application to modelling and control, IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS, vol. SMC-15, No. 1, pp. 116–132.

United Nations, 1982, proceedings of the seminars on flood vulnerability analysis and on the principals of floodplain management for flood loss prevention, September, Bangkok.

Veen Van Der, A & Logtmeijer, C 2005, ‘Economic hotspots: visualizing vulnerability to flooding’, *Natural Hazards*, vol. 36, No. 1, pp. 65–80.

Wang, Y, Li, Z, Tang, Z & Zeng, G 2011, ‘A GIS-Based spatial Multi-Criteria Approach for flood risk assessment in the Dongting Lake Region, Hunan, Central China’, *Water Resources Management*, vol. 25, No.13, pp. 3465–3484.

Watson, RT, Zinyowera, MC & Moss, RH (ed.) 1996, ‘climate Change 1995’, in Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Cambridge University Press, Cambridge.

Watts, MJ & Bohle, HG 1993, 'Hunger, famine and the space of vulnerability', *GeoJournal*, vol. 30, No. 2, pp. 117–125.

Yoon, SK, Kim, JS & Moon, YI 2014, ' Integrated flood risk analysis in a changing climate: A case study from the Korean Han River Basin', *KSCE Journal of Civil Engineering*, vol. 18, No. 5, pp. 1563–1571.

Yilmaz, AG 2014, 'The effects of climate change on historical and future extreme rainfall in Antalya, Turkey', *Hydrological Sciences Journal,* vol. 60, No. 12, pp. 2148-2162.

Younus, MAF & Harvey, N 2013, 'Community-Based flood vulnerability and adaptation assessment: a case Study from Bangladesh', *Journal of Environmental Assessment Policy and Management*, vol. 15, No. 3, pp. 1464-3332.

Yazdi, J & Neyshabouri, SAAS 2012, 'Assessing flood vulnerability using a rule-based fuzzy system', *Water Science and Technology* : A Journal of the International Association on Water Pollution Research, vol. 66, No. 8, pp. 1766–73.

Yen, J & Langari, R 1998, 'Fuzzy logic: Intelligence, Control, and Information', Prentice Hall, Englewood Cliffs, NJ.

Zhang, Y & You, WJ 2013, 'Social vulnerability to floods: a case study of Huaihe River Basin', *Natural Hazards*, vol. 71, No. 3, pp. 2113–2125.

Zou, Q, Zhou, J, Zhou, C, Song, L & Guo, J 2012, 'Comprehensive flood risk assessment based on set pair analysis-variable fuzzy sets model and fuzzy AHP', *Stochastic Environmental Research and Risk Assessment*, vol. 27, No. 2, pp. 525–546.

Zimmermann, HJ 2010, 'Fuzzy set theory', *Wiley Interdisciplinary Reviews: Computational Statistics*, vol. 2, No. 3, pp. 317-332.

Zheng, DXM & Ng, ST 2005, 'Stochastic time-cost optimization model incorporating fuzzy sets theory and non-replaceable front', *Journal of Construction Engineering and Management*, vol.131, No. 2, pp. 176–86.

Zadeh, L 1997, 'Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic', *Fuzzy Sets and Systems*, vol. 90, No. 2, pp. 111–127.

Zadeh, L 1973, outline of a new approach to the analysis of complex systems and decision processes. IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS, vol. SMC-3, no. 1, pp. 28-44.

Zadeh, LA 1965, 'Fuzzy sets', *Information and Control*' vol. 8, No. 3, pp. 338–53.