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Assessment of vulnerability to climate change: theoretical and methodological developments with applications to infrastructure and built environment

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ASSESSMENT OF VULNERABILITY TO CLIMATE CHANGE: THEORETICAL AND METHODOLOGICAL DEVELOPMENTS WITH APPLICATIONS TO INFRASTRUCTURE AND BUILT ENVIRONMENT

Fahim Nawroz Tonmoy

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ABSTRACT

Climate change impacts pose significant threat to our cities, built environments and infrastructure systems. Assessing vulnerability to climate change can help policymakers in incorporating climate futures in planning, better allocating adaptation resources, monitoring the effects of adaptation measures, and communicating risk and justifying policy to the public. Indicator Based Vulnerability Assessment (IBVA) has been widely used in a number of sectors because it is relatively simple to design, implement and communicate to policy makers. However, this approach faces significant difficulties from conceptual, theoretical and methodological points of view. A number of assumptions are typically made in methods used for aggregation of indicators—a linear, monotonic relationship between indicator and vulnerability; complete compensation between indicators; precise knowledge of vulnerable system by stakeholders who provide input data for the assessment exercise—none of which usually hold in reality. Aggregation approaches based on multi-attribute utility theory have stringent theoretical requirements (e.g., additive independence of indicators) that are hardly ever satisfied in the IBVA context.

The goal of the thesis is to develop a new set of aggregation methods for IBVA that are better suited for the mix of indicators arising from the biophysical, institutional and socio-economic components of vulnerability, and that can incorporate uncertainties, partial compensation and non-linearities. Following a meta-analysis of the IBVA literature in chapter 2, the thesis proposes a) a general mathematical framework for vulnerability assessment that better identifies sources of uncertainty and non-linearity; b) a new IBVA assessment methodology and computer tool based on a pair-wise outranking approach, borrowed from decision science and which foregrounds and incorporates the normative nature of some indicators, as well as partial compensation between indicators; c) a new IBVA methodology and computer tool that can represent various sources of non-linearity in the relationship between indicators and vulnerability; and d) a system dynamics model, integrated in IBVA, for studying vulnerability of infrastructure systems and better representing the mechanistic interdependency of their components.

These methods are applied to a real-life, indicator-based assessment of the vulnerability to sea-level rise of residents and infrastructure systems in Shoalhaven, south of Sydney, at local scale. The assessment is conducted in collaboration with the local council and includes an analysis of the sensitivity of vulnerability rankings to uncertainty and community preferences. In addition, the effect of using an outranking framework on the way vulnerability is conceptualized by stakeholders is critically appraised. Finally, future directions for IBVA are discussed and suggestions for further research are made.

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LIST OF PUBLICATIONS

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

A	adaptation
a	adaptation multiplier
A_c	adaptive capacity
a_c	increase in adaptive capacity as a result of adaptation
β_{cold}	cold slope of temperature vs mortality curve
β_{hot}	hot slope of the temperature vs mortality curve
c_i	concordance matrix
C_i	design capacity of an infrastructure node
D	damage
d	dimension of vulnerability
$D1$	ascending distillation process
$D2$	descending distillation process
d_i	discordance matrix
D_{ik}	degree of dependence of an infrastructure node i on node k
E	exposure
e	reduction in exposure as a result of adaptation
E_i	efficiency of an infrastructure node
$\overline{E_\iota}$	efficiency of the mother node of an infrastructure node
$g(\lambda)$	threshold of difference applied to credibility matrix
H	harm criteria
H_{av}	average equivalent number of households experiencing a single service interruption at a given period of time
H_{max}	maximum equivalent number of households experiencing a single service interruption at a given period of time
I	indicator
$\bar{I}$	normalized indicator
M	magnitude
M_{min}	minimum daily mortality
m	number of indicators in a vulnerability model
p	preference thresholds
p_d	directionality of vulnerability
q	indifference threshold
S	sensitivity

s	reduction in sensitivity as a result of adaptation
$\mathrm{S_i}$	credibility matrix
S_i	serviceability of an infrastructure node
θ	slope of indicator/harm versus vulnerability curve
V	vulnerability
v	dominance thresholds
$\overline{\mathrm{V}}$	vulnerability after adaptation event
w	votes

Abbreviations

AADT	annual average daily traffic
ABS	Australian bureau of statistics
AM	arithmetic mean
AR4	4th assessment report of intergovernmental panel on climate change
ATEAM	advanced terrestrial ecosystem analysis and modeling
CCVA	climate change vulnerability assessment
GCM	global circulation model
GIS	geographic information system
GM	geometric mean
IA	integrated assessment
IBVA	indicator based vulnerability assessment
IPCC	intergovernmental panel on climate change
IS	infrastructure systems
LGA	local government area
MAUT	multi attribute utility theory
MCDA	multi criteria decision analysis
NS	no stress scenario
NSW	new south wales
OP	outranking procedures
PCA	principal component analysis
SAW	simple additive weight
SCF	spearman correlation factor
SD	system dynamics
SES	socio ecological system
SEVA	Sydney environmental vulnerability assessment
SEVA-CODE	Sydney environmental vulnerability assessment (a computer code developed for indicator based vulnerability assessment based on an outranking algorithm)
SEVA-HOUSE	Sydney environmental vulnerability assessment of households

SEVA-I	Sydney environmental vulnerability assessment-I (an outranking formulation for indicator based vulnerability assessment)
SEVA-II	Sydney environmental vulnerability assessment-II (an extension of the outranking formulation, developed for indicator based vulnerability assessment)
SEVA-III	Sydney environmental vulnerability assessment-III (a framework for assessing vulnerability of infrastructure systems to sea level rise at a local scale)
SEVA-INFRA-SD	Sydney environmental vulnerability assessment of infrastructure using system dynamics
SEVA-SD	Sydney environmental vulnerability assessment using system dynamics
SLR	sea level rise
SLRAP	sea level rise and its associated processes
US	under stress scenario

Chapter 1

Introduction

1.1 Synopsis

This chapter provides the rationale behind the research undertaken in the course of this project. It describes the methodology followed and the structure of the thesis.

1.2 Background

1.2.1 Climate change impacts in cities

Anthropogenic climate change presents both threats and opportunities to our cities and urban infrastructure. Scientists are providing evidence that even under the most optimistic scenario of greenhouse gas global emission reduction, a certain degree of change in climate is inevitable in the near future (Giorgi and Lionello 2008; Change 2007; Change and Houghton 1999; IPCC 2007; IPCC 2001; Meehl et al. 2007; Garnaut 2008; Houghton et al. 2001; Stern 2007; Hughes 2003). The fourth assessment report (AR4) of the Inter Governmental Panel on Climate Change (IPCC) has assessed a range of scenarios of future greenhouse gas emissions, and concluded that these would lead to an increase in global mean temperatures of between 1.1 and 6.4 °C by the end of the 21st century, relative to the pre-industrial era (IPCC 2007). Although most of the political attention has focused on the potential for a global warming of 2°C, the AR4 projections clearly suggest that much greater levels of warming are possible by the end of the 21st century in the absence of mitigation. The centre of the range of AR4-projected global warming was approximately 4°C (Ebi et al. 2006). This warming is associated with changes in hydrological cycles, increased frequency and intensity of flooding, a rise in sea level, and prolonged and intense summer heat waves.

Such possible future climatic hazards have a great potential to impact populations around the world, especially in cities. Cities have become the centre of economic expansion, resulting in an exponential growth in urban populations. Between 2009 and 2050, the world population is expected to increase by 2.3 billion (from the current 6.8 billion to a projected 9.1 billion) (United Nations, 2010). During the same period, the population living in urban areas is projected to gain 2.9 billion (from the current 3.4 billion to a projected 6.3 billion). Thus, the urban areas of the world are not only expected to absorb almost all the population growth, but also to draw in some of the rural population (United Nations, 2010) . Furthermore, of the 63 most populated cities of the world (with 5 million or more inhabitants in 2011), 72 per cent are located on or near the coast (United Nations 2012). The coastal population (within 100 km of the shoreline and up to 100 m above sea level) is estimated at 1.2 billion people. The average coastal population density is 3 times the global average (Small and Nicholls 2003).

Therefore, cities, including coastal ones, are becoming denser in terms of built environment and infrastructure in order to sustain such a population growth. The term built environment refers to the man-made surroundings that provide the setting for human activity, ranging in scale from buildings and parks or green space, to neighborhoods and cities, and includes supporting infrastructure such as the water supply, waste water collection, telecom, or energy networks (Handy et al. 2002). Possible future climate change and its associated impacts will have significant implications for urban populations as well as the built environment and infrastructure that serve them. The built environment exerts a considerable influence over local climate and ecology, and moderates the way climate hazards are experienced by urban dwellers. Urban populations are already facing a range of weather-related risks such as summer heat waves, air pollution episodes and vector borne diseases, and global warming is likely to add to the existing risks (Kalkstein and Smoyer 1993). In particular, summer heat waves have already become a major public health concern: around 22,000 excess heat-related deaths were attributed to the August 2003 heat waves across five Western European countries – England, France, Italy, Portugal and Spain (Kovats et al. 2004) and 70,000 excess death were reported across the whole of

Europe during that summer (Robine et al. 2008). Scientists are suggesting that global warming is expected to compound these problems over the remaining part of this century, especially in urban areas (Wilby 2007).

Apart from these public health concerns, another major threat for coastal cities is sea level rise and its associated processes (e.g., long term coastal erosion, frequent inundation). Australia, with more than 60 per cent of its population living in coastal settlements in six State capital cities, is likely to be affected by such a rise in sea level ((ABS) 2003; Gurran and Blakely 2007). By the year 2100 an increase of 0.9 m above the 1990 level is projected for Australia's coasts (Walsh et al. 2004). Therefore, private properties and public infrastructure are at risk.

1.2.2 Adaptation to climate change

Humans have long adapted to climate variability, including natural, long-term and cyclical changes in rainfall and temperature. However, the current paradigm is different to past experience in at least three ways. First, the change in climate has been positively *linked to human patterns of land use and energy generation* (IPCC, 2007). In other words, it emanates from modes of economic growth and social interaction that human civilizations are locked into and the switch to a carbon-neutral economy will be very difficult as it would have implications for economic growth and energy security. Second, climate change is happening over a *relatively short time scale* measured in decades rather than centuries. Hence, the imperative for action is urgent given the wide-ranging threats to fundamental environmental services such as temperature-sensitive crop production, fluctuating water reserves, and safe shelter at risk from extreme weather events, sea level rise and outbreaks of disease. Third, anthropogenic climate change is *anticipated*, rather than recognized after the fact.

As a result, in preparation for the possible implications of future climatic impacts, policymakers, engineers, and urban planners are designing climate change adaptation plans. Climate futures can, in principle, be systematically incorporated in planning as a form of adaptation. However, to achieve such integration, the dynamic interactions between humans and the ecological systems on which they depend need to be understood, and knowledge about the processes generating vulnerability to climate-related events needs to be gained (Lim et al. 2004). In other words, it requires understanding the adjustment of social systems so they can better cope with a warmer world and its consequences in terms of water, food, disease and economic production; while addressing the needs of the most vulnerable populations within nations and internationally. In the literature, this exercise is usually termed Climate Change Vulnerability Assessment (CCVA).

Demand for CCVA has increased over the last few years among policymakers, engineers, and planners, mainly because it can help them to identify vulnerable “hot spots” (be it the most vulnerable country, city, area/community of a city), to better allocate adaptation resources, and to better understand structural weaknesses which make a given system vulnerable. CCVA’s can also be beneficial for monitoring the effects of adaptation measures or better communicating risk and justifying policy to the public (Klein 2003; Eriksen and Kelly 2007; Füssel 2007).

CCVA can be viewed as an analytical exercise whose goal is to assess the vulnerability of a valued attribute (e.g., health, safety, economic prosperity) of a socio-ecological system (SES) (e.g., locality, community, economic sector, infrastructure and its users) to one or more climate related hazards (e.g., heat waves, flood events, rise in sea levels) (El-Zein and Tonmoy 2013a; Tonmoy and El-Zein 2013a; Hinkel 2011). Here SES is understood as a set of interactions between a 'bio-geo-physical' unit and its associated social agents and institutions (Marion Glaser 2008) or as a coherent system of biophysical and social factors that interact regularly in a resilient, sustained manner (Redman et al. 2004). In other words, CCVA combines the bio-physical impacts of a possible climatic hazard with their possible socio-economic and institutional implications (Turner et al. 2003). The most commonly used definition of vulnerability in CCVA studies, is the one proposed by the International Panel on Climate Change (IPCC) which recognizes three dimensions of vulnerability, namely exposure, sensitivity, and adaptive capacity, with the first generally referring to the strength of the hazard and the degree to which it impacts physically some valued attribute of the SES under consideration, while the second and third reflect the complex repercussions of the impacts in human societies (Eriksen and Kelly 2007; Parry 2007).

Different approaches of CCVA are prevalent in the literature, both quantitative and qualitative. These approaches typically use the output of Global Circulation Models (GCMs) to examine how projected changes in climate variables might propagate through bio-physical systems at the regional to local scale (e.g., Ford et.al., 2010; Anisimov and Belolutskaya, 2003; Falloon et.al., 2007) . An ideal way of identifying the bio-physical impacts and their possible implications for social, economic, and institutional domains would be to build a mechanistic model that can represent these complex interactions of events. Two obstacles make such an approach extremely difficult to follow in practice. The first obstacle derives from the uncertainties attached to global climate projections as well as climate forecast at regional and local scale. The second obstacle relates to the difficulty of quantifying sociological and institutional processes generating vulnerability.

Therefore, researchers and practitioners have leaned towards an indicator-based approach that uses an indicator as a *proxy* for key processes that generate vulnerability of a system (under a given climatic scenario), be they bio-physical, socio-economic or institutional. These indicators can then be aggregated in order to build an overall index or measure of vulnerability. In the literature, this method is known as Indicator Based Vulnerability Assessment (IBVA). IBVA offers a relatively simple and easy-to-communicate approach to the multidimensional nature of vulnerability assessment. However, it is faced with a number of theoretical and methodological challenges that are discussed next.

1.3 General challenges of IBVA

The challenges facing IBVA can be seen to fall broadly into two categories, conceptual and methodological.

Conceptual and heuristic difficulties (what is vulnerability? by what proxies can it represented? what are the processes that reproduce it?) have received significant attention in the literature (Adger 2006; Adger 1996; Adger and Kelly 1999; Richards et al. 2013; Turner et al. 2003; SCHROEDER and GEFENAS 2009; Schneider 2001; O'Brien 2004; Kasperson et al. 2003; Cutter 1996; Brooks 2003). Their complexity derives in part from the existence of both objective and subjective components of vulnerability (vulnerability depends on how vulnerable a community is AND how vulnerable it perceives itself to be), as well as its forward-looking nature (vulnerability as susceptibility to harm, ie future harm). This makes vulnerability into a social concept which may be approximated but cannot be measured. In this thesis, specific frameworks and definitions of vulnerability are developed or borrowed, and their underlying assumptions are discussed; however, conceptual and heuristic challenges are not the primary concern of this research.

Methodological challenges arise at the indicator selection and aggregation stage of model building. First, proxy indicators, ideally representing processes generating vulnerability, are drawn from different knowledge domains (e.g., climatic, social, economic, engineering, institutional), in recognition of the concept's multi-dimensional nature, discussed earlier (e.g., biophysical, socio-economic and institutional; objective and subjective). As a result, IBVA typically must combine different data types (continuous, discrete, and ordinal variables), different forms of and, degrees of certainty about, relationships between indicators and vulnerability. A majority of the IBVA literature has used aggregation approaches based on Multiple Attribute Utility Theory (MAUT) (e.g., weighted additive or multiplicative aggregation). These approaches which are brances of Multi Criteria Decision Analysis (MCDA) are powerful, and relatively simple to use and communicate to policymakers. However, MAUT's theoretical requirements (especially additive independence of indicators and complete knowledge of system) are hardly ever satisfied in IBVA analyses, because of the hybrid nature of IBVA discussed above (El-Zein and Tonmoy 2013a). Second, a number of assumptions are typically made in IBVA studies (whether using MAUT or not)—a linear, monotonic relationship between indicator and vulnerability; complete compensation between indicators—none of which usually holds in reality. Hence, one challenge for IBVA is to be able to incorporate various forms of non-linear relationships and partial compensation between indicators. Third, data uncertainty occurs in different forms and at different levels of the analysis in IBVA, such as predictions of the GCMs, the downscaling of predictions to regional levels, the identification and quantification of processes generating vulnerability, the multiple stakeholder involvement in assessment exercises and the subjective aspects of vulnerability. The challenge for IBVA is to recognise these uncertainties and reflects them in the indicator selection and aggregation methods used.

In order to deal with these challenges, this research draws some insights from decision-making science, specifically from outranking methods, which will be briefly discussed below.

1.4 Outranking Methods

A set of methods called outranking procedures (OP), first proposed by Roy (1968), have evolved from the late 1960s to the 1990s in infrastructure and environmental decision making studies to help policy makers choose between different alternative actions under conflicting criteria (problem of incommensurate criteria) and a high level of uncertainty (problem of data uncertainty) (Hokkanen and Salminen 1997; Kangas. A 2001; Figueira. J 2005; Brooks 2003; El Hanandeh and El-Zein 2010). These methods have been extensively used over the last 30 years in environmental and non-environmental decision-making. They aim to generate rankings of comparable objects through structured pair-wise comparisons without resorting to a common value utility function. Compared to MAUT-based procedures, they have two significant advantages that are relevant in the context of IBVA: a) their theoretical requirements are less stringent than MAUT-based approaches (e.g., additive independence of criteria and complete knowledge of decision-making preferences) and b) a fuzzy preference structure which allows for partial compensation between criteria. In other words, outranking procedures are particularly well suited for problems with variable quality of data and high uncertainty attached to preference structures. It is clear therefore that the advantages that outranking methods bring to decision-making science are *potentially* highly relevant to IBVA. The extent to which this is actually the case has not been investigated before. An important objective of the thesis is to develop frameworks and tools that allow the use of outranking methods in IBVA and to investigate therefore the extent to which outranking methods can *actually* make a useful contribution to IBVA. These frameworks and methods will be applied to problems of vulnerability to climate hazards in coastal environments, which are discussed next.

1.5 Application of IBVA for assessing the vulnerability of coastal built-environment and infrastructure

Climate change impacts such as a rise in sea level, coastal erosion and coastal flooding will pose significant risk to lives, properties, and infrastructure that are on or near the coast. Therefore, coastal local governments have an interest in identifying the impact of climate change at the coast and the vulnerability of their residents and infrastructure to the impacts identified. Two aspects of coastal vulnerability are worth discussing.

First, most coastal vulnerability studies are conducted at larger scales that are useful for adaptation decision-making by central governments or regional authorities, but much less so to local councils. This is mainly because processes that generate vulnerability are different at different scales and the context of adaptation decision-making differs significantly between local government and higher authorities (Brooks et al. 2005; Neil Adger 1999; Preston et al. 2009). IBVA can make a potentially significant contribution to such assessments especially because processes generating vulnerability are arguably easier to identify at local scales compared to larger scales (Hinkel 2011; Adger 2006; Adger and Kelly 1999). To the best of my knowledge, no studies have been conducted at a local scale with a focus on assessing vulnerability of local infrastructure to a rise in sea level, as well as their users by scrutinizing the bio-physical, socio-economic and/or institutional implications and infrastructure interdependency.

Second, the life span of coastal infrastructure is typically long enough to be affected by SLR and associated erosion processes (Walsh et al. 2004). Often individual components in these infrastructure systems (e.g., power supply, water supply, waste water transport, roads, etc) are highly interdependent and any disruption of services to one component can impact other components and propagate through the whole system. This phenomenon is well known in the literature as infrastructure interdependency, mainly fore-grounded in studies conducted from a national or regional security perspective (Rinaldi 2004; Rinaldi et al. 2001; Min et al. 2007; UNEP 2001). This is a specific form of nonlinearity that IBVA in its current implementations appears to be ill-equipped to deal with. System Dynamics (SD), with its ability to model non-linear systems through the simulation of complex feedback mechanisms, can be used to incorporate infrastructure interdependency in IBVA exercises. Specifically, it can help in identifying and incorporating the non-linear and cascading impact of a possible failure of an infrastructure components (e.g., during a disaster event) and identify the most critical one.

In the context of climate change risk analysis, the SD concept has mainly been used for the development of sector specific mechanistic bio-physical models, mostly at macro scales (e.g., Dawadi and Ahmad, 2012; Wu et.al., 2013; Li and Simonovic (2002); Ahmad and Simonovic (2004); Le et.al., 2008; Parker et.al., 2003; Ford, 2009; Faust et.al., 2004) . To the best of my knowledge, no attempt has been made in the literature to incorporate an SD concept within an IBVA framework that attempts to cater for the biophysical, socio-economic and institutional components of risk.

1.6 Goal and Objectives of the Research

Considering these challenges, the goal of this research is to bring about theoretical and methodological improvements to IBVA by developing new and rigorous assessment frameworks and methods, and to apply them to the assessment of vulnerability to heat stress and sea level rise of a number of Sydney communities, at two different scales.

Specifically, the main objectives of the research are as follows:

1. develop a multi-dimensional framework for IBVA which takes into account effects of adaptation and allows a better definition of different types of uncertainty, incommensurability and nonlinearity.
2. based on this framework, develop an outranking formulation of IBVA that can accommodate uncertainty, incommensurability and nonlinearity.

3. integrate a system dynamics component into the outranking formulation for better simulation of infrastructure interdependency.
4. apply the new methods to the problem of vulnerability to heat stress in Sydney, based on published data and available databases.
5. apply the new methods to the problem of vulnerability to sea level rise of a set of exposed beach communities in Shoalhaven, by conducting an assessment exercise in coordination with the local council. Shoalhaven is a local government area about 100 kms south of Sydney.

Hence the thesis is structured as follows:

1. Conduct a meta-analysis of the literature to identify gaps in research and challenges to IBVA and to determine how the current literature is engaging with them (chapter 2).
2. Develop a general mathematical framework for Climate Change Vulnerability Assessment, including IBVA, that allows better definitions of different types of uncertainty, incommensurability and non-linearity (chapter 3).
3. Develop an analogy between Multi-Criteria Decision-Analysis (MCDA) and IBVA and build an outranking framework (SEVA-I) and a computer assessment tool for IBVA; apply the tool to the ranking of vulnerabilities to heat stress of 15 local government areas in Greater Sydney (chapter 4).
4. Expand SEVA-I to accommodate non-linearities in IBVA (SEVA-II) (chapter 5).
5. Develop a combined SEVA-II and System Dynamics framework and model to assess the vulnerability of infrastructure systems to a rise in sea level at a local scale (SEVA-III) (chapter 6).
6. Apply the above methods and frameworks to rank the vulnerabilities of eight beach communities in Shoalhaven, considering both private properties and public infrastructure systems (chapters 7 and 8). Chapter 7 describes the development of the IBVA models, designed specifically for Shoalhaven, using local knowledge and through consultation with multiple experts at the local council, while Chapter 8 describes the process of data collection for the models, presents the results of the IBVA analyses for Shoalhaven, evaluates

the new methods and discusses ways in which the assessment results can be used to prioritize Shoalhaven's adaptation actions.

Table 1 details the thesis structure.

Table 1-1: Thesis flow diagram

Chapter	Title	Theoretical and Methodological Contributions	New Computer Tools/ Models	Applications
1	Introduction	N/A	N/A	N/A
2	Methodological challenges and meta-analysis of the IBVA literature	• General literature review of IBVA and discussion of methodological challenges • Identification of trends and research gaps in IBVA literature	N/A	N/A
3	A general mathematical framework for CCVA	• Development of a general mathematical framework for CCVA problems, including IBVA • Definitions of different types of nonlinearity and incommensurability in IBVA problems.	N/A	N/A
4	An outranking formulation for IBVA problems with application to heat stress	• Development of an analogy between IBVA and MCDA problems • Development of an outranking formulation for IBVA	SEVA-I	• Ranking of vulnerability to heat stress of 15 coastal councils of Sydney
5	A non-linear framework for assessing vulnerability to climate change	• Extension of SEVA-I formulation to deal with non-linearities	SEVA-II	N/A
6	An infrastructure interdependency model for IBVA using system dynamics approach	• Integration of a system dynamics within an IBVA outranking framework	SEVA-SD SEVA-III	N/A
7	Assessment of vulnerability to sea level rise of eight beaches in Shoalhaven: I. Model development	• Development of a model of infrastructure vulnerability to sea level rise at beach scale • Development of a model of vulnerability of private households at beach scale	SEVA-INFRA and SEVA-HOUSE	N/A
8	Assessment of vulnerability to sea level rise of eight beaches in Shoalhaven: II. Results	• Assessment of vulnerability to sea level rise at local scale and discussion of implications for adaptation • Evaluation of the non-linear outranking framework for IBVA	N/A	• Ranking of vulnerability to sea level rise of eight beaches in Shoalhaven Council
9	Conclusion and future work	N/A	N/A	N/A
A.1,2,3,4 and 5	Appendix	N/A	SEVA Computer Codes	N/A

Chapter 2

Methodological challenges and meta-analysis of IBVA literature

2.1 Synopsis

This chapter discusses the most important methodological challenges facing indicator-based vulnerability assessment (IBVA) and conducts a meta-analysis of a representative sample of peer reviewed IBVA studies that were selected on the basis of citation and source of publication. This literature is large, and owing to its multi-disciplinary nature, is open to a number of different research paradigms (e.g., risk assessment, natural disaster management, urban planning), and therefore it is difficult to extract major directions, findings, and methodologies from this body of work. A large number of assessments are based, partly or totally, on indicators which bring up specific methodological problems and constraints. This chapter attempts to elicit major thematic and methodological focuses in this corpus and establish the extent to which it has engaged with issues of geographical and temporal scales, aggregation, and non-linearity.

Some of the major findings of this chapter such as the health of ecosystems and bio-diversity (28%), the quantity and quality of freshwater (14%), agricultural productivity and soil quality (7.5%), and public health (10%) have attracted the highest number of studies. Less than a third of papers sampled in this study give some consideration to uncertainty and an even smaller proportion to non-linearity. Assessments typically use methods of aggregation that are based on the Multiple Attribute Utility Theory (MAUT) despite the fact that IBVA rarely satisfies the theoretical requirements of this approach. Only a small percentage of studies critically scrutinize prevalent assessment methodologies or attempt to develop new ones, despite the fact that well founded questions have been raised in key theoretical papers about the methodological aspects of vulnerability assessment.

2.2 Introduction

Climate Change Vulnerability Assessment (CCVA) literature is highly diverse in terms of its content because a wide range of SESs (e.g., agricultural, marine, urban, sylvan), subject to a number of possible climatic stresses are considered. In addition, different approaches to assessment, quantitative and qualitative, are encountered. For example, case studies typically use the output of GCMs to examine how projected changes in climate variables might propagate through bio-physical systems at regional to local scales (e.g., Ford et.al., 2010; Anisimov and Belolutskaya, 2003; Falloon et.al., 2007). On the other hand, temporal and spatial analogues typically study a *reference* region or a *reference* time to determine how a *target* region or a *target* time might be (or has been) affected by climate change (Ford et al. 2010). Yet another approach, the indicator based vulnerability assessment (IBVA), has been widely used because it allows the bio-physical and socio-economic components of risk to be combined, and it is relatively simple to conduct and easy to communicate to the public and policymakers. Other risk analysis approaches such as Bayesian belief networks have been used, to a lesser extent, in the literature (Hough et al. 2010; Richards et al. 2013). However, their use appears limited to assessing the biophysical risk of climate change. All in all, this diversity in content and approaches has generated a CCVA literature that is large, multi-disciplinary, and appears to stem from a number of different paradigms (e.g., risk assessment, natural disaster management, urban planning, food security, etc). As a result, eliciting major directions, findings, and methodologies from this body of work is not a trivial task.

2.3 Conceptual and Theoretical Challenges of Climate Change Vulnerability Assessment

No single, widely accepted definition of vulnerability exists in the literature, despite the fact that a number of authors have attempted to pinpoint the concept. One commonly used definition (illustrated in Figure 2-1) has been presented by the

International Panel on Climate Change (IPCC) in its Third Assessment Report (IPCC 2001) :

> "[Vulnerability is] the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001).

The three dimensions of vulnerability elicited in this definition (exposure, sensitivity, and adaptive capacity) are seen as the outcome of the interaction of two traditions of vulnerability research in physical and social sciences—a synthesis that provides a better account of the contextual and social dynamics of climate hazards and the multiple linkages that govern their impacts (Adger 2006; Füssel 2007). However, this definition has come under significant criticism for its lack of precision in relation to the concepts of exposure, sensitivity and adaptive capacity, the relationship between them, as well as their relationship to vulnerability (Füssel and Klein 2006). Furthermore, Hinkel (2011) has argued that vulnerability and the related concepts are inconsistently defined in the broader literature. Climate change is one stressor amongst several, generating vulnerability (e.g., poverty, water insecurity, insecure employment) and often amplifies the effects of other stressors.

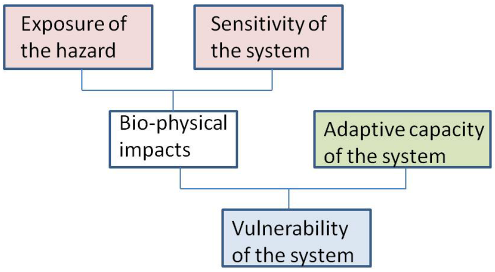


Figure 2-1: Components of vulnerability (adopted from IPCC, 2001)

Conceptual models of vulnerability found in the literature fall broadly in one of three categories. The first category represents a "biophysical" approach within a risk-hazard framework which conceptualizes the vulnerability of a system as a dose response relationship between an exogenous hazard and its effect on that system

(Dilley and Boudreau 2001; Downing and Patwardhan 2004). The second category is inscribed within a social constructivist framework which regards social vulnerability as a pre-existing condition of a household or a community generated by unequal access to resources (Füssel and Klein 2006; Blaikie P 1994; Adger and Kelly 1999). The third group of studies conceptualizes vulnerability as the differential abilities of communities to cope with external stress (Füssel and Klein 2006; Turner et al. 2003). This approach recognises that it is not the mere availability of adaptation options, but the capacity of communities and institutions to actually implement them that determines their vulnerability to climate change (Füssel and Klein 2006). For more discussion of conceptual frameworks of vulnerability, readers are referred to Watts and Bohle (1993), Bohle (2001), Adger (2001), Kasperson et al. (2003), Turner et al. (2003), Luers (2005a) and Füssel (2007).

The most important difference between the general risk-based and vulnerability frameworks is that the latter considers the socio economic implications of a given risk whereas the former usually focuses on the probability of occurrence of the event and its possible biophysical consequences. Faber and Stewart (2003) discussed the general risk based frameworks that are used in general in engineering and highlighted that the technical risk is typically defined as the expected consequences associated with a given activity. Considering an activity with only one event with potential consequences risk R is thus the probability that this event will occur P multiplied by the consequences given the event occurs C, i.e.$R=P\times C$. Linkov et al. (2011) argued that although such conceptualization of risk identifies and quantifies risk, it gives no insights into whether the identified risks are socially acceptable or not. In other words, general risk assessment frameworks do not usually reflect the socioeconomic implications of a given risk.

A number of attempts have been made to classify knowledge on vulnerability to climate change. The assessment reports of the Intergovernmental Panel on Climate Change (IPCC), namely IPCC (2007), identify major developments, approaches, and methods in climate change vulnerability research. Hofmann et al. (2011) offer a classification of knowledge on the impact of climate change and the adaptation and vulnerability in Europe through a conceptual meta-analysis, by identifying key assessment approaches in use and key sectors in which they have been applied. However, the study is limited to publications that are, a) relevant to Europe and, b) cited by the Working Group II contribution to Fourth Assessment report (IPCC 2007). Ford et al. (2010) examine how case studies and analogue methodologies have been used in climate change vulnerability research. However, none of these studies, including IPCC reports, pay sufficient attention to other equally important aspects of assessment such as spatial scale, the temporal framework of analysis, and aggregation and uncertainty.

This chapter focuses on indicator based vulnerability assessment (IBVA). IBVA has come under significant criticism on account of its methodological shortcomings (Hinkel 2011; Füssel and Klein 2006). However, because it is usually based on indicators that are readily available, IBVA is widely used and therefore deserves particular scrutiny. The goal of this chapter is threefold: a) to describe the broad characteristics of the IBVA literature in terms of its themes and focus, b) to analyse the more significant methodological challenges of IBVA, and c) to assess the extent to which the IBVA literature has engaged with these challenges. To this end, a meta-analysis of the literature was conducted based on a set of representative peer reviewed publications that were selected through a structured approach. The chapter is divided into three parts. First, it presents and discusses the most important methodological challenges of IBVA. Second, it describes the methodology followed in the meta-analysis of the literature. Third, it presents and discusses the findings.

2.4 Methodological challenges of indicator-based climate change vulnerability assessment

2.4.1 Introduction

For the sake of clarity, this chapter calls Climate Change Vulnerability Assessment (CCVA) any attempt at assessing vulnerability to climate change, be it quantitative or qualitative. Quantitative approaches can be based on indicators, mechanistic models, or a mix of both. On the other hand, vulnerability assessments that are based on indicators are referred to as Indicator-Based Vulnerability Assessment (IBVA); in some IBVAs, some of the indicators can be the outcome of mechanistic models. No single term has been applied in the literature to this exercise despite its widespread use. Therefore, in this thesis, it is referred to as IBVA.

As mentioned earlier, there is extensive literature on vulnerability research available in the context of social and global change. However, the application of these concepts in policy driven assessments has been limited by a lack of robust metrics to model vulnerability within and across systems (Luers et al. 2003). Strictly speaking, vulnerability is a concept that cannot be measured in the way an observable phenomenon such as the mass of an object, energy, or temperature are measured (Moss 2001). Nevertheless, the following three steps can be followed in order to make the concept operational, i.e. to build a methodology for comparing vulnerabilities of systems: a) define a vulnerability framework and identify processes creating vulnerability, b) select the indicators, and c) model or aggregate the indicators (Hinkel 2011). These three steps will be examined in turn.

2.4.2 Operational Vulnerability Definition

Vulnerability can be viewed as possible future harm, referring to a value judgment, for example: “how bad is the system under a specific hazard?” A proxy indicator of “badness” is then sought, such as the number of people who might die during a flood event or a decline in the population of a given species due to ocean acidification. The first step in building the most basic vulnerability model is to define the problem at hand by answering the following three questions:

1. Which *socio-ecological system* (SES) is the object of study, e.g., locality, community, industrial sector, ecosystem?

2. Vulnerabilities of which *valued attributes* of this SES are to be assessed, e.g., health, prosperity, biological productivity, bio-diversity?

3. Vulnerabilities to which *climate related stress(es)* are to be assessed?

2.4.3 Selection of Indicators

Selection of indicators is clearly conditioned by the choice of valued attributes and SES of concern and aims to represent all of the important processes that generate vulnerability (Hinkel 2011). However, the selection may involve a degree of subjectivity and uncertainty. Mechanistic models, when they are available or possible to build, are usually preferred because they can represent processes more accurately than indicators. Indicators are essentially "weak" models. For instance, it is known that the indicator bears a relationship to vulnerability, and the direction of the relationship is also known (increasing or decreasing vulnerability with increasing indicator), but it is not always possible to characterise this relationship with accuracy. Nor do we usually have access to deductive arguments to guide us in combining these indicators to build a proxy measure of vulnerability. It is precisely because of this epistemic uncertainty that aggregation, which is discussed next, is critical, since it can only be partly guided by a mechanistic knowledge of the system under study.

2.4.4 Aggregation of Indicators

2.4.4.1 Why aggregate?

Once indicators have been selected and evaluated for each SES, they can be combined by way of modelling or aggregation, to generate an overall "measure" of vulnerability. At its simplest, aggregation is a form of mapping which aims to identify those SESs for which a confluence of indicators points to higher vulnerability. At its more complex, it can generate vulnerability indices or vulnerability rankings which can inform policy making and adaptation.

As mentioned above, mechanistic modelling is useful when the exact relationships between system variables (indicators) are known via simple closed-form equations or more complex relationships implemented in a simulation model. Global circulation models can be used as an example of this kind. Modelling is often used in the assessment of the vulnerability of natural ecosystems (Füssel and Klein 2006; Füssel 2007; Ionescu et al. 2009). This is because it is usually possible to simulate the exogenous climatic impacts and the ecosystem's sensitivity to those impacts. The vulnerabilities of anthropogenic systems, on the other hand, are more difficult to model in a mechanistic sense, not least because of the complexity of processes determining sensitivity and adaptive capacity, and the necessarily qualitative nature of at least some of the research generating knowledge about it. Adaptive capacity is the critical property of a system which describes the ability to cope or mobilize scarce resources to anticipate or respond to climate related stresses (Nathan 2011). It carries in other words strong socio-economic and political dimensions. Aggregation, therefore, becomes the only available option if some ranking of vulnerabilities is to be generated, based on the assembled indicators.

2.4.4.2 What forms of aggregation are used?

As the exact relationship between an indicator and vulnerability is not usually known, IBVA uses a form of aggregation that is sometimes called vulnerability mapping, especially when the systems in question are spatially defined communities. Mapping is most commonly performed by combining multiple indicators into single indices of vulnerability for a given stressor under a given dimension, and then combining multiple indices in order to build an overall, relative estimate of vulnerability (e.g., Bernier et al., 2009; Yoo et al., 2011). These “combinations” are usually simple arithmetic or geometric means, based on the Multiple Attribute Utility Theory (MAUT) that is widely used in economics, engineering, decision science, development studies and, to a lesser extent, social sciences (Alessa et al. 2008; Brenkert and Malone 2005; Lexer and Seidl 2009; Malone and Brenkert 2008). Some studies also use empirical equations for aggregation in order to develop a vulnerability index (Aguilar et al. 2009; Abuodha and Woodroffe 2010; Duriyapong and Nakhapakorn 2011). The advantage of building indices is that a wider range of variables can be incorporated, ideally leading to a more comprehensive model of reality. The World Economic Forum, for example, has created an Environmental Sustainability Index based on 67 variables represented by 22 indicators within 5 broad dimensions (environmental systems, reducing environmental stresses, reducing social vulnerability, social and institutional capacity, and global stewardship) (Vincent 2004). Likewise the UNDP Human Development Index (HDI) is an annually-updated composite index measuring three dimensions of human development; a long and healthy life, knowledge, and a decent standard of living (UNDP 2013). It is arguably one of the most common benchmarks against which development is measured, and can highlight non-progressing countries for multilateral aid assistance (Vincent 2004). UNEP (2001) discussed the potential use of vulnerability indices at different geographical scales with various policy contexts. Moss (2002) described a quantitative approach for building a national level vulnerability index (for assessing the vulnerability of natural resources and socio economic systems to potential future changes in climate) using an index called vulnerability resilience indicator prototype model (VRIP). Briguglio (1995) developed Small island developing state vulnerability index (SIDS) for assessing economic vulnerability of small islands that are prone to climatic hazards. An Environmental Vulnerability Index (EVI) was developed by Kaly (1999) for south pacific islands to assess their risk to environmental change.

Most of these indices are developed by aggregating vulnerability indicators using arithmetic or geometric mean, which are based on MAUT. However, such methods of aggregation face theoretical and practical difficulties which have been recognized by a number of authors (Ebert and Welsch 2004; Böhringer and Jochem 2007; Füssel 2007; Klein 2009; Tonmoy and El-Zein 2012). For example, the MAUT- requirement of additive independence of indicators is virtually impossible to achieve in the context of IBVA. In addition, MAUT-based aggregation in IBVA typically allows complete compensation between different indicators when in fact this may not be realistic (e.g., beyond a certain level of sea rise, nor degree of adaptive capacity can help small island states cope with inundation). Another problem is that a monotonic relationship is usually assumed between indicator and vulnerability which does not allow the simulation of non-linearities and thresholds (Preston et al. 2009; Tran et al. 2010; Rinner et al. 2010). Non-linearity has been recognised in the conceptual literature on vulnerability, with at least one framework defining vulnerability as a degree of departure from a threshold (Luers 2005a).

2.4.5 Scale and Uncertainty

2.4.5.1 Spatial Scale

Processes generating vulnerability can be fundamentally different at different scales. As an example, access to resources, diversity of income sources, as well as the social status of individuals plays a vital role in determining vulnerability at a household level (Ghimire et al. 2010; Hahn et al. 2009; Stephen and Downing 2001). On the other hand, vulnerability at a larger scale (e.g., regional or national) is determined more strongly by institutional and market structures such as the prevalence of informal and formal social security and insurance, infrastructure and income (Adger and Kelly 1999; Hinkel 2011). A number of scholars have argued that at local compared to regional, national and international scales, it is easier to define systems, identify socio-economic and bio-physical processes that determine vulnerability and build inductive arguments to characterise them, and that, consequently, IBVAs should be conducted at smaller rather than larger scales (Adger and Kelly 1999; Vincent 2004). In any case, vulnerability may be the outcome of policies and processes operating concurrently at different spatial and temporal scales. Information and knowledge gained through vulnerability studies conducted at a higher geographical scale (e.g., national or regional level) can be useful for adaptation decision making at the smaller scale (e.g., city or council level), but not sufficient, not least because the decision-making context in these two scales are different.

2.4.5.2 Temporal Scale

Implicit in the concept of vulnerability is, as mentioned above, the idea of *future* harm (Hinkel 2011). However, the question remains as to whether the framework is referring to future harm from today’s standpoint or some point in the future. In other words, it is important to be clear as to whether the object of the assessment is today's vulnerability (determined in part by past adaptation) or one which might unfold in the future depending on prior adaptation. The answer to this question should in turn dictate the point in time at which indicators are measured and provide a degree of temporal consistency to the analysis. Dessai and Hulme (2004) pointed out that the temporal framework adopted in studies usually reflects epistemic choices and disciplinary boundaries; specifically, while research into the impact of climate emanating from physical sciences tends to project into the future, social scientists are more interested in understanding the processes generating vulnerability today.

IBVA studies, especially those carrying a significant socio-economic component, often combine indicators at different points in time (e.g., a mixture of current socioeconomic data with future climate projections) and associate them with what is rather ambiguously termed as “climate change vulnerability”, without any reference to time (present or future). A consistent approach, in the case of the above example, would combine projections of future adaptive capacity with future climate data. Such an effort has been made, for example, in the ATEAM project (Advanced Terrestrial Ecosystem Analysis and Modelling) in Europe to assess the vulnerability of ecosystems due to future climate change (Metzger et al. 2006; Metzger et al. 2008). However, attempts at temporal consistency appear limited in the literature.

2.4.5.3 Uncertainty

Uncertainty in any assessment of vulnerability to climate change emanates from a number of sources, at both the biophysical and social ends of the analysis. The most significant uncertainty is arguably an epistemic one attached to predictions of GCMs, and due to processes and feedback mechanisms that are unknown, poorly understood, difficult to quantify or probabilistic in nature (Reilly et al. 2001; Füssel and Klein 2006; Patt et al. 2005a; Heal and Kriström 2002; Dessai Suraje 2009; Dessai and Hulme 2004). The process of downscaling GCM predictions to regional and local levels adds another layer of uncertainty that is mostly due to unknown processes at these scales or poor precision due to the spatial resolution of GCMs, or both. All of these sources of uncertainty are important and have received significant attention in the literature (New et al. 2007; Hawkins and Sutton 2009; Adger and Vincent 2005). However, this thesis is concerned with the additional uncertainty attached to indicator-based studies that combine the bio-physical and socio-economic ends of risk assessment that are typically represented by the three dimensions of exposure, sensitivity, and adaptive capacity. These assessments start either from a climate change scenario and attempt to quantify vulnerability at some point in the future, or they might study vulnerability to climate hazards in the present. Either way, at least three sources of uncertainty need to be considered in the process of indicator selection and manipulation.

Epistemic uncertainties operate at the indicator-selection stage. They emanate from an incomplete knowledge of processes generating vulnerability, be they bio-physical, socio-economic or institutional, and can result in significant deficiencies in indicator-based models (Füssel 2007; Füssel and Klein 2006; Hinkel 2011; Turner et al. 2003). Because IBVA is quantitative, important processes may be overlooked and, for processes that have been identified, suitable indicators may not be available.

Fundamental uncertainties relate to the exact relationship between indicators and the ‘vulnerability’ which they are supposed to indicate, as well as the ‘convertibility’ of one indicator into another. The two problems are obviously related. These relationships are often unknown or only known qualitatively. This is due to the combined bio-physical and socio-economic nature of the assessments which leads to an inductive and/or normative approach to indicator selection, as opposed to deductive, theory-driven approaches (Vincent 2007; Adger 2006; Kelly and Adger 2000; Brooks et al. 2005; Barnett 2001; Patt et al. 2005a). Deductive approaches are difficult to develop and in making them operational, researchers often come up against the problem of a lack of availability of suitable data. As a result, it is practically impossible to select a set of additively independent indicators, generate a one-on-one correspondence between indicators and processes generating vulnerability, or establish mechanistically the way indicators should combined to reflect vulnerability generated by a combination of processes.

Imprecision derives from the random and non-random fluctuations of indicators, especially if they are averaged over spatial or temporal scales and/or projected into the future. One particular form of imprecision is due to the relatively subjective process by which some indicators (or the weights attached to them, when weights are used) are evaluated. This can be the result of vagueness in individual judgment or variances in the judgment of multiple stakeholders or experts (Refsgaard et al. 2007; Dessai and Hulme 2004; New et al. 2007; Heal and Kriström 2002; Reilly et al. 2001). Imprecision and subjectivity can in principle be quantified with probability distributions, and intervals of confidence or fuzzy sets, but either way the analytical framework must recognize and accommodate these uncertainties.

2.5 A meta-analysis of the IBVA literature

2.5.1 Analysis Objectives and Design

2.5.1.1 Objectives

What has been the thematic focus of the IBVA literature? To what extent has it engaged with the methodological challenges raised above? In order to answer these questions, a meta-analysis was conducted by analysing a sample of 134 peer reviewed papers that were selected on criteria of relevance and citation. Specifically, it was sought to characterise this literature in relation to:

1. broad content (theoretical, methodological, applied or a combination of these);
2. knowledge domain (bio-physical dimension of risk, socio-economic and institutional dimension of risk, or a combination of these);
3. Socio-Ecological System (SES) under consideration (e.g., crop production systems, coastal communities, emergency response systems, species under threat);
4. valued attribute(s) of the SES to be protected/maximised (e.g., economic productivity, well-being, health);
5. physical hazard(s) under consideration (e.g., sea level rise, heat waves, floods);
6. geographical scale (e.g., local, municipal, regional, national);
7. temporal frame of reference (e.g., its consistency or lack thereof, present versus future vulnerability, 2050, 2100);
8. aggregation methods employed (e.g., multi-attribute utility theory, GIS overlaying);
9. weight estimation methods (e.g., equal weights, stakeholders interviews, mathematical methods);
10. explicit consideration of uncertainty, or the lack thereof;

11. explicit consideration of the non-linear and threshold processes, or the lack thereof.

2.5.1.2 Papers Selection

It was aimed for a sample of between 100 and 150 publications, i.e. one that is sufficiently large yet reasonably manageable. This was achieved through trial and error in order to generate a reasonable selection process that yielded a number of publications within this range. The selection process was as follows.

Two prominent and multi-disciplinary science databases, Scopus and Web of Science, were targeted. To start with, a keywords search that aimed to capture as much of the relevant literature as possible was conducted. Hence, the terms [“climate change” OR “global warm”] was used and was intersected with [“vulnerability” OR “resilience”], to be found in keyword, title, or abstract of publication. The resulting sample, called search set 1, yielded over 3000 papers in each database, as shown in Table 2-1; there was, of course, a significant overlap between the two databases but this was dealt with further down the selection process. Then, the following operations were performed on search set 1 to progressively reduce it in size and make it more sharply relevant to the topic, namely research around IBVA:

a. Only publications containing the word “indicator” were selected (search set 2).
b. The study limited its interest to journal articles because they are usually more rigorously peer reviewed and are therefore of a higher quality than other types of publications (search set 3).
c. In Scopus the study selected all papers from journals which had yielded at least 2 papers on the query in search set 3. Among the 114 journals brought up by search set 3, 20 yielded at least 2 papers, thus reducing the number of papers to 67 (search set 4).
d. From the remaining 94 papers in Scopus (search set 3 minus search set 4), all papers with at least 9 citations were re-included (search set 5). This resulted in a total of 89 papers from Scopus when all papers from search set 4 and search set 5 were included in the sample.

e. The same procedure was conducted in WS (except that journals with 3 rather than 2 papers were included), with a total number of 109 papers from WS in the sample.
f. Finally, a manual search of the papers dropped from search set 3 (159) of both databases was conducted and, considering the relevance to the objectives, 14 more papers were re-included (search set 8).
g. When search set 4, 5 and 8 from both databases were combined, a total of 212 papers were obtained (search set 9).
h. By removing an overlap of 56 papers between the 2 databases, as well as 24 papers that turned out to have only weak links to climate change, a final study sample of 134 papers remained.

Clearly, choosing cut-off points of 9 citations and 2 or 3 articles per journal (points c, d and e) is arbitrary. These numbers were reached by trial and error with the aim of achieving sample of manageable size.

A comparison of search sets 1 and 2 indicated that the number of IBVA journal papers was about 6%-7% of the total number of papers on vulnerability to climate change over that period of time. The final study sample contained at least 37% of all indicator-based papers identified in the two databases. This was the final number of selected papers, as a percentage of papers in search set 2, assuming that search set 2 had the same number of overlap and weak link papers as search set 9. The actual percentage was likely higher since search set 2 most probably had a larger number of duplicates and weak link papers than search set 9. Hence, the final study sample (Appendix A6) was expected to be highly representative of the peer reviewed IBVA corpus.

Table 2-1: Search criteria and successive steps in building meta-analysis sample (search conducted on 3 February 2012)

Search Set	Search Criteria	Scopus	WS*
1	["climate change" OR "global warm"] AND ["vulnerability" OR "resilience"]	3683	3293
2	["climate change" OR "global warm"] AND ["vulnerability" OR "resilience"] AND ["indicator"]	209	234
3	["climate change" OR "global warm"] AND ["vulnerability" OR "resilience"] AND ["indicator"] AND [journal article]	161	196
4	Within Scopus search set 3, all articles in journals with at least 2 papers [20 journals]	67	
5	All publications with at least 9 citations within [Scopus search set 3 minus Scopus search set 4]	22	
6	Within WS search set 3, all articles in journals with at least 3 papers [18 journals]		80
7	All publications with at least 9 citations within [WS search set 3 minus WS search set 6]		29
8	Manual selection based on relevance	14	
9	**Total selection (search sets 4, 5, 6, 7 and 8)**	**212**	
Final Study Sample	**Final number of selected articles after removal of repetition and checking out relevance within search set 9**	**134**	

*WS: Web of Science

2.6 Results and Discussion

2.6.1 Yearly Distribution

Figure 2-2 shows the yearly distribution of the papers in the study sample and in the larger search set 1. In both cases the number of yearly publications rose almost tenfold in ten years. Around 77% of the total number of papers in each set was published between 2006 and 2011. This suggests there has been a significant growth of climate change vulnerability research. In addition, the similarity in the patterns observed in the 2 data sets supports the hypothesis that the study sample (134 papers) is a reasonably representative sample of the targeted literature, albeit skewed towards the peer reviewed journal publications.

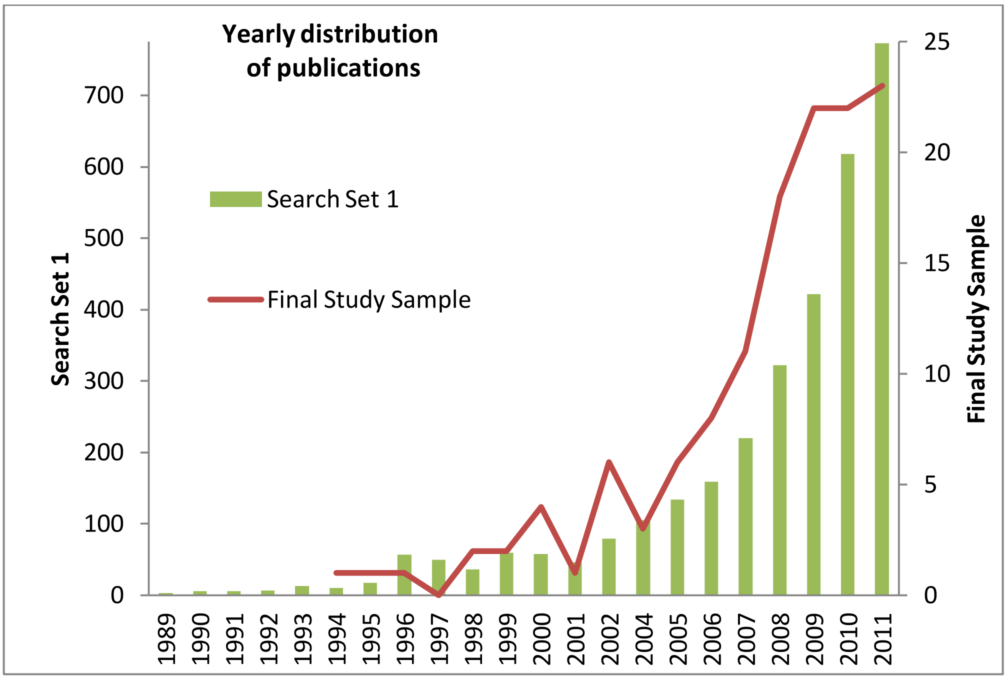


Figure 2-2: Yearly distribution of publications

2.6.2 Thematic Focus

65% of papers in the study sample consist of vulnerability assessment studies applied to a specific setting (see Table 2-2). 15% of papers were dedicated to theoretical issues around vulnerability assessment (definitions, conceptual frameworks, measurability, and so on), with another 10% engaging with the theoretical aspects of vulnerability assessment and reporting an assessment study. Most methodological papers (9% of the total) also contained an applied component, while another 1% was dedicated exclusively to methodological issues.

Table 2-2: Thematic focus of the papers

Thematic Focus	**Human systems**				**Natural systems**		**Total Count**	**% of total**
	Both biophysical and socio-economic knowledge domain (A)		**Only biophysical knowledge domain (B)**		**Only biophysical knowledge domain (C)**			
	Count	**% of A**	**Count**	**% of B**	**Count**	**% of C**		
Theoretical	19	24%	0	0	1	3%	**20**	**15%**
Theoretical and Applied*	11	14%	0	0	2	5%	**13**	**10%**
Applied*	40	51%	15	79%	32	86%	**87**	**65%**
Methodo-logical	0	0%	0	0	2	5%	**2**	**1%**
Methodo-logical and Applied*	8	10%	4	21%	0	0%	**12**	**9%**
Total	**78**	**100%**	**19**	**100%**	**37**	**100%**	**134**	**100%**

*Applied means that the paper conducts an indicator-based assessment of a specific SES

2.6.3 Socio-Ecological Systems

For the purpose of this meta-analysis, two broad categories of SES were defined: "Natural Systems" and "Human Systems". The latter refers to any study that focused, in part or in total, on some aspect of the well being of a human community inscribed in the ecological, social, and institutional systems on which it depends. The community may be defined through any number of possible ties (e.g., economic, geographical, ethnic, industrial). "Natural systems", on the other hand, refers to studies whose primary goal was to examine a species or a natural ecosystem as such. Although interest in "natural systems" may well stem from some anthropogenic service that the system provides, this service does not occupy centre stage in these studies. Although this categorisation is largely anthropocentric, it was found useful in helping to describe the IBVA literature.

28% and 72% of publications studied “natural systems” and “human systems”, respectively (Figure 2-3). 22% and 78% of “natural systems” papers were specifically concerned with “marine ecosystems” (e.g., barrier reefs) and “terrestrial and atmospheric ecosystems” (e.g., vulnerability of national park, forests, specific flora or fauna species etc.) respectively.

19% of “human systems” studies in the sample focused on hydrology (e.g., how climate change might impact rainfall and water budgets in a given region), 15% on agricultural systems (e.g., vulnerability of crop production of a specific community), 16% on urban ecosystems (e.g., vulnerability of a specific urban setting or community) and 8% on coastal settlements (e.g., vulnerability of a coastal community or its infrastructure). On the other hand, around 29% of studies did not focus on a single SES; rather, they built an indicator based model that represents multiple systems. For example, Brenkert and Malone (2005) modelled overall national vulnerability by providing a case study for India and Indian states, by selecting vulnerability indicators from multiple sectors (e.g., agriculture, water resources, health systems) and aggregated them to get a sense of overall vulnerability. Moss (2002) used an indicator based approach to assess the national vulnerability of a number of countries by extracting a set of key indicators for key sectors (e.g., water sector, environment), without explicitly identifying the valued attribute in each of these sectors.

Table 2-2 also shows the thematic focus of “human systems” papers. 78 out of 97 papers combined socio-economic and bio-physical indicators, consistently with the IPCC vulnerability framework they used. This would suggest that the methodological problems associated with this combination, which was discussed earlier, are highly relevant to this particular segment of the literature.

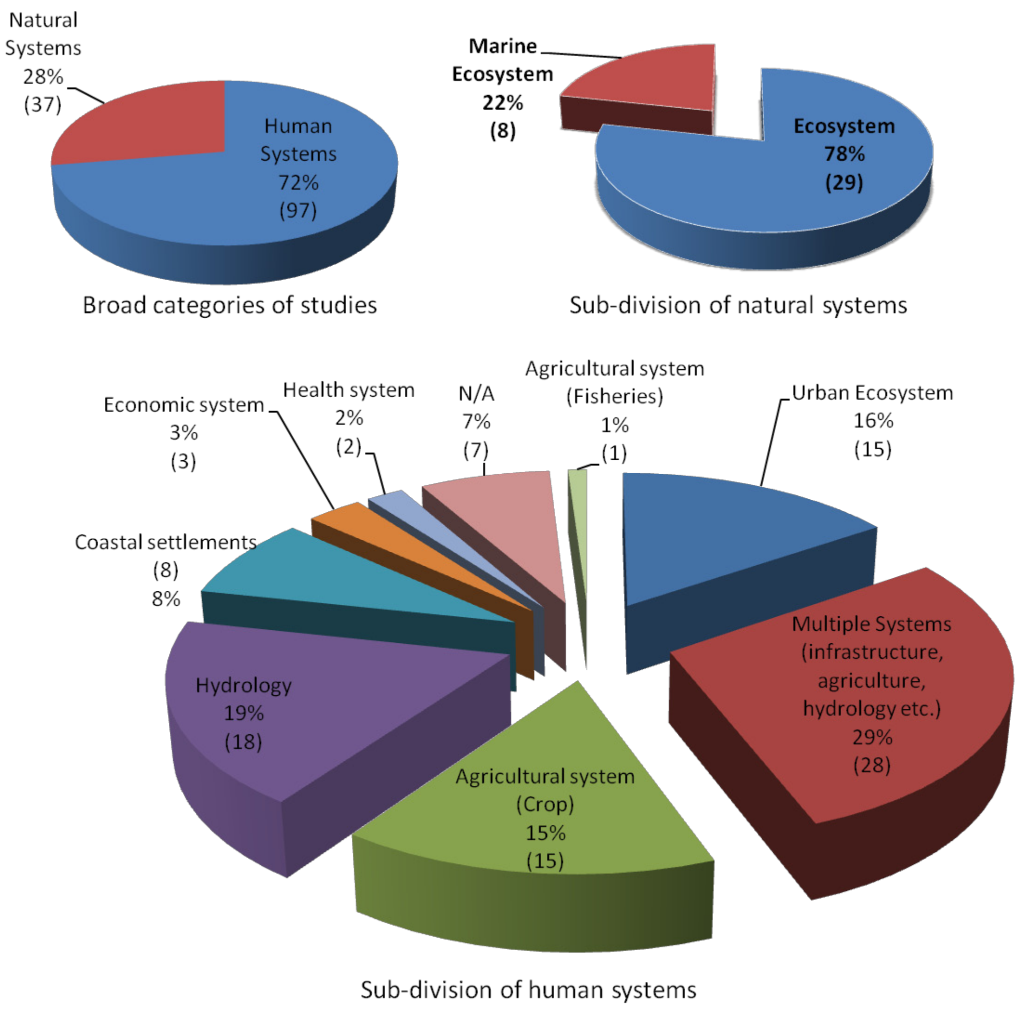


Figure 2-3: Distribution of papers according to the socio-ecological system under consideration (number of papers shown in brackets)

2.6.4 Valued Attribute of Concern

When assessing vulnerability to climate related hazards, one or more specific attributes of the socio-ecological systems in question usually comes under scrutiny. This "valued attribute" is either implicitly assumed or explicitly articulated in the studies. Table 2-3 shows the distribution of valued attributes of concern in the study sample. Ecosystem health and bio-diversity together accounted for about 28% of all studies, while soil quality and agricultural productivity made up another 7.5%. A relatively large number of studies (12%) were concerned with the quality and quantity of freshwater resources. Public health also attracted a high level of interest (around

10% of studies). For example, Van Lieshout et al. (2004) developed a global model of malaria transmission to estimate the potential impact of climate change on seasonal transmission and populations at risk of the disease.

Table 2-3: Distribution of valued attributes of concern (explicitly stated in papers or inferred during the meta-analysis)

Distribution of valued attribute of concern	Count	%
Health of ecosystems	**35**	**26.2%**
Marine ecosystems	5	3.7%
Fauna species	12	9.0%
Flora species	4	3.0%
Vegetation cover and forests	8	6.0%
Other ecosystems	6	4.5%
Biodiversity	**2**	**1.5%**
Soil quality	**2**	**1.5%**
Agricultural productivity	**8**	**6.0%**
Water resources quality and quantity	**16**	**11.9%**
Physical integrity of shorelines	**4**	**3.0%**
Integrity of infrastructure	**2**	**1.5%**
Well being of farmers	**6**	**4.5%**
Well being of coastal population	**4**	**3.0%**
Household livelihood	**2**	**1.5%**
Public health	**14**	**10.4%**
Economic returns of tourism	**2**	**1.5%**
National economy	**2**	**1.5%**
Large scale mixed social and economic attributes (e.g., socio economic well being)	**29**	**21.6%**
Not applicable	**6**	**4.5%**

On the other hand, a significant proportion of papers (22%) operated on a large geographical scale (regional or national) and combined a collection of indicators that seemed to reflect a mix of valued attributes, usually without specifying what they were. One such example is the study by Brenkert and Malone (2005), referred to earlier. Another example is provided by Vincent (2007) who discusses critical issues of uncertainty in determining adaptive capacity at different scales, from a household to a nation, and uses indicators from a mixed bag of sectors with different valued attributes (e.g., economic wellbeing, institutional stability, global interconnectivity, access to water resources).

Finally, the relatively small number of papers dealing with the integrity of infrastructure systems was notable, although this may be because these systems lend themselves to mechanistic simulations that do not require the use of indicators. Another reason of this low count can be limiting the search of this meta-analysis to journal articles only. Sometimes, infrastructure authorities commission vulnerability or hazard studies and present the results of these studies as a form of technical report in opposed to journal article.

2.6.5 Physical Hazard under Consideration

30% of papers in the study sample were concerned with single hazards, while the remaining 70% (93 papers) addressed multiple ones. This is unsurprising given that the compound effect of multiple hazards can be significant and difficult to predict by considering single hazards separately. Figure 2-4 shows the distribution of hazards considered in single hazard studies. An increased frequency of droughts and temperature extremes together accounted for more than 50% of the studies, with the figure increasing to around 75%, if sea level rise and ocean acidification and warming are included. This distribution seems to match the most important bio-physical climate stressors identified by the IPCC working group 1 (e.g., IPCC, 2001; IPCC, 2007).

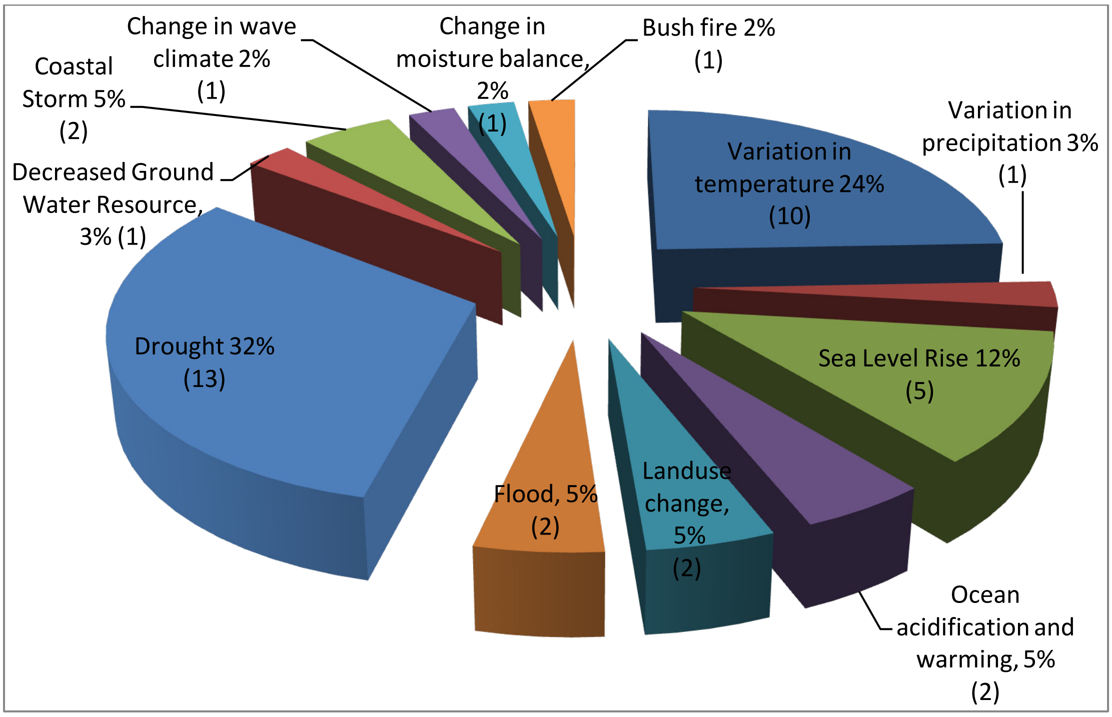


Figure 2-4: Distribution of papers according to climate-related stress considered in single-stress studies (number of papers shown in bracket)

2.6.6 Geographical Scale

Geographical scale plays an important role in determining the relevant processes that generate vulnerability. Here, studies termed “global” generally assess the impact of a specific hazard on the whole world, at least nominally. Studies grouped under “national” compared the vulnerabilities of different nations. “Regional” scale refers to studies conducted at a sub-national level that were typically larger than a city. “Urban/suburban” refers to studies conducted at city scale or smaller geographical units. Finally, studies that consider the vulnerability of a specific community, usually defined by a given locality (e.g., a specific suburb, a group of neighbouring villages) down to a household level are termed “local”. Figure 2-5 shows that 65% of studies are conducted at regional or higher levels. Only 17% of vulnerability studies were conducted at a local level which is, arguably, the scale at which processes generating vulnerability are most well defined and the scientific validity of the assessment is likely to be at its highest (Adger and Kelly 1999; Hinkel 2011).

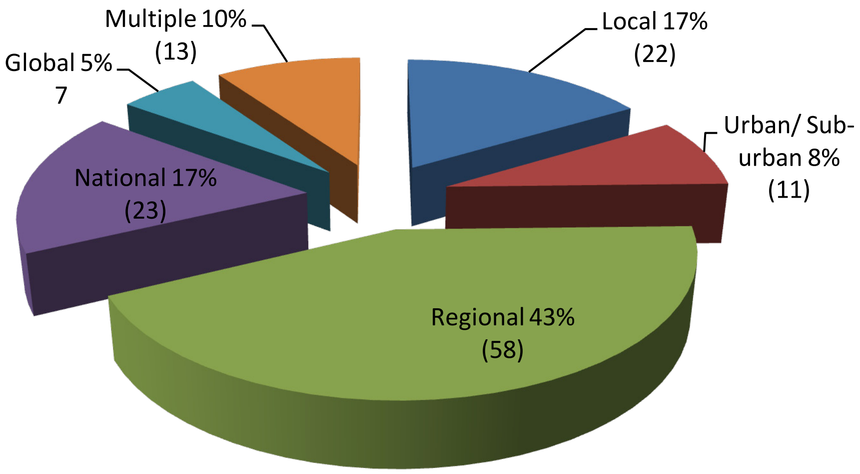


Figure 2-5: Distribution of papers according to the geographical scale of studies (number of papers shown in brackets)

2.6.7 Temporal Frame of Reference

Vulnerability is expected to change over time. It is therefore important that vulnerability studies are conducted within a well defined time frame. A simple but fundamental temporal element consists of specifying whether present vulnerability or vulnerability at some given time in the future is being sought in the study. This appears to be the exception rather than the norm in the literature, where 91 out of 134 studies in the sample were non-specific on this issue. Many studies combine future climate projections with present-day socio-economic indicators without clarifying that what they are assessing is in fact a present day vulnerability to future climate events. It is unsurprising therefore that apart from papers presenting “temporal analogues”, little appears to be said in the IBVA literature about the way vulnerability might have changed in the past or might evolve in the future.

2.6.8 Aggregation Methods Employed

Figure 2-6a shows that MAUT and GIS-based MAUT accounted for 24% of aggregation methods employed in the study sample. However, when studies that do not aggregate indicators as well as those that do not consider socio-economic processes generating vulnerability are excluded (i.e., those focusing exclusively on natural ecosystems), it was observed that in this smaller sample, MAUT-based aggregation (i.e. additive and multiplicative approach) and GIS-based MAUT, forms of aggregation were employed in 61% of publications (Figure 2-6b). This is due to the fact, discussed earlier, that mechanistic simulation models accounting for socio-economic and institutional factors are much more difficult to build, with researchers resorting instead to the simplicity of additive or multiplicative aggregation. A number of agricultural studies used empirical equations to calculate such indicators as the crop vulnerability index and crop sensitivity index. On the other hand, only 10% of studies in the smaller sample used more sophisticated methods such as multi-criteria decision analysis (4%) or fuzzy logic (6%). As is shown later in this thesis, these methods are usually better suited for the mix of quantitative and qualitative data that characterizes indicator-based vulnerability models.

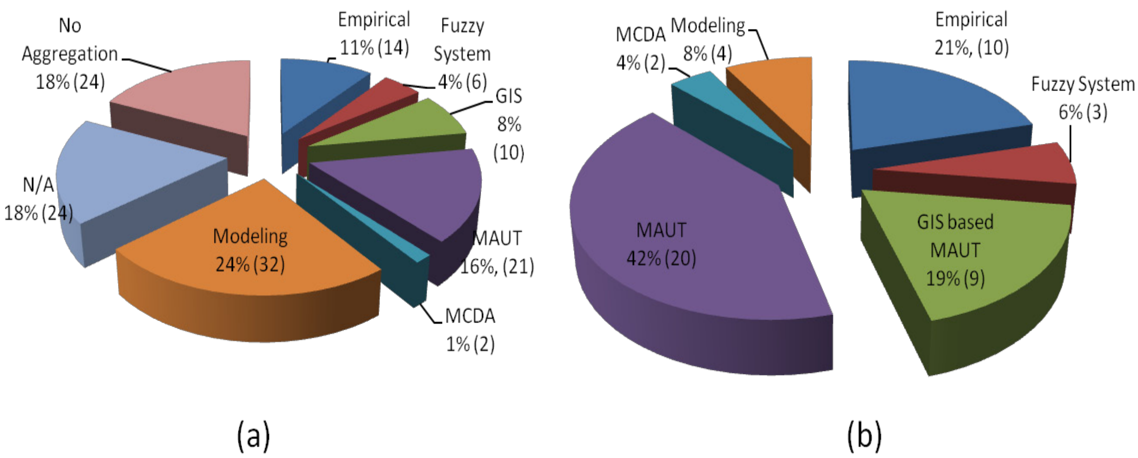


Figure 2-6: Distribution of papers by aggregation methods employed: a) for the whole study sample (134 papers) and b) 48 studies that consider both biophysical and socio-economic domains, excluding 23% of studies with no aggregation (number of papers shown in bracket)

2.6.9 Weight Estimation Method Employed

Assignment of weights to indicators is another important step of IBVA, especially when MAUT approaches are used. 70% (93) of the papers in the study sample did not use indicator weights while conducting IBVA (Table 2-4). This included papers that were purely theoretical or qualitative in nature and did not aggregate indicators. Among the remaining 41 papers that specify their weight estimation method, equal weights turned out to be the most common method with 37% (15 out of 41) of these papers using them, usually with little justification provided. 34% of these (14 out of

41) papers employed expert judgment as a method for generating weights (Table 2-4). This was consistent with the fact that modelling a complex system involves multiple stakeholders and expert judgment from stakeholders is an important source of knowledge.

A few studies used Principal Component Analysis (PCA) as a method to estimate weights. PCA is data intensive and derives weights based on the intrinsic variability of the indicators rather than the relationship between indicator and vulnerability (El-Zein and Tonmoy 2013a). A relatively smaller (7 out of 41) number of studies in the sample used the more sophisticated mathematical methods shown in Table 2-4.

Table 2-4: Distribution of papers by weight estimation methods employed for the whole study sample

Weight estimation Method	Description	Count	% of study sample
Equal Weight	All attributes of the analysis is assumed equally important	15	11%
Multi-Way Data Analysis	Multi-way analysis examines the association of one dependent variable with a set of independent, determining or classifying variables.	1	1%
Principal Component Analysis	Principal component analysis (PCA) is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components.	5	4%
Expert Judgment	A group of experts decide about the importance of different attributes of the analysis	14	10%
Analytic Hierarchy Process (AHP)	The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions.	2	1%
Other statistical analysis	N/A	4	3%
Not Applicable	N/A	93	70%

2.6.10 Explicit Consideration of Uncertainty, Nonlinearities and Thresholds

Only 23% of papers in the study sample explicitly engaged with one or more of the different sources of uncertainty that was discussed earlier. For example, in assessing susceptibility to drought, Eierdanz et al. (2008) used fuzzy-set theory to incorporate uncertainty stemming from vague definitions and a lack of knowledge about vulnerability. Eakin and Bojórquez-Tapia (2008) took into account the uncertainty inherent in weights allocated to household vulnerability indicators, through multi-criteria analysis and fuzzy logic.

Table 2-5 shows the proportion of papers assessing the vulnerability of human systems that explicitly considered one or more forms of non-linearity. Only around 10-12% of papers have done so. Since the bio-physical dimension of risk usually lends itself more easily to mechanistic modelling than its socio-economic and institutional dimensions, one might have expected a higher proportion of papers that focussed on the former to have attempted to incorporate non-linearity in the models. However, this was not borne out by the study sample. The small number of studies that considered non-linearity mainly used the "vulnerability surface approach" proposed by Luers (2005a) which defines vulnerability as a degree of departure from a threshold. Studies such as those conducted by Seidl (2011) and Lexer and Seidl (2009) used MCDA methods (e.g., PROMETHEE) to characterize non-linearity.

Table 2-5: Distribution of studies according to their explicit consideration of non-linearities for different knowledge domains

	Knowledge domain	**Count**	**Non-Linearity Considered?**	**Count**	**% of Group A**	**% of Group B**
Human Systems	Biophysical and socio economic (Group A)	83	YES	8	10%	-
			NO	64	77%	-
			Not Relevant	11	13%	-
	Only Biophysical (Group B)	50	YES	6	-	12%
			NO	43	-	86%
			Not Relevant	1	-	2%

2.7 Discussion

Mounting interest in vulnerability to climate change has generated a large and diverse literature over the last few decades. The IBVA body of work that was examined in this chapter is only one part of the larger vulnerability literature: around 6%-7%, based on this study's own publication count. The former, therefore, does not necessarily reflect trends and methods prevalent in the latter. The reliance of IBVA on indicators clearly sets epistemological limits on its scope and relative ability to answer pertinent research questions. First, IBVA is premised on our ability to identify and characterise processes generating vulnerability. In other words, it is made possible by quantitative and qualitative research in climatic, physical, and social science research that is very much a work in progress (and which was not targeted in this meta-analysis). Second, the uncertainties that have been discussed earlier, especially those related to the relationship between vulnerability and indicators are likely to remain because of the heuristic and epistemological limits on our ability to understand and quantify vulnerability.

Nevertheless, IBVA has been widely used because it is relatively easy to build, and the outcomes (e.g., indices, rankings or "hot spots") and rationale behind them can be readily communicated to policy makers and the public. More importantly, IBVA allows knowledge from different scientific ends of vulnerability research (climatic, geophysical, social, and institutional) to be combined, which is necessary and difficult to achieve by other methods. However, as shown earlier, these advantages can come at the cost of decreased analytical validity. Hence, examining the conceptual and methodological underpinnings of IBVA is important.

In summary, the meta-analysis yielded the following findings:

a. Public health and water resources are the two sectors that have attracted the highest number of IBVA studies. Multi-sectoral papers tend to be national in scale and unspecific about the valued attribute of concern. Most assessments in the study sample considered multiple climate related stresses, and in those papers that considered a single stress, droughts, temperature extremes and sea rise, acidification and warming were the most prevalent hazards.
b. Only 10% of the IBVA studies were concerned with the conceptual and methodological foundations of this approach despite the fact that serious

questions were raised in the literature about the methodological aspects of this form of vulnerability assessment.

c. A number of theoretical papers argued that indicator based vulnerability assessment is likely to be most valid at smaller rather than larger geographical scales. However, only 17% of studies appear to be conducted at local scales. In addition, most studies remain unspecific about their temporal frame of reference, i.e., whether vulnerability is being assessed in the present or at some specific point in the future.

d. Among the studies that aggregate indicators and consider both the bio-physical and socio-economic processes generating vulnerability, 61% used methods based on Multiple Attribute Utility Theory (MAUT) such as the arithmetic mean, the geometric mean, or GIS based MAUT approaches whose theoretical requirements are difficult to satisfy in the context of IBVA. Among the studies that are explicit about their weight estimation method, 37% simplified the analysis by using equal weights. Only a third of papers in the sample considered issues associated with uncertainty, while an even smaller proportion included some form of non-linearity and threshold effects.

Chapter 3

A general mathematical framework for CCVA

3.1 Synopsis

The previous chapter identified major methodological challenges of IBVA problems and concluded that a methodological development of issues such as aggregation of indicators, and dealing with non-linearities and uncertainties have received little attention in the literature, despite their importance. This chapter presents a general mathematical framework for Climate Change Vulnerability Assessment (CCVA) whose aim is to identify and define different sources of uncertainty and non-linearity in an IBVA problem. Although the framework begins with the well known IPCC vulnerability conceptualization (IPCC 2007), the proposed approach has been extended to cover any multi-dimensional conceptualization of vulnerability**.**

3.2 Introduction

Vulnerability assessment is a complex form of risk appraisal which considers the bio-physical and socio-economic dimensions of the environmental hazard. Drawing on the findings of the meta-analysis conducted in Chapter 2, the literature on climate change vulnerability assessment can be viewed as falling broadly into three categories. A number of papers over the last ten years have engaged with the theoretical and semantic aspects of vulnerability in order to negotiate a multiplicity of definitions and some confusion surrounding the concept (Adger 2006; Adger and Kelly 1999; Cutter et al. 2003). This has led to a level of agreement about the need for precision in defining processes generating vulnerability, and the importance of scale and the place-specific nature of assessments. A second, albeit small, set of studies proposed specific methodologies (as opposed to conceptual frameworks) to guide practitioners in conducting assessments (e.g., Füssel, 2007; Füssel and Klein, 2006; Luers, 2005a; Tonmoy et.al., 2012), while a third, and by far the largest, reports actual assessment studies (Hahn et al. 2009; Duriyapong and Nakhapakorn 2011; Brenkert and Malone 2005; Preston B.L et al. 2008). To my knowledge, no paper, including methodological ones, has specifically tackled the various non-linearities present in assessments, nor has there been a formal attempt at incorporating them in assessment studies.

Broadly, two approaches have been used in the quantitative impacts studies of climate change in the literature (Tonmoy and El-Zein 2013a). Scenario-based analyses downscale predictions of GCM and then combine them with mechanistic bio-physical or bio-chemical models (e.g., hydrological, epidemiological, atmospheric) in order to sketch GCM's implications at regional and local scales. The advantage of this approach is that it is usually based on robust climate science and a sound understanding of the dynamics of the system in question and can represent threshold effects and non-linearities. However, restrictions on the spatial resolution of GCMs and the complexity of incorporating the social, economic, and institutional dimensions of risk, limit the scope of this approach.

On the other hand, indicators offer an attractive and relatively simple way of quantifying different dimensions of the risk, bio-physical, institutional and socio-economic (Füssel 2007; Hinkel 2011). As discussed in the earlier chapter, the challenge of indicator-based vulnerability assessments (IBVA) lies in identifying and selecting measurable indicators that can represent all the significant processes generating vulnerability and then combine them using sound aggregation principles in order to produce a measure of vulnerability. While indicators can usually be identified with relative ease, the exact relationship they hold to vulnerability is either difficult or impossible to determine with precision. This relationship usually turns out to be more complex than the monotonic association that is assumed in most analyses. One partial way out of this impasse is to combine impact studies for simulating the bio-physical dimensions of the hazard with indicators representing the socio-economic and institutional dimensions. However, another difficulty facing IBVA lies in developing aggregation principles that can take into account the different types of indicators (continuous, discrete, and ordinal variables); different types of relationships between indicators and vulnerability (linear and non-linear, deterministic and stochastic, scalar and fuzzy); as well as different possible relationships of compensation and non-compensation *between* the indicators (El-Zein and Tonmoy 2013a). As shown in the meta-analysis conducted in the previous chapter, the vast majority of the IBVA literature has used simple aggregation approaches that are based on Multiple Attribute Utility Theory (MAUT) (e.g., simple additive weight or multiplicative weight). Although MAUT is a powerful decision analysis tool with a wide range of use in engineering and economics, its strict theoretical requirements (e.g., indicator independence, complete knowledge on the system, etc) are hardly ever met in the context of IBVA (El-Zein and Tonmoy 2013a). Moreover, a number of assumptions are typically made in IBVA studies that use MAUT- a linear, monotonic relationship between indicator and vulnerability and complete compensation between indicators—none of which usually hold in reality.

It should be noted that MAUT is a branch of Multi Criteria Decision Analysis (MCDA). Different methods and approaches of MCDA have been applied previously in climate change related studies and most of them were focused on climate mitigation policy decision making (Greening and Bernow 2004; Ringius et al. 1998; Konidari and Mavrakis 2007). These studies often frame their exercise as an MCDA problem. On the other hand, CCVA studies (which are usually conducted as a preliminary step to decision making) often use aggregation techniques for vulnerability indicators, without framing the exercise as an MCDA problem. This leads to methodological problems and this thesis addresses some of them.

The main objective of this chapter is to present a new mathematical framework for vulnerability which allows us to clearly define different forms of non-linearity in vulnerability assessments. Although the new framework begins with the IPCC well-known vulnerability conceptualisation (IPCC, 2007), the proposed new approach has been extended to cover more generally any multi-dimensional conceptualization of vulnerability. This chapter is not particularly concerned with the semantic aspects of vulnerability, although it acknowledges their importance, instead, it starts from a definition of vulnerability (generally accepted in the literature and presented at the beginning of the next section) and abides by it throughout.

3.3 Use of climate change vulnerability studies in climate change policy makings:

Adaptation to climate change is an integral part of the United Nations Framework Convention on Climate Change (UNFCCC) in two related but distinct ways that relate two different policy domains. The first is the prevention of dangerous interference with the climate system by the stabilisation of greenhouse gas concentrations in the atmosphere, commonly referred to as “mitigation”. The second is reduction of vulnerability to climate change by the process of “adaptation”(Burton et al. 2002). At a country scale, vulnerability studies play a crucial role in both domains. In the context of “mitigation”, impact studies are an essential input to policy decisions about what constitutes “dangerous interference with the climate system”. Prevention of dangerous interference is specified as the “ultimate objective” of the UNFCCC (Article 2). The growing scientific understanding of the probable net impacts of climate change is being used to inform policy makers in their task of making choices about the level of urgency in the political climate change negotiations, and therefore, the targets and schedules that need to be adopted if “dangerous interference” is to be avoided (Burton et al. 2002).

In the context of “adaptation” policy, the emphasis shifts from the gross and net impacts of climate change to vulnerability of climate change, and how and where to deploy adaptation responses to reduce such vulnerability. At larger geographic scale, objective comparison of level of vulnerability between countries is needed as a way of allocating priorities for funding and intervention for example, in the context of adaptation fund setup under UNFCCC (Klein 2003). Burton et al. (2002) argued that “...such comparisons are important to the developing countries both because that they wish to reduce their vulnerability to climate change in the most effective ways, and because they are essentially in competition with each other for whatever international funds may become available to help them meet the costs of adaptation. It is to the advantage of each country, therefore, to be able to show how vulnerable it is to climate change; how much adaptation policies and measures will cost; where it lacks sufficient capacity to adapt without external assistance; and generally how donor funds can be effectively used. Donor countries also have an interest in these questions because they wish to be reassured that their assistance in helping to meet the costs of adaptation will be money well spent, i.e. it will allow developed countries to meet their commitments to assist."

Use of vulnerability assessment in local adaptation decision making has been discussed by Næss et al. (2006) based on local case studies that have been conducted at different municipalities of Norway. They argued that the process of development of vulnerability studies has fostered communication with stakeholders informing them the consequences of the climate change impacts and identification of the institutional capacity to deal with those impacts. However, the exercise can be hindered by the institutional challenges in making use of vulnerability assessments: in particular the local capacity to use information; the structural fit between assessment information and local policy processes; and the processes through which institutions may change in response to external stresses.

3.4 Vulnerability to Climate Change: from Conceptual Framework to Assessment

3.4.1 Vulnerability Framework and Definitions

Vulnerability assessment aims to develop some measure, quantitative or qualitative, of the susceptibility to damage of, or damage likely to be inflicted on the valued attribute of an SES, as a result of its exposure to one or more climate stresses. Table 3-1 presents a number of basic definitions adopted in this chapter. For the purpose of the discussion below, damage is denoted by D, vulnerability by V, and the magnitude of the climate stress in question by M. Here M is a positive real number. It is reasonable to assume that as the magnitude M of the climate stress increases so does the damage D. This framework defines vulnerability as the ratio of damage to magnitude, i.e. as the marginal rate of damage relative to the magnitude of the stress (El-Zein and Tonmoy 2013b), hence:

$$D = \mathbf{V}M \qquad \textbf{3-1}$$

Table 3-1: Definitions

Term	Definition	Sources
Vulnerability	"...the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. [It] is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity."	(IPCC 2001)
Socio-Ecological System (SES)	SES is the coupled human-environment system which consists of the 'bio-geo-physical' unit and its associated social actors and institutions	(Marion Glaser 2008)
Exposure	The degree to which a system is exposed to climate change impacts.	(IPCC, 2001)
Sensitivity	"...degree to which a system is affected by, or responsive to, climate stimuli."	Smith et al. (2000)
Adaptation	Adaptation to climate is the process through which people reduce the adverse effects of climate on their health and well-being, and take advantage of the opportunities that their climatic environment provides	Burton 1992, quoted in Smith et al. (2000)
Adaptive Capacity	the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences	(IPCC 2001)

where V is a positive number (for clarity, D and M are represented in italics and the slope connecting them, i.e. vulnerability, in bold-faced font, throughout). In some cases V is largely independent of M and (3-1) simply reflects a linear relationship between D and M. For example, within a given range, the extent of physical damage inflicted on houses in a "do nothing" scenario may be roughly proportional to the level of sea rise that caused it, i.e. V does not depend on M. In reality such relationships are seldom linear because more often than not, D is a non-linear function of M. Rivers bursting their banks and sea waves breaching beach fortifications are examples in which a threshold effect generates a non-linear relationship between D and M. It is possible to represent such non-linearity by introducing a dependence of V on M:

$$D=\mathbf{V(M)}M \qquad \textbf{3-2}$$

Hence, it is now possible to speak about assessing vulnerability to a given *magnitude* of stress, i.e. developing some measure of V(M) at a given M. Such non-linearity (i.e. dependence of V on M) is called as the *fundamental non-linearity* of the conceptual framework, to distinguish it from other forms of non-linearities that will be introduced below. Provided D is differentiable over M, it is possible to generalise from equation (3-2) and define vulnerability as:

$$\mathbf{V(M)} = \frac{\partial \mathbf{D}}{\partial \mathbf{M}} \qquad \textbf{3-3}$$

Using the IPCC (2007) well-known definition of vulnerability, it is also possible to write V(M) as:

$$\mathbf{V(M)} = \mathbf{f[E(M), S(M), A_c(M)]} \qquad \textbf{3-4}$$

Where,

E (M) is the degree of exposure of the valued attribute of the SES to the stress in question,

S (M) is its sensitivity to the stress and

A_c(M) is the adaptive capacity of the SES, i.e. its ability to reduce its exposure and/or sensitivity through adaptation event(s).

Hence, according to equation (3-4), vulnerability is a (as yet unspecified) function of exposure, sensitivity, and adaptive capacity. One of the criticisms levelled at the IPCC definition in the literature is that little is proffered about the nature of function f (Hinkel, 2011). One of the simplest possible incarnations of equation (3-4) is given by:

$$\mathbf{V(M)} = \frac{\mathbf{E(M)S(M)}}{\mathbf{A_c(M)}} \quad \textbf{3-5}$$

It is also possible to define vulnerability as an additive, rather than a multiplicative, combination of its dimensions:

$$\mathbf{V(M)} = \mathbf{E(M)} + \mathbf{S(M)} - \mathbf{A_c(M)} \quad \textbf{3-6}$$

The concepts represented by equations (3-5) and (3-6) are referred to here as "multiplicative vulnerability" and "additive vulnerability", respectively. It should be noted that additive vulnerability (3-6) suffers from at least one serious limitation. It produces unrealistic outcomes in some cases. For example, for $E=0$, $S>0$ and $Ac=0$, equation 3-6 yields a positive value of vulnerability despite the absence of any exposure. For other choices of E, S and Ac, vulnerability can even be negative. Intuitively, a multiplicative representation appears to make more sense when representing climate-related risks because of the compound effect likely to be generated by multiple sources of vulnerability. However, both equations (3-5) and (3-6) suffer from an implicit assumption that a deficit in adaptive capacity can be fully compensated for by a decrease in exposure or sensitivity, and that an excess of exposure can be fully compensated for by an increase in adaptive capacity or a reduction in sensitivity, and so on. In reality there may be conditions under which this is not possible. For example, it is widely recognized that beyond a threshold of sea level rise, the adaptive capacity of small island states will be overcome and no increase in that capacity can protect the island residents and their built environments from devastating damage. This is the well known problem of *non-compensation* or *incommensurability*. Here it is called the *dimensional incommensurability* of the vulnerability framework (with reference to the 3 dimensions of vulnerability), to distinguish it from another case of incommensurability that will be introduced later. It is possible to cater for the problem of dimensional incommensurability through alternative definitions of vulnerability. For example:

$$\mathbf{V(M) = Max[E(M), S(M), A_c(M)^{-1}]} \quad \mathbf{3\text{-}7}$$

or

$$\mathbf{V(M) = Min[E(M), S(M), A_c(M)^{-1}]} \quad \mathbf{3\text{-}8}$$

Under both equations (3-7) and (3-8), no compensation between the three dimensions of exposure, sensitivity and adaptive capacity is possible. Instead, in the case of equation (3-7), an SES is as vulnerable as its weakest dimension. Under equation (3-8), an SES is as resilient as its strongest dimension. The concepts represented by equations (3-7) and (3-8) are termed as “non-compensating strong vulnerability” and “non-compensating weak vulnerability”, respectively.

Yet another alternative would be to assess exposure, sensitivity, and adaptive capacity separately, based on which a qualitative evaluation of vulnerability is made *without* combining the three dimensions quantitatively. This would allow the analyst to make a judgment that lies somewhere between the two extremes of equations (3-7) and (3-8). In this case vulnerability can be represented as a tensor in an $(\vec{\mathbf{e}}, \vec{\mathbf{s}}, \vec{\mathbf{a}})$ space that represents the three dimensions of exposure, sensitivity, and adaptive capacity:

$$\vec{\mathbf{V}}\mathbf{(M) = E(M)}\vec{\mathbf{e}} + \mathbf{S(M)}\vec{\mathbf{s}} - \mathbf{A_c(M)}\vec{\mathbf{a}} \quad \mathbf{3\text{-}9}$$

“Here, $\vec{\mathbf{V}}$ is multidimensional and tensors are used to represent three dimensions of vulnerability. The word tensor denotes a multi-dimensional array that describes linear relations between vectors, scalars, and other tensors (Kline 1990). In this context, each one of e, s and a represents a single dimension of the vulnerability tensor. This representation is called “general multi-dimensional vulnerability”. In reality, compensation is often possible *to some extent*, and it is in fact the possibility of (even partial) compensation that usually makes adaptation effective. The question therefore arises as to whether it is possible, in conducting vulnerability assessments, to incorporate incommensurability as well as limited and full compensations, as the case may be. The answer is positive as will be shown later.

It is now possible to incorporate the effect of adaptation events, as opposed to adaptive capacity, into this framework. Adaptation can be conceived of as an event, or series of events, deliberate or non-deliberate, reactive or proactive, that can lead to a reduction in vulnerability. Note here that *adaptive capacity* is related to, but distinct from, *adaptation:* the former makes it more likely for the latter to take place at some point in the future. It is possible to represent the effect of adaptation as a modification of equation (3-2):

$$\overline{D} = [\mathbf{V}(\mathbf{M}) - \mathbf{A}(\mathbf{M})]M \tag{3-10}$$

where $\overline{D}$ denotes damage with adaptation events taken into account, A(M) represents the reduction in vulnerability brought about by adaptation, and V(M) is the vulnerability prior to this adaptation. Note that, consistently with the previous assumption, it is implied that A depends on M. This is to say that the same set of adaptation events might lead to different degrees of vulnerability reduction, depending on the magnitude of the stress. While this might not always be the case, it is certainly a possibility that needs to be kept in mind. There can be of course other ways of incorporating the effects of adaptation events in equation (3-2), such as defining adaptation as a reduction in damage rather than vulnerability:

$$\overline{D} = \mathbf{V}(\mathbf{M})M - \mathbf{A}(\mathbf{M}) \tag{3-11}$$

or representing the effect of adaptation by a(M), a percentage reduction in both vulnerability and damage:

$$\overline{D} = \overline{\mathbf{V}}(\mathbf{M})M \tag{3-12}$$

$$\overline{\mathbf{V}}(\mathbf{M}) = \mathbf{a}(\mathbf{M})\mathbf{V}(\mathbf{M}) \tag{3-13}$$

where $\overline{\mathbf{V}}(\mathbf{M})$ is vulnerability after adaptation events, a(M) is an adaptation multiplier that is a real number varying between 1 (no adaptation or unsuccessful adaptation) and 0 (perfect adaptation which eliminates all likelihood of damage). Formulations (3-10), (3-11) and (3-12)-(3-13) are conceptually similar, if not equivalent and, in this chapter, equations (3-12)-(3-13) are used. Going a step further, it is assumed that the effect of successful adaptation events can take the form of a reduction in exposure, a reduction in sensitivity and/or an increase in adaptive capacity. For example, the vulnerability of an elderly person to a heat wave can be reduced by installing an air conditioning system in her flat (reduced exposure to heat), treating her existing cardiovascular condition (reduced sensitivity to heat) with drugs, or setting up a heat warning system which provides her with transport to a community shelter during a heat wave, if she so wishes (increased adaptive capacity). Note here that,

a) the above three examples are adaptation events acting on different dimensions of vulnerability;
b) the last example is an adaptation event leading to improved adaptive capacity of the subject;
c) the resulting increase in adaptive capacity in this example, when activated during a heat wave, would reduce vulnerability by reducing exposure to heat (i.e., when the elderly person leaves her apartment and moves to a cool shelter).

Therefore, a straightforward approach for incorporating adaptation in the vulnerability framework would be to apply an adaptation-event multiplier to each dimension of vulnerability:

$$\bar{\mathbf{E}}(\mathbf{M}) = \mathbf{e}(\mathbf{M})\mathbf{E}(\mathbf{M}) \tag{3-14}$$

$$\bar{\mathbf{S}}(\mathbf{M}) = \mathbf{s}(\mathbf{M})\mathbf{S}(\mathbf{M}) \tag{3-15}$$

$$\bar{\mathbf{A}}_{\mathbf{c}}(\mathbf{M}) = \mathbf{a}_{\mathbf{c}}(\mathbf{M})\mathbf{A}_{\mathbf{c}}(\mathbf{M}) \tag{3-16}$$

where $\bar{\mathrm{E}}(\mathrm{M})$, $\bar{\mathrm{S}}(\mathrm{M})$ and $\bar{\mathrm{A}}_{\mathrm{c}}(\mathrm{M})$ indicate exposure, sensitivity and adaptive capacity *after* a set of adaptation events (while the corresponding items without bars denote the entity *before* adaptation events); e(M) and s(M) are the percentage reductions in exposure and sensitivity as a result of adaptation and a_c(M) is the percentage increase in adaptive capacity as a result of adaptation. e(M) and s(M) vary between 0 (complete removal of vulnerability) and 1 (no effect on vulnerability). $a_c(M) \leq 1$ with $a_c(M)=1$ indicating no effect on vulnerability. Equations (3-14) to (3-16) can also represent mal-adaptation, in the sense of events or actions leading to an increase rather than a decrease in vulnerability. In such cases $e(M)>1$, $s(M)>1$ and/or $a_c(M)<1$. It is also conceivable that the same adaptation event might have conflicting effects on vulnerability (e.g., reduction of exposure and reduction in adaptive capacity).

Now, modifying for the effect of adaptation, equations (3-5) to (3-9) become, respectively:

$$\overline{\mathbf{V}}(\mathbf{M}) = \frac{[\mathbf{e}(\mathbf{M})\mathbf{E}(\mathbf{M})].[\mathbf{s}(\mathbf{M})\mathbf{S}(\mathbf{M})]}{\mathbf{a_c}(\mathbf{M})\mathbf{A_c}(\mathbf{M})} \tag{3-17}$$

$$\overline{\mathbf{V}}(\mathbf{M}) = \mathbf{e}(\mathbf{M})\mathbf{E}(\mathbf{M}) + \mathbf{s}(\mathbf{M})\mathbf{S}(\mathbf{M}) - \mathbf{a_c}(\mathbf{M})\mathbf{A_c}(\mathbf{M}) \tag{3-18}$$

$$\overline{\mathbf{V}}(\mathbf{M}) = \mathbf{Max}\{\mathbf{e}(\mathbf{M})\mathbf{E}(\mathbf{M}), \mathbf{s}(\mathbf{M})\mathbf{S}(\mathbf{M}), [\mathbf{a_c}(\mathbf{M})\mathbf{A_c}(\mathbf{M})]^{-1}\} \tag{3-19}$$

$$\overline{\mathbf{V}}(\mathbf{M}) = \mathbf{Min}\{\mathbf{e}(\mathbf{M})\mathbf{E}(\mathbf{M}), \mathbf{s}(\mathbf{M})\mathbf{S}(\mathbf{M}), [\mathbf{a_c}(\mathbf{M})\mathbf{A_c}(\mathbf{M})]^{-1}\} \tag{3-20}$$

$$\overline{\vec{\mathbf{V}}}(\mathbf{M}) = \mathbf{e}(\mathbf{M})\mathbf{E}(\mathbf{M})\vec{\mathbf{e}} + \mathbf{s}(\mathbf{M})\mathbf{S}(\mathbf{M})\vec{\mathbf{s}} - \mathbf{a_c}(\mathbf{M})\mathbf{A_c}(\mathbf{M})\vec{\mathbf{a}} \tag{3-21}$$

where $\overline{V}(M)$ is vulnerability *after* a given adaptation event or series of events. By comparing equations (3-5), (3-13), and (3-17) it is clear that:

$$\mathbf{a}(\mathbf{M}) = \frac{\mathbf{e}(\mathbf{M})\mathbf{s}(\mathbf{M})}{\mathbf{a_c}(\mathbf{M})} \tag{3-22}$$

Equation (3-12) together with one of equations (3-17), (3-18), (3-19), (3-20) and (3-21) are therefore a mathematical representation of vulnerability that takes into account the three dimensions of exposure, sensitivity and adaptive capacity, as well as the impact of adaptation events. It is possible to generalise these equations beyond the IPCC framework to incorporate any number of dimensions $\vec{\mathbf{d}}$:

$$\bar{\mathbf{V}}(\mathbf{M}) = \prod_{1}^{\mathbf{n_d}} \{[\mathbf{d}(\mathbf{M})\mathbf{D}(\mathbf{M})]^{\mathbf{p_d}}\} \tag{3-23}$$

$$\bar{\mathbf{V}}(\mathbf{M}) = \sum_{1}^{\mathbf{n_d}} [\mathbf{p_d}\mathbf{d}(\mathbf{M})\mathbf{D}(\mathbf{M})] \tag{3-24}$$

$$\bar{\mathbf{V}}(\mathbf{M}) = \mathbf{MAX}_{\mathbf{1}}^{\mathbf{n_d}}\{[\mathbf{d}(\mathbf{M})\mathbf{D}(\mathbf{M})]^{\mathbf{p_d}}\} \tag{3-25}$$

$$\bar{\mathbf{V}}(\mathbf{M}) = \mathbf{MIN}_{\mathbf{1}}^{\mathbf{n_d}}\{[\mathbf{d}(\mathbf{M})\mathbf{D}(\mathbf{M})]^{\mathbf{p_d}}\} \tag{3-26}$$

$$\vec{\bar{\mathbf{V}}}(\mathbf{M}) = \sum_{1}^{\mathbf{n_d}} \left[\mathbf{p_d}\mathbf{d}(\mathbf{M})\mathbf{D}(\mathbf{M})\vec{\mathbf{d}}\right] \tag{3-27}$$

$$\mathbf{a}(\mathbf{M}) = \prod_{1}^{\mathbf{n_d}} \{[\mathbf{d}(\mathbf{M})]^{\mathbf{p_d}}\} \tag{3-28}$$

where n_d is the number of dimensions in the framework; $\vec{\mathbf{d}}$ is a given dimension vector; D(M) is the degree of vulnerability represented by dimension d; d(M) is the adaptation multiplier for dimension d; p_d is a factor reflecting the directionality of the relationship between vulnerability and D(M): p_d=1 or -1 depending on whether vulnerability increases or decreases, respectively, with increasing D(M). In the remainder of the chapter the IPCC framework will be used because of its prevalence in the literature, while keeping in mind that the proposed assessment approach can be readily applied to a framework with any number of dimensions.

The following sections will mathematically identify different sources of challenges of an IBVA ranking problem using the developed framework.

3.5 Vulnerability Assessment: Non-linearity, Fuzziness and Uncertainty

Let $s_k=\{s_1, \ldots., s_n\}$ be a set of n comparable SESs which need to be ranked according to the vulnerability of a valued attribute (e.g., health, economic well-being, productivity etc.) to one or more climate hazards (e.g., increase in average temperatures, rise in sea level, increased frequency of flooding etc.), under a given dimension d of vulnerability. Indicator-based vulnerability assessments (IBVA) express the 3 dimensions of vulnerability as functions of measurable indicators. Hence, equation (3-9) applied to a specific socio-economic system (SES) k becomes:

$$\overrightarrow{\mathbf{V_k}}(\mathbf{M}) = f_{ek}(I_{e1k}, I_{e2k}, I_{e3k}, \ldots)\vec{\mathbf{e}} + f_{sk}(I_{s1k}, I_{s2k}, I_{s3k}, \ldots)\vec{\mathbf{s}} + f_{ck}(I_{c1k}, I_{c2k}, I_{c3k}, \ldots)\vec{\mathbf{a}} \qquad \textbf{3-29}$$

where f_{dk} (d=e, s or c) is a function expressing a given dimension d of vulnerability (e: exposure; s: sensitivity; c: adaptive capacity) of SES k (k=1,n) in terms of a set of m_e indicators I_{dik} ($i=1,m_e$). In keeping with the comment made earlier about the *fundamental non-linearity*, f_{dk} may depend on the magnitude of the stress M. The choice of indicators is of course critical and can be challenging. Ideally, each indicator is chosen so as to represent a process generating vulnerability, based on intuitive or deductive reasoning. Typically, a mixed bag of indicators is used, one in which our degree of knowledge of the relationship between an indicator and the vulnerability it is representing, is *highly variable*. In fact, what is usually known about the relationship between indicators and vulnerability as a minimum can be summed up by the following:

$$f_{dk} \propto I_{d1k}, I_{d2k}, I_{d3k}, \ldots \qquad \textbf{3-30}$$

However, this doesn't go very far. It simply reiterates the reason why these indicators were selected in the first place. A simple, if dangerous, way out of this impasse is to make the following assumption:

$$f_{dk} = \sum_{j=1}^{m_d} w_{dj}\bar{I}_{djk} \qquad \textbf{3-31}$$

the bar on variable I_{djk} denote normalised indicators, and w_{dj} is a weight for the j^{th} indicator. Normalisation can be conducted in a number of different ways; however, most commonly:

$$\bar{I}_{djk} = \frac{I_{djk} - I_{dj}^{min}}{I_{dj}^{max} - I_{dj}^{min}} \qquad \textbf{3-32}$$

Where,

$$I_{dj}^{min} = \min_{k} I_{djk} \qquad \textbf{3-33}$$

$$I_{dj}^{max} = \max_{k} I_{djk} \qquad \textbf{3-34}$$

This particular normalisation leads to a new variable which ranges between 0 and 1. Equation (3-31) essentially generates a function based on multi-attribute utility theory (MAUT) as a form of aggregation of the indicators. This immediately presents us with a few problems that are related to some basic requirements underlying MAUT addition.

i. all indicators are independent of each other (additive independence);
ii. the analyst has a complete understanding of the system;
iii. all indicators are commensurable with each other, i.e. a deficiency in one indicator can be made up for with an excess in any other indicator, with the exact rate of exchange between two indicators determined by the choice of respective weights;
iv. vulnerability is a linear monotonic function of indicators.

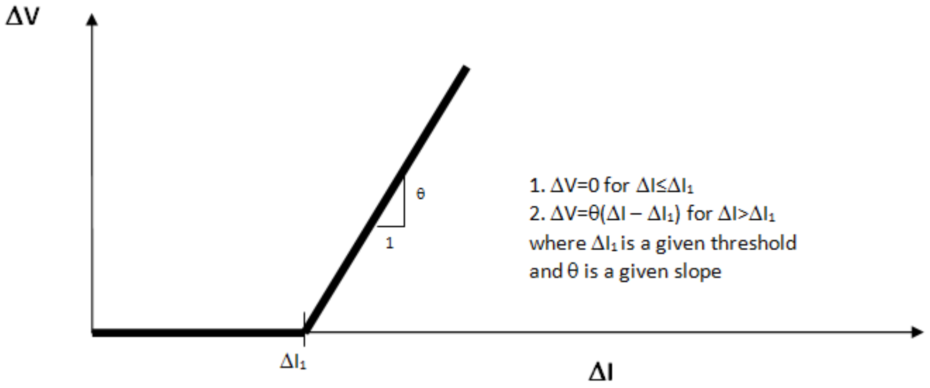
Note that points iii and iv are NOT necessary requirements of MAUT. However, they are almost always found in MAUT-based IBVA in the literature. Unfortunately, these assumptions rarely hold in reality in the context of IBVA, which renders the use of additive aggregation, such as the one described above, scientifically questionable. On the other hand, as discussed earlier, it is not usually possible to build function f (3-30), as an alternative to additive MAUT. In this thesis, theses problems, points i and ii, are called the *fundamental uncertainty* problem. A further discussion of fundamental uncertainties was made in the previous chapter (Chapter 2, section 2.4.5.3). On the other hand, the linear monotonic function is usually an oversimplified representation of a much more complex relationship which, in many cases, can be depicted through mechanistic modelling based on deductive arguments. Therefore, the problems brought up by points iii and iv above are called, *the indicator incommensurability* problem and *the deductive non-linearity* problem, respectively.

It is possible to illustrate these problems by referring to a simple model where the average daily temperature T and the average daily humidity H are used as indicators of exposure of a set of communities to heat stress. Epidemiological evidence from city-scale studies shows that in many cases, an increase in each of these two indicators can lead to an increase in daily mortality. However, the interactions between temperature and humidity are complex and will not yield to an easy trade-off between the two as a simple additive weight aggregation would imply (indicator incommensurability). In addition, the relationship between mortality and temperature is highly non-linear with sharp increases in deaths observed beyond a threshold value of T, called comfort temperature (deductive non-linearity).

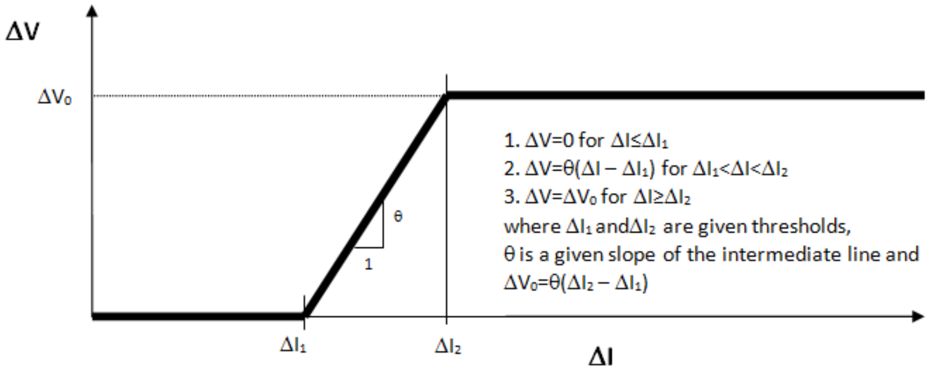
One way of dealing with indicators incommensurability is to avoid building any utility function, i.e. avoid converting these indicators into compatible scales altogether. Instead, an alternative approach conducts pair-wise comparisons of SESs based on one indicator at a time, then rank the vulnerabilities of these SESs by following formal aggregation rules that elicit the balance of evidence from all pair-wise comparisons. This approach has been applied in multi-criteria decision-analysis (MCDA) over the last 40 years and has yielded a set of methods called outranking procedures (Roy 1968; Hokkanen and Salminen 1997; El Hanandeh and El-Zein 2010). It is especially useful where a degree of subjectivity or multiple subjectivities are involved in the assessment process, which is the case in CCVA because expert judgement and stakeholder values are usually necessary inputs into the process (especially when it comes to sensitivity and adaptive capacity), alongside mechanistic modelling of the physical impact of the hazard on the SES. In the following chapter, it will be shown that IBVA is analogous with MCDA and that outranking procedures can be used to derive more scientifically valid forms of aggregation in IBVA (El-Zein and Tonmoy 2013a).

Outranking methods aggregate indicators by measuring the truth of the statements, “a is more vulnerable than b”, “b is more vulnerable than a” or “a and b are equally vulnerable”, where a and b are two SESs. Outranking procedures start by recognising the *fuzziness* of the answer to the above question. Fuzziness can be described through the following illustrative example. Based on empirical evidence from the social sciences, it is often assumed that the adaptive capacity of a community is partly reflected by its collective income and assets—the wealthier it is, the higher its adaptive capacity and the less vulnerable it is to the hazard in question. However, it is very difficult to characterise the exact relationship between wealth W and adaptive capacity A_c, while on the other hand it is reasonable to assume that small differences in wealth do not translate into differences in adaptive capacities A_c or vulnerabilities V. In other words, below a certain threshold of difference ΔW_1 (or more generically ΔI_1 for any indicator I) the corresponding ΔA_c (or ΔV) is negligible. Such a relationship can be represented by a discontinuous step function as shown in Figure 3-1a. Likewise, beyond a certain point ΔW_2 (or ΔI_2), an increase in wealth is no longer expected to yield an increase in adaptive capacity or vulnerability. Combining the two thresholds, a two-step function can be built as shown in Figure 3-1b. Fuzziness, in other words, is an intuitive form of non-linearity. In this thesis it is called the *intuitive non-linearity* consistently with previous definitions of non-linearity; conversely, a relationship in which $\Delta V/\Delta I$ is continuous is *intuitively-linear*.

A summary of the relevant features of CCVA, identified through the framework is given in Table 3-2.



a. Step-function



b. Two-step function

Figure 3-1: Fuzziness: non-linear relationships between difference in vulnerabilities ΔV and difference in indicators ΔI

Table 3-2: Summary of different relevant features of CCVA identified through the framework

Problem	Description
Dimensional incommensurability	One dimension of vulnerability may not be convertible into another
Indicator incommensurability	One indicator of vulnerability may not be convertible into another, even within the same dimension
Fundamental non-linearity	Vulnerability V may depend on the magnitude of the hazard M
Deductive non-linearity	A non-linear relationship between vulnerability V and indicator I may exist
Intuitive non-linearity or fuzziness	A discontinuous relationship between change in vulnerability V and change in indicator I may exist

3.6 Conclusion

This chapter presented a general mathematical framework for CCVA. Key features of this framework are, a) it began with the well known IPCC vulnerability conceptualization and mathematically expanded it to cover any multi-dimensional conceptualization of vulnerability, and b) it mathematically formalized the inclusion of adaptation events in the context of CCVA. The developed framework was used to identify different sources of compensation problems, non-linearities, and uncertainties that are relevant in the context of an IBVA problem. In order to deal with the challenges that were identified, the following two chapters will develop an outranking based mathematical formulation for an IBVA ranking problem.

Chapter 4

An outranking formulation for IBVA problems with application to heat stress

4.1 Synopsis

The previous chapter demonstrated mathematically that IBVA problems face multiple methodological challenges (e.g., uncertainty, compensation and non-linearity). This chapter builds an analogy between the structures of Multi-Criteria Decision-Making (MCDA) and IBVA problems and shows that a set of techniques called Outranking Methods, based on a Condorcet approach and developed in MCDA to deal with incommensurability and uncertainty, offer IBVA a sound alternative to MAUT for aggregation that can incorporate forms of uncertainty and partial compensation. Vulnerability aggregation problems are reformulated within an outranking framework and an outranking method ELECTRE III is used to assess the relative vulnerability to heat stress of 15 local government areas in metropolitan Sydney. The results show that the outcomes of the outranking procedures are stable and markedly different to rankings generated by MAUT approaches (simple additive weight and geometric mean). Outranking methods, it is argued, may be better suited for assessments that are based on a mix of qualitative, semi-quantitative and quantitative indicators, and are characterized by threshold effects and uncertainties about the exact relationships between indicators and vulnerability outcomes.

4.2 Introduction

A large number of vulnerability studies can be found in the literature. Some are focused on specific economic sectors, usually agricultural (Luers et al. 2003; Belliveau et al. 2006; Gbetibouo et al. 2010) while others, often indicator-based, map vulnerabilities across geographical areas at a given scale (Wilhelmi et al. 2004; O'Brien et al. 2004; Vincent 2007). Proxy indicators are customarily used to construct indices of vulnerability. As discussed in Chapter 2, one of the most significant methodological challenges of vulnerability metrics is to convert a selected set of indicators into a ranking of comparable socio-ecological systems, according to their vulnerabilities to one or more climate hazards. This process of aggregation is usually performed on the basis of multi-attribute utility theory (MAUT). MAUT can provide a powerful decision analysis approach that is widely used in economics, engineering, decision science, and development studies. However, when it is used in the context of IBVA, its theoretical requirements are difficult to achieve in practice. As an example, MAUT typically converts indicators into comparable scales and requires their additive independence, which is virtually impossible in IBVA (Clemen and Reilly 1999). The uncertainties attached to stakeholder preference are not usually taken into account (Hinkel 2011). For example, a methodology developed by de Chazal et al. (2009) to incorporate multiple-agents in vulnerability assessments, nevertheless makes the unlikely assumption of a single, coherent score from each group of stakeholders. In fact, various sources of uncertainty in vulnerability assessment have been highlighted in the literature, which will be discussed below (Vincent 2007; Malone and Brenkert 2008; Patt et al. 2005b; Fussel 2010; Füssel and Klein 2006; Parry et al. 2007; Kelly and Adger 2000; Barnett 2001; Araújo et al. 2005). While it has been argued that probabilities ought to be used for describing the likelihood of climate change (New et al. 2007), there is much less agreement about the extent to which they are helpful in understanding and communicating the social dimensions of vulnerability, especially adaptive capacity (Dessai Suraje 2009).

The theoretical and practical challenges posed by aggregation of indicators have been recognized by many authors (Ebert and Welsch 2004; Böhringer and Jochem 2007; Füssel 2007; Klein 2009; Clemen and Reilly 1999; Greco 2004; Keeney and Raiffa 1993; Hinkel 2011; Linkov et al. 2006). However, to the best of my knowledge, no paper on vulnerability to climate change has focused on this issue from an IBVA perspective, even less suggested alternatives to utility-based approaches for IBVA. This chapter is concerned with this particular methodological problem. Specifically, it argues for a different approach to the generation of vulnerability rankings. The approach, based on a family of techniques known as Outranking Methods, generates rankings of comparable objects through structured pair-wise comparisons without resorting to a common-value utility function. Three significant advantages of these methods are that they do not convert non-commensurate variables into commensurate scales, they do not require indicator additive independence, and they can accommodate uncertainty in preference structures and imprecision in measured conditions. Outranking methods, first proposed by Roy (1968), were developed in the field of multi-criteria decision analysis (MCDA), a sub-discipline of decision science, in order to aid policy makers in choosing between different alternative actions under conflicting criteria and a high level of uncertainty (Hokkanen and Salminen 1997; Kangas. A 2001; Figueira. J 2005; El Hanandeh and El-Zein 2010).

In the remainder of this chapter, IBVA problems are first reformulated within an outranking framework and second, a widely used outranking method, ELECTRE-III, is applied to assess the relative vulnerabilities to heat stress of 15 local government areas (LGA) in metropolitan Sydney. Summative and multiplicative MAUT are compared to outranking results and the robustness and sensitivity of ELECTRE III rankings are assessed.

4.3 Uncertainty in Indicator-Based Vulnerability Assessments

Uncertainty in any assessment of vulnerability to climate change emanates from a number of sources, at both the biophysical and social ends of the analysis. Chapter 2 discussed different forms of uncertainty that are relevant in the context of IBVA, e.g., epistemic uncertainties, fundamental uncertainties and imprecision. In this chapter the proposed methodology caters for fundamental uncertainties and imprecision, and although the importance of epistemic uncertainties for IBVA studies is recognized, they are beyond the scope of this chapter.

4.4 Aggregation in Indicator-Based Vulnerability Assessment

The problem of aggregating a number of vulnerability indicators to generate vulnerability rankings can be represented as follows. Let $s_j=\{s_1, \ldots., s_n\}$ be a set of n comparable socio-ecological systems (SES) which are to be ranked according to the vulnerability of a valued attribute to one or more climate hazards based on a set of m indicators $I_i=\{I_1, \ldots, I_m\}$. Each indicator has a linear or non-linear relationship to vulnerability, even though it is not always possible to characterize this relationship with precision. A *vulnerability matrix* I_{ij} $(i = 1,m; j = 1,n)$ is constructed with each column representing an SES and each row a given indicator, with I_{ij} denoting the value I_i for S_j. If each indicator, independently from the others, yields the same ranking of SESs as all other indicators, no aggregation is needed. This case is of course idealistic and in IBVA the indicators are almost always conflicting. Depending on the type of aggregation used, a set of weights or votes $w_i=\{w_1, \ldots., w_m\}$ may be allocated to the set of indicators, with w_i reflecting the importance of indicator I_i relative to other indicators. Table 4-1 clearly shows that the structure of IBVA problems is analogous to multi-criteria decision analysis (MCDA) structure, with alternatives and criteria in the latter becoming SESs and indicators in the former, and similar issues of incommensurability, uncertainty and multiple stakeholders found in both types of problems.

The predominant, MAUT-based approach to aggregation in the literature on vulnerability assessment, consists of converting each indicator into a normalized value on cardinal or ordinal scales or standardizing it relative to a mean, then generating a weighted sum or product as a utility-value function (Clemen 1996):

$$\mathrm{AM_j} = \frac{1}{\sum_{i=1}^{m} w_i} \sum_{i=1}^{m} w_i \bar{I}_{ij} \tag{4-1}$$

$$\mathrm{GM_j} = \sqrt[m]{\prod_{i=1}^{m} \bar{I}_{ij}} \tag{4-2}$$

where AM_j and GM_j are summative (arithmetic mean) and multiplicative (geometric mean) utility functions for SES j, respectively; $\bar{I}_{ij}$ is the normalized version of vulnerability matrix I_{ij},. Vulnerabilities of SESs are ranked based on the values of AM_j or GM_j. Henceforth, this chapter will refer to procedures using (4-1) as MAUT-Arithmetic and those using (4-2) as MAUT-Geometric. This approach is not confined to climate research and is widely used in the literature on environmental and human development indices (Clemen 1996; Linkov et al. 2006).

The use of MAUT for building indices has generated some debate in the literature. For example, Ebert and Welsch (2004) analyzed both summative and multiplicative aggregations in relation to a specific validity criterion, namely that the resulting index should yield identical rankings when different normalizations or standardizations are used. They found that multiplicative aggregations have better validity than additive ones, and better reflect synergetic processes between indicators. However, multiplicative aggregation can be difficult to communicate to stakeholders and experts. Munda and Nardo (2009) argued that a

Table 4-1: Analogy between IBVA and MCDA problems

	IBVA		**MCDA**	
Problem Definition	To rank socio-ecological systems according to the vulnerability of a valuable attribute to one or more climate hazard		To rank decision alternatives according to their performances on a set of criteria	
	Socio-Ecological Systems	$s_j=\{s_1, …., s_n\}$	Decision Alternatives	$O_j=\{o_1, …., o_n\}$
	Vulnerability-Generating Processes		Decision Objectives	
	Vulnerability Indicators	$I_i=\{I_1, …, I_m\}$	Attributes/Criteria	$C_i=\{C_1, …, C_m\}$
	Vulnerability Matrix	$I_{ij}\ (i = 1, m; j = 1, n)$	Decision Matrix	R_{ij} (i=1,m; j=1,n)
	Indicator Weights/Votes*	$w_i=\{w_1, …., w_m\}$	Criteria Weights/Votes*	$W_i=\{W_1, ..., W_m\}$
Problem Features	Input from multiple experts and stakeholders		Input from multiple decision-makers, experts and stakeholders	
	Inconvertibility of indicators		Incommensurability of criteria	
	Uncertainties (fundamental; fuzziness; data)		Uncertainties (benefits and impacts; fuzziness; data)	
Thresholds of Difference	Indifference Threshold q_i		Indifference Threshold q_i	
	Relative Vulnerability Threshold p_i		Preference Threshold p_i	
	Dominance Threshold v_i		Veto Threshold v_i	

*"weights" in MAUT methods become "votes" in outranking methods

Condorcet approach based on pairwise comparisons is better suited for building country-based environmental indices. A full review of the literature on indices is beyond the scope of this chapter and the reader is referred to Parris and Kates (2003), Gudmundsson (2003), Ebert and Welsch (2004), Böhringer and Jochem (2007), Barnett et al. (2008), Munda and Nardo (2009) and Alexander et al. (2010). Instead, the chapter will focus specifically on IBVA.

As discussed earlier, IBVA's fundamental uncertainties and imprecision make MAUT requirements for additive independence and complete knowledge of system interactions by the analyst very difficult to satisfy. For example, a number of socio-economic indicators are typically selected to represent the adaptive capacity of a community (e.g., % of population with high school degree, average household income, % of population in single parent households), but these indicators are often correlated and knowledge of how they might combine to indicate higher or lower vulnerability is very difficult to generate. As a result, IBVA studies commonly use a utility-value function without providing an objective basis for its construction, especially in relation to the weights applied to each indicator and the assumption of complete compensation between indicators (Hinkel 2011; El-Zein and Tonmoy 2013b). Questions such as how much an "advantage" in adaptive capacity makes up for an increase in exposure or whether there is a limit beyond which compensation is no longer possible are crucial, and yet are largely ignored in IBVA (problem of incommensurability discussed in chapter 3). This problem is compounded by the subjective component of the assessment, especially the problem of eliciting perceptions of vulnerability from multiple stakeholders (which, in the MCDA analogy, corresponds to eliciting the preference structure of multiple decision makers).

This chapter argues therefore that an outranking framework, based on a Condorcet approach and pairwise comparisons, may be better suited to the inherent uncertainty and imperfect knowledge that characterizes IBVA problems than MAUT methods because the theoretical requirements of the former are less stringent.

4.5 Outranking Formulation for IBVA Problems

4.5.1 Background

A set of methods called outranking procedures (OP) evolved from the late 1970s to the 1990s as an alternative to MAUT in infrastructure and environmental decision-making studies to deal with the problem of incommensurate criteria and uncertainty. Given that MCDA and IBVA have analogous structures and share similar features Table 4-1, outranking techniques developed for MCDA are applicable to IBVA. Rather than convert decision criteria into commensurable scales and build a utility function, outranking methods proceed by conducting comparisons of each pair of alternatives against each criterion, based on fuzzy preference and indifference relationships, and building a credibility matrix which reflects, on a scale of 0 to 1, the strength of the statement "Alternative A is at least as good as Alternative B". ELECTRE III is one of the most widely used outranking procedures in the literature especially because, compared to other outranking methods, it offers a more sophisticated characterization of uncertainty in preference structures. Although for the remainder of the thesis the formulation is based on ELECTRE III, other outranking procedures can be considered.

4.5.2 ELECTRE III Outranking Procedure

In ELECTRE III, (Roy 1978; Hokkanen and Salminen 1997; El Hanandeh and El-Zein 2010) the degree to which the pairwise comparisons support the above statement (concordance) AND whether any criterion strongly contradicts it (discordance) are quantified. Concordance is based on a preference threshold, above which a difference in performance between A and B is considered significant and an indifference threshold below which such a difference is insignificant. Discordance is based on a veto threshold which caters for complete incommensurability by allowing a single, excessively high or low, criterion/indicator to alter the ranking of an alternative/SES, regardless of its performance against other criteria/indicators. Hence, by adopting fuzzy definitions of preference, non-compensation and relative compensation, ELECTRE III goes beyond the simple Condorcet model of preference suggested by Munda and Nardo (2009) and accommodates a wider range of preference configurations. In addition, by using two ascending and descending ranking pre-orders, it provides an elegant way of eliciting incomparability, i.e. cases when the non-compensatory nature of some indicators yield conflicting relative ranks of two alternatives.

On the other hand, three limitations of ELECTRE-III have been discussed in the literature: rank reversal, intransitivity and complexity (J.R. Figueira 2010; De Montis et al. 2000). First, intransitivity sometimes occurs in ELECTRE III, whereby decomposing a set of alternatives into smaller analysis sets, under otherwise identical conditions yields a change in ranking. J.R. Figueira (2010) has shown that this stems from binary relations of indifference which are in fact intransitive and, hence, faithfully mirror decision making. Second, rank reversal occurs if an alternative is replaced with a worse one, all other things being equal, and the new ranking yields, counter-intuitively, a change in rankings. (Rank reversal is sometimes referred to in the outranking literature as *violation of independence with respect to irrelevant actions*). Roy (1973) and Roy and Martel (2006) have argued that rather than a numerical aberration, rank reversal is once again an authentic reflection of real decision making when data quality is poor and preference structures are uncertain. The extent to which rank reversal and intransitivity are present in IBVA, and whether they are acceptable outcomes of the analysis, will need to be considered on a case-by-case basis. It is possible for example, to assess the robustness of rankings by conducting repeated analyses that test for the existence of rank reversal and intransitivity.

Third, the complexity of the outranking procedure in ELECTRE-III can be difficult to communicate to stakeholders who tend to prefer simple methods and clear outcomes. However, this is part of a bigger problem of interaction between science and decision making, with stakeholders sometimes failing to see and scientists failing to communicate that assessment methods such as ELECTRE-III are decision-aiding rather than decision-making tools (De Montis et al. 2000).

In what follows:

a) Vulnerability problems are formulated in an outranking framework, based on ELECTRE III, using a “vulnerability” notation rather than a “decision-making” one. It is named as Sydney Environmental Vulnerability Assessment (SEVA-I) framework.
b) Thresholds of difference are defined for vulnerability and translate them into verbal questions that can be used in eliciting data from stakeholders for model building,

while allowing for the possibility of simulating non-linear relationships between vulnerability and indicators.

4.5.3 *Outranking Vulnerability Assessment Framework*

In the presentation below it is assumed, without loss of generality, that the higher the value of the indicator, the more vulnerable the SES. For each pair of SESs, Three different categories of relative vulnerability can be defined:

1. b is strictly more vulnerable than a according to criterion I_i if and only if $I_{ib} - I_{ia} \geq p_i$, where $p_i \leq 0$ is the *relative vulnerability threshold for indicator I_i*;
2. b is indifferent to a according to criterion I_i if and only if $|I_{ib} - I_{ia}| \leq q_i$, where $q_i \leq 0$ is the *indifference threshold for indicator I_i*;
3. b is weakly more vulnerable than a according to criterion I_i if and only if $q_i < I_{ib} - I_{ia} < p_i$.

The ELECTRE III ranking process is conducted in three stages:

Stage 1: Concordance and Discordance Matrices

A concordance matrix for each indicator I_i is defined by:

$$c_i(a,b) = \begin{cases} 0 & \text{if } I_{ib} - I_{ia} \geq p_i \\ \dfrac{p_i - (I_{ib} - I_{ia})}{p_i - q_i} & \text{if } q_i < I_{ib} - I_{ia} < p_i \\ 1 & \text{if } I_{ib} - I_{ia} \leq q_i \end{cases} \qquad \textbf{4-3}$$

$c_i(a,b)$ is a measure of the truth of the statement that “a is at least as vulnerable as b according to indicator I”. Note that it may be more convenient in some cases to write equation (4-3) in terms of relative rather than absolute differences between indicators; this would require thresholds to be defined as percentages. Equation (4-3) is a representation of vulnerability as a fuzzy-set relationship shown in Figure 4-1. p_i and q_i are usually constants, and how to determine them is discussed below.

The discordance matrix for each indicator i is defined by:

$$d_i(a,b)=\begin{cases}0 & \text{if } I_{ib}-I_{ia}\le p_i\\ \dfrac{(I_{ib}-I_{ia})-p_i}{v_i-p_i} & \text{if } p_i< I_{ib}-I_{ia}<v_i\\ 1 & \text{if } I_{ib}-I_{ia}\ge v_i\end{cases}\qquad 4\text{-}4$$

where v_i is called *dominance threshold* for indicator i and reflects a difference between indicator values above which b becomes more vulnerable than a, *regardless of the performances of a and b on other indicators*. We will refer to q_i, p_i and v_i collectively as *thresholds of difference* to emphasize that they provide a reference for disparities between indicators rather than the indicators themselves.

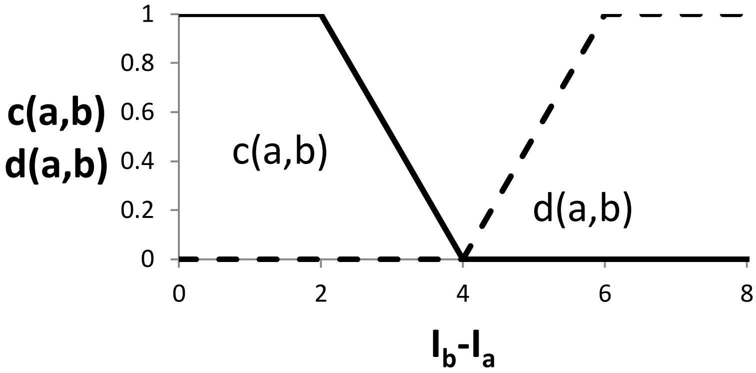


Figure 4-1: Vulnerability represented by a fuzzy-set relationship : concordance and discordance for (q=2, p=4, v=6)

Stage 2: Outranking Matrix

The statement, “a is at least as vulnerable as b” (denoted aVb) is considered true provided:

i. a “majority” of indicators supports it (concordance principle);
and
ii. no single indicator vetoes it (discordance principle).

The concordance principle can be measured by the following concordance index:

$$c(a,b)=\frac{1}{\sum_{i=1}^{m} w_i}\sum_{i=1}^{m} w_i c_i(a,b)\qquad 4\text{-}5$$

where w_i is a vote for indicator I_i, applied to the pair-wise comparisons, rather than a weight in a global utility function. An outranking matrix combines the concordance and discordance principles in order to quantify the degree to which aVb is true. It is given by:

$$S(a,b) = \begin{cases} c(a,b) & \text{if } d_i(a,b) \leq c(a,b) \ \forall\, i = 1, m \\ c(a,b) \prod\limits_{i \in I_v(a,b)} \dfrac{[1 - d_i(a,b)]}{[1 - c(a,b)]} & \text{otherwise} \\ \text{where } I_v(a,b) \text{ is the set of indicators for which } d_i(a,b) > c(a,b) & \end{cases} \qquad \textbf{4-6}$$

Stage 3: Distillation and Ranking Procedures

The most vulnerable SES is the one that outranks the largest number of SESs and is outranked by least. Hence, S(a,b) is used next to build two partial, descending and ascending pre-orders D_1 and D_2 as follows. A matrix T can be defined as:

$$T(a,b) = \begin{cases} 1 & \text{if } S(a,b) \geq \lambda - g(\lambda) \\ 0 & \text{otherwise} \end{cases} \qquad \textbf{4-7}$$

where $\lambda = \max S(A,B)$ and $g(\lambda)$ is a threshold of indifference applied to the outranking matrix in such a way that only values of S(a,b) close enough to λ yield T(a,b)=1. g(λ) is typically set at 0.15 (Vallée and Zielniewicz 1994) when λ=1 or, more generally, at -0.15λ+0.3. The sum of rows in T(a,b) computes the number of SESs for which aVb is true, while the sum of columns is the number of SESs for which bVa is true. A vector Q(a) is defined as the difference between these two sums:

$$Q(a) = \sum_{k=1}^{m} T(a,k) - \sum_{k=1}^{m} T(k,a) \qquad \textbf{4-8}$$

Equation (4-8) is used to generate two ascending (D_1) and descending (D_2) pre-orders and a final ranking as $D_1 \cap D_2$. Therefore, $g(\lambda)$ represents a cutoff point of “defuzzification”, ie the conversion of the continuous scale of the outranking matrix into a binary one that is used to generate final rankings. Hence, the sensitivity of rankings to $g(\lambda)$ will need to be assessed.

4.5.4 Determination of Thresholds of Difference

In aggregating indicators for an IBVA problem, the most important advantages of an outranking approach such as ELECTRE III are as follows:

a) no conversion of indicators into a normalized scale is performed; pair-wise comparisons of SESs on each criterion are conducted instead and aggregation is performed on the outcome of these comparisons (concordance index) rather than a normalized indicator;

b) the analyst is compelled to spell out their assumptions about compensation and non-compensation between indicators at the outset, through the definitions of v_i and w_i, with the possibility of specifying complete compensation, complete non-compensation, as well as a degree of compensation in between (discordance matrix).

c) the analyst is compelled at the outset to quantify the *fundamental* uncertainties discussed above, through the definitions of q_i, p_i and $g(\lambda)$.

The determination of thresholds q_i, p_i and v_i, as well as the votes w_i is therefore an important part of problem definition, which in terms of vulnerability, can be defined and determined by the following questions:

1. "All other indicators being equal, what is the difference in values of indicator I_i for two SESs below which the vulnerabilities of the two systems are the same?" (indifference threshold q_i).
2. "All other indicators being equal, what is the difference in values of indicator I_i for two SESs above which one system is strictly more vulnerable than the other?" (relative vulnerability threshold p_i).
3. "What is the difference in values of indicator I_i for two SESs above which one system is strictly more vulnerable than the other AND no advantage by any other indicator, or combination of other indicators, can compensate for it?" (dominance threshold v_i).
4. "In determining whether a 'majority' of indicators support the statement that one SES is at least as vulnerable as another, what is the strength of the 'vote' by indicator I_i relative to a reference indicator?" (vote w_i).

Note that the preposition “All other indicators being equal” is used only for the purpose of eliciting thresholds for individual indicators and that, in generating rankings the outranking analysis considers of course ALL indicators together.

In the literature on MCDA, different methods for calculating the thresholds have been proposed (e.g., Roy et al. (1986); Rogers and Bruen (1998); Roy (1978)). M. Maystre (1994) argues that q and p should be interpreted as minimum and maximum margins of uncertainty, respectively. However, in IBVA, the two thresholds can reflect uncertainty, imprecision, subjectivity, or non-linearity. For example, small differences between indicators may be too small to indicate differences in vulnerability (q_i) because, a) they fall within statistically random or non-random fluctuations of the indicator (e.g., as they are up-scaled to the spatial level of the analysis), b) stakeholders have offered a normative judgment about the nature of the indicator in its relationship with vulnerability, or c) a non-linear relationship has been mechanistically established between indicator and vulnerability. Which of these three approaches to setting thresholds is used will depend on the indicator in question and, given the mix of bio-physical, institutional, and socio-economic indicators in IBVA, a mix of approaches would be expected.

4.5.5 Development of a computer tool (SEVA-Code)

The algorithm of SEVA-I was coded in MATLAB to develop a decision support system for IBVA. It is called the Sydney Environmental Vulnerability Assessment Code (SEVA-Code). In its current form SEVA-Code uses a spreadsheet interface for communicating data with MATLAB. Here the user can build the IBVA model in a spreadsheet (including indicators, thresholds and votes) and run the analysis from MATLAB where outranking algorithms have been coded. The outputs of the analysis (e.g., rankings) can then be exported back to the spreadsheet for further analysis. This tool was used for all the analysis conducted in this thesis. Codes of SEVA-Code are attached in the Appendix.

4.6 Illustrative Example

Table 4-2 illustrates the fundamental outranking relationships and their effects on vulnerability assessment using a simple hypothetical model of 3 SESsx3 indicators. The nine scenarios shown have the same vulnerability matrix but different thresholds of difference.

Table 4-2: Analysis Set 1: Nine Simple Scenarios and Effects of Thresholds on Rankings in ELECTRE III (1: most vulnerable; 3: least vulnerable; *SES2 more vulnerable than SES1 and SES3, but SES1 and SES3 are incomparable to each other)

Cases	Indicator	q	p	v	SES1	SES2	SES3
Case 1 Dominated by indifference	I_1	5	6	∞	24	27	28
	I_2	5%	6%	∞	12%	11%	8%
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking				**1**	**1**	**1**
Case 2 Dominated by a single, linear indicator	I_1	**0**	**8**	∞	**24**	**27**	**28**
	I_2	5%	6%	∞	12%	11%	8%
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking				**3**	**2**	**1**
Case 3 Dominated by a single, non-linear indicator	I_1	**0.8**	**3.5**	∞	**24**	**27**	**28**
	I_2	5%	6%	∞	12%	11%	8%
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking				**3**	**2**	**1**
Case 4 Dominated by a single, non-linear indicator	I_1	**1.1**	**3.5**	∞	**24**	**27**	**28**
	I_2	5%	6%	∞	12%	11%	8%
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking				**3**	**1**	**1**
Case 5 Determined by two, non-linear indicators	I_1	**1.1**	**3.5**	∞	**24**	**27**	**28**
	I_2	**1%**	**2%**	∞	**12%**	**11%**	**8%**
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking				**2**	**1**	**2**
Case 6 Modified by dominance threshold	I_1	1.1	3.5	∞	24	27	28
	I_2	**1%**	**2%**	**3.5%**	**12%**	**11%**	**8%**
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking				**2**	**1**	**3**
Case 7 Incomparable	I_1	**0**	**0.25**	**0.5**	**24**	**27**	**28**
	I_2	**0%**	**0.25%**	**0.5%**	**12%**	**11%**	**8%**
	I_3	**0%**	**2.5%**	**5%**	**50%**	**60%**	**45%**
	Vulnerability Ranking				**-**	**-**	**-**
Case 8 Partly incomparable	I_1	**1.1**	**3.5**	**3.8**	**24**	**27**	**28**
	I_2	**1%**	**2%**	**3.5%**	**12%**	**11%**	**8%**
	I_3	20%	30%	∞	50%	60%	45%
	Vulnerability Ranking*				**2**	**1**	**2**
Case 9 All 3 indicators influencing outcome	I_1	**4**	**6**	**8**	**24**	**27**	**28**
	I_2	**1%**	**2%**	**3.5%**	**12%**	**11%**	**8%**
	I_3	**6%**	**11%**	**20%**	**50%**	**60%**	**45%**
	Vulnerability Ranking				**2**	**1**	**3**

Equal votes w_i are given to the three indicators. It is assumed that vulnerability increases with the increase of the indicator value. Case 1 represents a scenario in which all pairwise differences between indicators are smaller than the relevant indifference threshold and all SESs are equally vulnerable. Moving to cases 2-4, the thresholds for I_2 and I_3 remain the same, while those of I_1 change. In case 2, all I_1 differences ($|I_1-I_2|$; $|I_2-I_3|$ and $|I_3-I_1|$) fall between q_i and p_i: vulnerability is determined by I_1 and increases linearly with it. In case 3, q_i and p_i for I_1 lead to both strict and weak relative vulnerabilities. If the I_1 indifference threshold is increased to 1.1, as happens in case 4, then SES2 and SES3 have equal vulnerabilities because $|I_2-I_3|<q1$. In case 5 the first two indicators determine the final ranking, because the differences between indicators cover all three cases of indifference, weak and strict relative vulnerabilities. In this case, unlike the previous ones, the respective votes given to indicators have some impact on the outcome. Case 6 demonstrates the effect of the dominance threshold, now set to 3.5% for I2, whereby SES3 cannot be found to be more vulnerable than SES1, regardless of the pair's performance on other indicators. In case 7 there is a vulnerability dominance of SES3 over SES1 according to I1 and vice versa according I2. Likewise, SES2 has contradictory dominance relationships with SES1 and SES3. Hence, incomparability arises which reflects conflicting indicators AND complete absence of compensation when differences exceed the dominance threshold. Case 8 is similar to case 7 except that incompatible dominance occurs only between SES1 and SES3 and a partial ranking is obtained. Finally, in case 9, all indicators influence the outcome, with various levels of "strict vulnerability", "weak vulnerability" and "indifference", as well as "dominance" occurring.

4.7 Real Life Application: Vulnerability to Heat Stress in Sydney

An indicator-based model of vulnerability to climate change for 15 Local Government Area (LGA) in Sydney, first developed by Preston B.L et al. (2008) has been adopted. The LGA is a statistical division of local government in Australia. Specifically the indicators suggested by Preston B.L et al. (2008) were used for the 15 LGAs. However, the data was built and updated and thresholds of differences were developed to allow the application of the outranking approach. The 15 LGAs shown in Figure 4-2 were originally selected because they form a group of coastal councils interested in developing climate adaptation policies. Sydney, like other cities in Australia and elsewhere, suffers from higher mortality on hot days (Vaneckova et al. 2008; Hu et al. 2008). Vulnerability to heat was represented by a set of 6

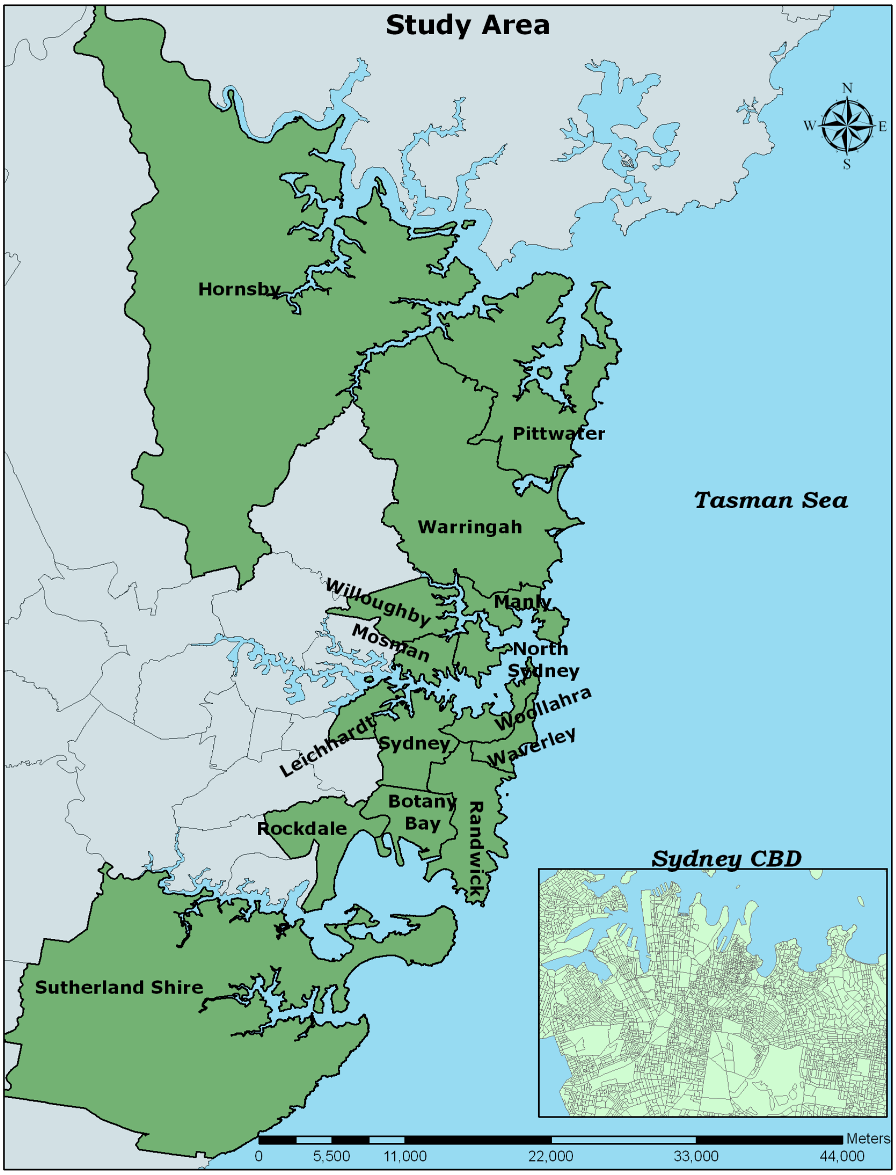


Figure 4-2: Location of the 15 Local Government Areas in the Study

indicators representing exposure, 4 indicators for sensitivity, and 12 indicators for adaptive capacity (see Table 4-3). Exposure and sensitivity indicators were based on predictors of heat related mortality and morbidity from epidemiological literature. For the rationale behind the selection, the reader is referred to Preston B.L et al. (2008). A measure of error for each indicator was inferred or collected from data descriptors and methodologies provided by the sources, and used to derive thresholds. The full vulnerability matrix, as well as the data sources and the thresholds for the base case, are presented in tables shown in appendix (Table A 1, Table A 2, Table A 3, Table A 5). Both the Spearman's and Pearson's correlation factors were used to compare sets of rankings, although only the former is shown because the two factors yielded consistent results.

Table 4-3: Indicator-based model of vulnerability to heat for 15 local government areas in Sydney (2006 data unless otherwise indicated)

Exposure	Sensitivity	Adaptive Capacity
Present average January maximum temperature (2005-2010)	% population≤65 years of age	% population completing year 12
Average January minimum temperature (2005-2010)	% population≤65 years of age and living alone	% population that speaks language other than English
Number of Days > 30°C per Year (2005-2010)	% population≤4 years of age	Median home loan repayment
Land cover (30 m grid)	% of housing as multiunit dwellings	% home ownership
Population density		Median household income
Road density		% household with internet access
		Current ratios of assets to liabilities of local council
		Per capita business rates of local council
		Per capita residential rates of local council
		Per capita community service expenses of local council
		Per capita environmental and health expenses of local council
		% of population requiring financial assistance

The presence of rank reversal was systematically tested by re-analysing the base case with one LGA withdrawn at a time and rankings compared to those of the base case (appendix Table A 4). This was conducted for all LGAs except the most and least vulnerable.

The rankings were found to be robust, with the first and last LGA never changing and an average and minimum Spearman coefficients, relative to the base case, of 0.94 and 0.92, respectively. Where rank reversal did occur it was around the middle ranks where the relatively small differences in scores between LGAs makes them more prone to instability. Sensitivity of rankings to changes in g (≤) (up to ±33%) were also tested and once again the results were found to be robust.

Table 4-4: Base case rankings (1: most vulnerable; SCF: Spearman Correlation Factor; E-III: ELECTRE-III; Exp: Exposure; Sensi: Sensitivity; AC: Adaptive Capacity)

	MAUT-Arithmetic All Dimensions	**MAUT-Geometric All Dimensions**	**E- III All Dimensions**	**E- III Exp**	**E-III Sensi**	**E- III AC**
SCF Relative to ELECTRE III All Dimensions	**0.95**	**0.76**	**1**	**0.80**	**0.27**	**0.79**
SCF Relative to MAUT-Arithmetic All Dimensions	**1**	**0.75**	**0.95**	**0.87**	**0.23**	**0.73**
Botany Bay	2	2	2	3	1	2
Hornsby	14	15	13	11	15	4
Leichhardt	8	4	9	3	13	11
Manly	12	9	11	14	2	13
Mosman	13	13	15	11	5	15
North Sydney	5	7	5	8	5	6
Pittwater	15	14	14	15	13	12
Randwick	3	3	3	6	9	3
Rockdale	1	1	1	2	9	1
Sutherland	7	10	5	6	9	6
Sydney	4	12	4	1	9	4
Warringah	11	5	8	11	5	6
Waverley	6	6	5	3	2	6
Willoughby	9	8	11	8	9	10
Woollahra	10	11	9	8	5	13

Table 4-4 shows vulnerability rankings of the 15 LGAs for the base case. Both MAUT and ELECTRE III identified Rockdale, Botany Bay and Randwick as the most vulnerable and Mosman, Pittwater and Hornsby as the least vulnerable. The former three have a relatively low adaptive capacity, although Botany Bay and Rockdale's exposures are ranked high as well. Interestingly, Rockdale is ranked ninth in terms of sensitivity but still comes first overall on account of its relatively low adaptive capacity. Hornsby and Pittwater have large areas covered with vegetation and therefore have a low urban heat island effect (represented by the last three indicators of exposure), whereas Mosman is an LGA with a large proportion of population with a high socio-economic background. "Sydney", which denotes the Central Business District, has high exposure as a result of the urban heat-island effect but relatively low sensitivity because its population does not include a large proportion of people over 65 and under 4.

MAUT-Arithmetic and ELECTRE III yield similar but not identical rankings. This is expected for the base case because q_i and p_i reflect a relatively small amount of uncertainty, no non-linearity and no dominance ($v_i=\infty$). The differences in rankings generated by MAUT-Arithmetic and MAUT-Geometric are rather large because the latter is multiplicative and therefore synergetic, i.e., it penalises LGAs with low performance more heavily in more than one indicator, regardless of any thresholds or weights. Nevertheless, the same groups of the three most and three least vulnerable LGAs were identified by the three methods, and the variations in rankings occur in the group of LGAs that fall between these two extremes.

The sensitivity of ELECTRE III rankings to thresholds of difference and to votes are shown in Table 4-5. Rankings are robust under changes of up to 100% in q_i and p_i. As expected, the introduction of dominance thresholds for all indicators has a bigger impact on rankings than changes in q_i and p_i, with a Spearman correlation factor of 0.84 when $v_i=2p_i$. The last six rows in Table 4-5 show the change in rankings when votes in ELECTRE III and weights in MAUT-Arithmetic were increased by 100% for all indicators of one dimension at a time, while the other votes are kept the same. The outranking results were once again robust to changes in votes, and the rankings of MAUT-Arithmetic were more sensitive to changes in weights of sensitivity and adaptive capacity indicators compared to the equivalent outranking sensitivity to votes. This is due to the fact that votes in ELECTRE III are applied to the concordance matrix generated from the pairwise comparisons, rather than a utility function.

Table 4-5: Sensitivity: effects on rankings of changes in thresholds of difference, votes and weights (SCF: Spearman Correlation Factor)

			SCF Relative to Base Case ELECTRE III	SCF Relative to Base Case MAUT-Arithmetic
ELECTRE III	Base Case	Base Case* (q_i,p_i,v_i=∞)	1	0.94
	Sensitivity to Thresholds	$0.5q_i$; $0.5p_i$	0.97	0.93
		$2q_i$; $2p_i$	0.94	0.93
		$4q_i$; $4p_i$	0.82	0.90
		$v_i=4p_i$	0.86	0.84
		$v_i=2p_i$	0.84	0.73
		$g(\lambda)=-0.1\lambda+0.2$	0.99	0.90
		$g(\lambda)=-0.2\lambda+0.4$	0.93	0.86
	Sensitivity to Votes	Exposure votes $w_i=2$	0.95	-
		Sensitivity votes $w_i=2$	0.94	-
		Adaptive capacity votes $w_i=2$	0.98	-
MAUT-Arithmetic	Sensitivity to Weights	Exposure weights $w_i=2$	-	0.98
		Sensitivity weights $w_i=2$	-	0.93
		Adaptive capacity weights $w_i=2$	-	0.87

4.8 Conclusions

MAUT-based aggregation procedures have remained dominant in the IBVA literature despite the fact that their theoretical requirements of additive independence and complete system knowledge are almost never satisfied in the context of IBVA. This chapter has argued that outranking procedures, previously only applied to decision-making problems, can be used for vulnerability assessment and may provide a better approach for teasing out policy-relevant information from uncertain vulnerability data.

Outranking procedures implicitly recognize the quantitative and qualitative dimensions of the assessment and work with descriptive categories that are matched with the level of quantitative sophistication of available data. One interesting effect of this is that, as shown earlier, outranking procedures can yield incomparability of two SESs, usually as a result of conflicting dominance thresholds and an absence of compensation. Indeed, an outranking approach forces the analyst to spell out and characterize the degree of uncertainty in the relationship between indicator and vulnerability, while allowing for a mix of cardinal and ordinal variables to be included. The process of building the indicator based model can in fact be structured around the four questions we proposed as a way of determining difference thresholds and votes because they provide a systematic way of canvassing proposed indicators and bringing to the fore assumptions underlying the model.

Furthermore, outranking methods yield rankings and ranking-based scores rather than indices. I believe this is both a limitation and a strength in the context of IBVA. It is a limitation because it does not allow us to compare indices calculated in different studies and different contexts, albeit following a common, benchmarked procedure—which is what indices are meant to do, and it is a strength because it highlights the comparative nature of index-building, and a sometimes forgotten fact that while it may be possible to compare vulnerabilities, it is not possible to *measure* them or reduce them to a single variable.

The following chapter expands the developed IBVA formulation (SEVA-I) to deal with different forms of non-linearities that have been identified in Chapter 3.

Chapter 5

A non-linear framework for assessing vulnerability to climate change

5.1 Synopsis

The previous chapter has developed an outranking based formulation (SEVA-I) and a computer tool (SEVA-code) for IBVA, and applied them to assess heat stress vulnerability of the populations of 15 coastal councils of Sydney. In this chapter the functionality of SEVA-I is extended (and converted to a framework) to enable it to deal with the non-linearities identified in Chapter 3. This new approach is illustrated by applying it to a simplified model of urban vulnerability to heat while focusing on the non-linear relationship between mortality and temperature above a ‘comfort temperature’ that has long been evidenced in the epidemiological literature. Vulnerability rankings yielded by linear and non-linear characterizations of the relationship between temperature and mortality are compared and the incorporation of non-linearity is found to have a significant impact on the rankings.

5.2 Introduction

The earth’s climate system is highly non-linear and the vulnerability of a community to a climate hazard is no exception. While this fact is widely accepted, indicator-based vulnerability assessments (IBVA) hardly ever take such non-linearities into account. These studies, using MAUT based simple aggregation approach (i.e. simple additive weight or multiplicative method) usually convert all indicators into a global utility function and produce a linear, threshold-free scaling of the effects of an indicator on vulnerability. However, such a linear assumption is not mandatory in MAUT because different forms of the normalization technique can account for any non-linear relationship (Steele et al. 2009).

Limitations of using MAUT based approaches in the context of IBVA have been discussed in detail in previous chapters (Chapters 2 and 4). In Chapter 4 it has been shown that in the context of IBVA, outranking procedures developed in decision-making science offer a more theoretically sound approach to aggregation than MAUT based ones because unlike MAUT based approaches they do not have stringent requirements (e.g., independence of indicators, complete knowledge of the system etc), rather they allow the analyst to incorporate the incommensurability, fuzziness, and some specific forms of uncertainty associated with indicators. SEVA-I was developed in Chapter 4 by adapting an outranking method ELECTRE-III. Outranking procedures are especially powerful in representing fuzzy relationships, but in their present form they cannot accommodate other forms of non-linearity such as deductive non-linearity (identified in chapter 3). This is an impediment to their application to IBVA because as shown in earlier chapters, all three forms of non-linear relationships are present in these assessments. Therefore, this chapter expands outranking procedures used in SEVA-I and proposes a new outranking formulation for an indicator based approach which can accommodate non-linear relationships between an indicator and the vulnerability it represents (identified in chapter 3), as well as different degrees of compensation between indicators (from total compensation to complete incommensurability) and can be used to conduct assessments at different scales. This is done by introducing the concept of *harm criterion* as a mediator between an indicator and the vulnerability it represents. Hence, the new assessment approach can aggregate a mix of indicators with various degrees of subjectivity and non-linearity, without converting them into a single utility function and without requiring them to be mutually compensating. This is called the Sydney Environmental Vulnerability Assessment-II (SEVA-II). Table 5-1 summarises the different forms of incommensurability and non-linearity identified in Chapter 3, as well as the ability of different mathematical formulation to accommodate them.

This chapter has two objectives. First, based on the framework proposed in Chapter 3, a new outranking approach to aggregation is formulated which incorporates different combinations of compensation and non-linearity (SEVA-II). Second, the new approach is illustrated by applying it to a simplified model of vulnerability to heat stress and assessing whether the incorporation of non-linearity and fuzziness have a significant impact on the ranking of vulnerabilities.

Table 5-1: Summary of different forms of incommensurability and non-linearity in vulnerability assessments

Problem	Description	Assumptions Made in Different Mathematical Formulation		
		MAUT based simple additive or multiplicative approach	SEVA-I*	SEVA-II
Dimensional incommensurability	One dimension of vulnerability may not be convertible into another	Always fully convertible	Flexible convertibility	Flexible convertibility
Indicator incommensurability	One indicator of vulnerability may not be convertible into another, even within the same dimension	Always fully convertible	Flexible convertibility	Flexible convertibility
Fundamental non-linearity	Vulnerability V may depend on the magnitude of the hazard M	Linear and non-linear	Linear and non-linear	Linear and non-linear
Deductive non-linearity	A non-linear relationship between vulnerability V and indicator I may exist	Always linear	Always linear	Linear and non-linear
Intuitive non-linearity or fuzziness	A discontinuous relationship between change in vulnerability V and change in indicator I may exist	Always linear	Linear or non-linear	Linear or non-linear

*This refers to the adaptation of the ELECTRE III outranking procedure to vulnerability assessment presented in chapter 4.

5.3 The Sydney Environmental Vulnerability Approach-II (SEVA-II)

This framework introduces *Harm* as a concept mediating the relationship between the indicator and the vulnerability it represents. This was initially suggested by Hinkel (2011). *Harm* can be conceived of as a more concrete, less abstract form of vulnerability that is more amenable to quantification. In conventional IBVA studies, an indicator selected to represent vulnerability is usually taken to satisfy the following three conditions:

1. it represents a process generating vulnerability;
2. it holds a linear, monotonic relationship with vulnerability;
3. it is either readily available or computable.

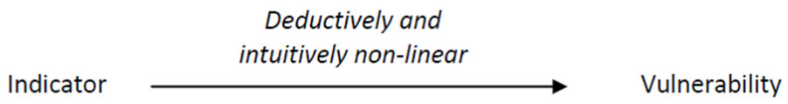
In SEVA-II we replace indicators with *harm criteria*. A harm criterion must satisfy the following conditions:

1. it must represent a process generating vulnerability;
2. it must hold either a linear, monotonic relationship *or an intuitively non-linear relationship* with vulnerability;
3. it must be either readily available or computable; computable *harm criteria* may be the output of deductively non-linear relationships or models whose input is a set of readily available indicators.

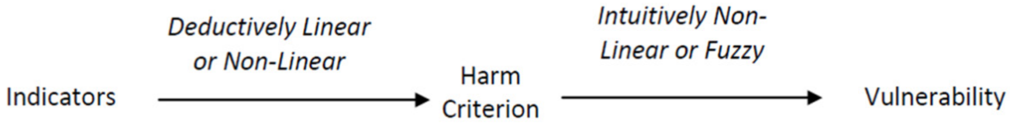
A harm criterion then, like an indicator, acts as a proxy for a process generating vulnerability (e.g., percent of population over 65 in a community as a proxy indicator of the increased vulnerability to heat with age; the percentage of people on lower income in a community as a proxy indicator of the increased vulnerability to flooding events with poverty). However, a harm criterion, as opposed to an indicator, allows us to achieve two key objectives in the process of building a vulnerability model:

a. to relax the conditions concerning linearity;
b. to separate deductive and intuitive non-linearity in order to better deal with both of them.

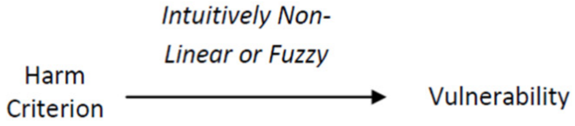
Figure 5-1 shows these features graphically, with Figure 5-1c highlighting the fact that, when the harm criterion is readily available (and no deductive non-linearity is present), there is no need for indicators.



a. Indicator-vulnerability relationship



b. Indicator-harm criterion-vulnerability relationship in SEVA when harm criterion is computed from a set of indicators



c. Harm criterion-vulnerability relationship in SEVA when harm criterion is readily available

Figure 5-1: The harm concept mediating the relationship between indicator and vulnerability in the presence of deductive non-linearity

5.4 Illustration of the framework

To illustrate how harm criteria can be used in vulnerability assessments, a simplified model is presented below with the aim of ranking the vulnerability to heat stress of a number of communities (e.g., neighbourhoods or city districts). The model shown in Table 5-2 and Table 5-3, is not a complete and accurate representation of vulnerability to heat: it is only an illustrative one used to demonstrate key relationships between indicators, harm criteria, and vulnerability. Harm criteria H_1, H_2, and H_3 are usually readily available as primary data from demographic and population census databases. Hence, there is no need for indicators to help in computing them. Harm criterion H_4, on the other hand, can be predicted by combining a measure of temperature increase generated by a climate model under a given scenario with an epidemiologically based relationship that estimates the resulting number of excess deaths. The relationship between I_4 and H_4 is usually deductively non-linear: it is often represented by the so-called U-shaped or V-shaped curves (see Figure 5-2), whose parameters depend on

Table 5-2: Hypothetical 4-harm criteria model of vulnerability to heat stress (NA: Not Applicable; A: Available; C: Computable; D-NL: Deductive Non-Linearity; I-NL: Inductive Non-Linearity; Ref: References)

Harm Criterion	**Description**	**Dir**[a]	**Process**	**D-NL ?**	**Predictive Indicator**	**Relationship**	**I-NL ?**	**Comp**	**Ref**
H_1 (A)	% of population > 65 years of age	↑	older population is at higher risk of death	No	NA	NA	No	Total	Curriero et al. (2002)
H_2 (A)	% of built-up land cover	↑	urban heat-island (UHI) effect leads to more deaths	No	NA	NA	No	Total	Harlan et al. (2006); Vaneckova et al. (2010)
H_3 (A)	median monthly household income in $	↓	lack of access to adaptive resources leads to more deaths	No	NA	NA	Yes	Partial	Reid et al. (2009); Johnson and Wilson (2009)
H_4 (C)	daily mortality counts as a temperature-dependent variable	↑	higher temperature leads to more deaths	Yes	I_4[b]	$H_4=-\beta_{cold}(I_4-I_{min1})+M_{min}$ for $I_4 \le I_{min1}$ $H_4=M_{min}$ for $I_{min1} \le I_4 \le I_{min2}$ $H_4=\beta_{hot}(I_4-I_{min2})+M_{min}$ for $I_{min1} \le I_4$ (see note c below)	Yes	Partial	Curriero et al. (2002); McMichael et al. (2008); El-Zein et al. (2004)

a :Dir= Direction:≤ (≤) indicates that vulnerability increases (decreases) with increasing harm. b: I_4 is average daily temperature; c: entities M_{min}, I_{min1}, I_{min2}, β_{cold} and β_{hot} are defined in Figure 5-2.

climatic, demographic, and socio-economic factors(e.g., McMichael, 2008). It is important to emphasise here that the construction of the model is guided by epistemological, as much as ontological considerations: deductive non-linearities emerge from the kind of data that is available to us, and not just from the nature of the

Table 5-3: Adopted values for hypothetical 4-harm criteria model of vulnerability to heat stress

	SES1	SES2	SES3	SES4
H1	35%	29%	38%	25%
H2	43%	48%	52%	38%
H3	$875	$800	$1000	$955
H4-L*	87	50	125	113
H4-DNL*	100	107	125	113
I4	30°C	28°C	34°C	31°C

*L= Linear, DNL= Deductively Non-Linear

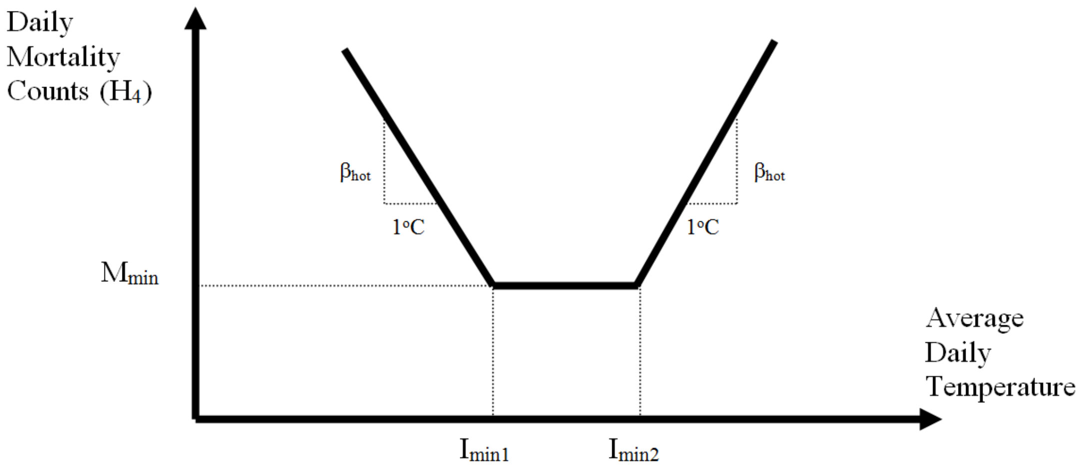
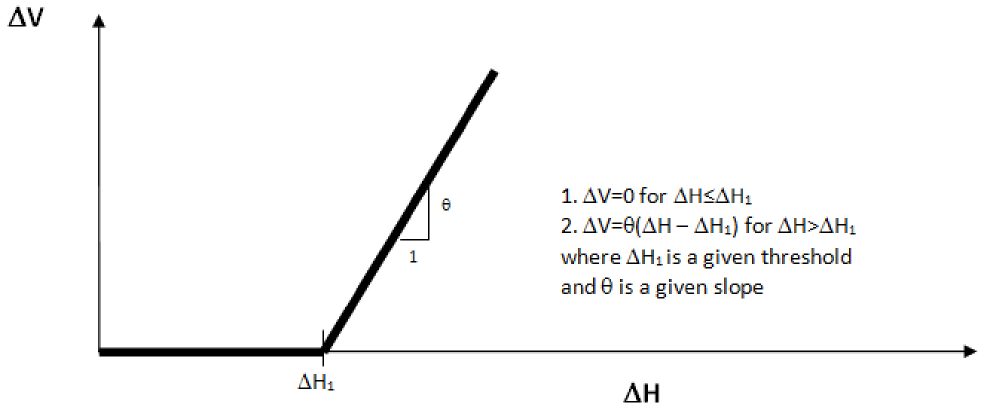
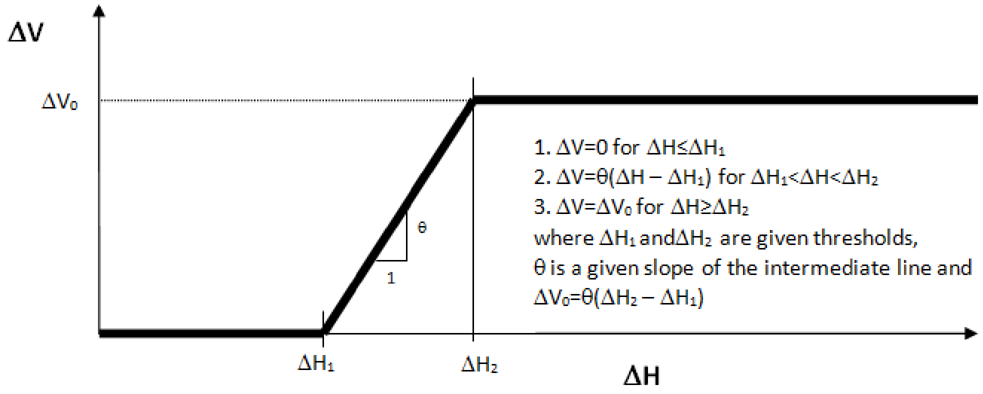


Figure 5-2: Idealised U-shaped relationship between daily mortality and average temperature taken from the literature on the epidemiology of heat: M_{min} is minimum daily mortality; I_{min1} and I_{min2} define a range for minimum-mortality temperature; β_{cold} and β_{hot} are cold and hot slopes (Curriero et al. 2002; McMichael et al. 2008; El-Zein et al. 2004)

relationship itself. For example, had our aim been to assess vulnerability at a certain point in the past and one had a way of measuring H4 directly rather than predicting it through I4, there would be no need to consider the non-linearity in question. Finally, the model assumes that H1 and H2 are intuitively linear—they hold a linear relationship to vulnerability—while H3 and H4 are intuitively non-linear, following the two-step function shown in Figure 5-3. That is to say that small differences in income and predicted excess mortality do NOT translate into differences in vulnerability (how small is *small* will be defined below); likewise, beyond a given threshold, bigger differences in income and excess mortality no longer translate into bigger differences in vulnerability. This model will be used in the results section to illustrate how SEVA-II can be employed to conduct vulnerability assessments.



a. Step-function



b. Two-step function

Figure 5-3: Fuzziness: non-linear relationships between difference in vulnerabilities ΔV and difference in indicators ΔH

It is now possible to express equation (3-29) of Chapter-3 in terms of harm criteria rather than indicators:

$$\vec{\mathbf{V_k}}(\mathbf{M}) = f_{ek}(H_{e1k}, H_{e2k}, H_{e3k}, \dots)\vec{\mathbf{e}} + f_{sk}(H_{s1k}, H_{s2k}, H_{s3k}, \dots)\vec{\mathbf{s}} + f_{ck}(H_{c1k}, H_{c2k}, H_{c3k}, \dots)\vec{\mathbf{a}} \tag{5-1}$$

where H_{dik} is either given or can be computed as a nonlinear function of a set of indicators I_{d1k}, I_{d2k}, I_{d3k}..... or the outcome of a complex mechanistic model, which may contain thresholds and tipping points, with a set of indicators as input:

$$H_{dik} = f_{dik}(I_{d1k}, I_{d2k}, I_{d3k}, \dots) \tag{5-2}$$

Hence, introducing harm allows, not only for non-linear relationships to be represented, but also for multiple interactions between indicators.

Starting from equation (5-1), which is now taken as fully representing the vulnerability of the system, the aggregation and ranking of vulnerabilities is conducted as follows. Without loss of generality it is assumed that the higher the value of the harm criterion the more vulnerable the SES. (However, it is possible to use positive counterparts of *harm* such as *resource* or *benefit*, and opposites of vulnerability such as *immunity* or *resilience*. A list of antonyms for the concepts used in the framework is given in Table 5-4). Also, for simplicity of notation, the dimension index d is dropped and H_{ik} instead of H_{dik} is used, and so on, with the understanding that any H_{ik} corresponds to a specific dimension of vulnerability.

Table 5-4: Vulnerability concepts and antonyms*

Negative	**Positive**
Vulnerability	Immunity or Resilience
Harm	*Resource or Benefit*
Exposure	Protection or In-exposure
Sensitivity	Insensitivity or Indifference
Adaptive Deficiency	Adaptive Capacity

*harm (benefit) acts as an analytical intermediary between vulnerability (immunity) and its three dimensions of exposure (protection), sensitivity (insensitivity) and adaptive deficiency (adaptive capacity)

Using the outranking concept of SEVA-I for each pair of SESs, three different categories of relative vulnerability are defined (representing the two-step function shown in Figure 5-3b):

1. b is indifferent to a according to harm criterion H_i if and only if $|H_{ib} - H_{ia}| \leq q_i$, where $q_i \leq 0$ is the *relative vulnerability indifference threshold for harm criterion* H_i;
2. b is strictly more vulnerable than a according to harm criterion H_i if and only if $H_{ib} - H_{ia} \geq p_i$, where $p_i \leq 0$ is the *relative vulnerability threshold for harm criterion* H_i ($p_i \leq q_i$);
3. b is weakly or proportionately more vulnerable than a according to harm criterion H_i if and only if $q_i < H_{ib} - H_{ia} < p_i$.

Note that q_i and p_i correspond to ΔH_1 and ΔH_2 in Figure 5-3a, respectively. The set of rules 1 to 3 express the fuzziness of the relationship between harm and vulnerability.

In order to cater for incommensurability or partial compensation between harm criteria, a fourth rule is introduced as follows:

4. b is at least as vulnerable as a, if there exists one criterion for which $H_{ib} - H_{ia} > v_i$, *regardless of the performances of a and b on all other harm criteria*, where $v_i \leq p_i$ is called *dominance threshold* for harm criterion H_i.

Hence v_i sets a limit beyond which a disparity in the values of harm criterion for 2 SESs is so great, that the resulting difference in vulnerability cannot be compensated for by reverse disparity in another harm criterion. In other words, compensation is either partial or completely absent.

q_i, p_i and v_i are collectively referred as *thresholds of difference* to emphasize that they provide a reference to disparities between harm criteria and not to the harm criteria themselves. Note that, under some circumstances, it is more convenient to define p_i, q_i and v_i as percentages, whereby the relationships shown above can be written in terms of the percent difference $(H_{ib} - H_{ia})/H_{ia}$ rather than the difference $H_{ib} - H_{ia}$. It is also possible to define v_i as a dominance threshold relative to the value of the criterion rather than the difference in values, in which case rule 4 can be stated as:

5. b is at least as vulnerable as a, if there exists one criterion for which $H_{ib} > v_i$ and $H_{ia} \leq v_i$, *regardless of the performances of a and b on all other harm criteria*, where $v_i \leq p_i$ is called *dominance threshold* for harm criterion H_i.

In this chapter, only the original definitions shown in rules 1 to 4 will be used. The values of each harm criterion for each SES are assembled in a vulnerability matrix (each row representing a harm criterion and each column representing an SES, see (Table 5-3). Converting the vulnerability matrix into a ranking of SESs according to their vulnerabilities to a climate change hazard can now be made using outranking algorithms of SEVA-I discussed in Chapter 4. However, concordance and discordance equations (4-3 and 4-4) now have to be modified by replacing indicator (I) with harm criteria, H (5-3 and 5-4).

Therefore, formulation of concordance matrix for each harm criterion H_i is defined by:

$$c_i(a,b) = \begin{cases} 0 & \text{if } H_{ib} - H_{ia} \geq p_i \\ \dfrac{p_i - (H_{ib} - H_{ia})}{p_i - q_i} & \text{if } q_i < H_{ib} - H_{ia} < p_i \\ 1 & \text{if } H_{ib} - H_{ia} \leq q_i \end{cases} \qquad 5\text{-}3$$

$c_i(a,b)$ is a measure of the truth of the statement that "a is at least as vulnerable as b according to harm criterion H_i". The discordance matrix for each harm criterion H_i is defined by:

$$d_i(a,b) = \begin{cases} 0 & \text{if } H_{ib} - H_{ia} \leq p_i \\ \dfrac{(H_{ib} - H_{ia}) - p_i}{v_i - p_i} & \text{if } p_i < H_{ib} - H_{ia} < v_i \\ 1 & \text{if } H_{ib} - H_{ia} \geq v_i \end{cases} \qquad 5\text{-}4$$

The statement "a is at least as vulnerable as b" (denoted aVb) is true provided:

iii. a "majority" of harm criteria supports it (concordance principle); and
iv. no single harm criterion vetoes it (discordance principle).

Remaining parts of the ranking exercise (e.g., building credibility matrix and distillation) follow SEVA-I, that has been discussed in Chapter 4 (equations 4-5 to 4-8).

5.5 Significance of Thresholds of Difference

Thresholds of difference now need to be defined in terms of harm criteria rather than indicators (see appendix Table A 6). These thresholds dictate the extent of intuitive non-linearity and compensation and are consistent with the concept of thresholds of difference for indicators that were developed in Chapter 4. SEVA-II distinguishes between eight possible types of harm criteria depending on the presence or not of deductive non-linearity, intuitive non-linearity and degrees of compensation and non-compensation (see Table 5-5). Note that, the existence of any partial or no compensation generates intuitive non-linearity; therefore, it is not possible to have partial compensation with intuitively linear harm criteria. As seen in Table 5-5, the 8 different types can be obtained by specifying different limit conditions of thresholds of difference and/or dependence of harm (H) on a set of indicators. These limit conditions control the building of concordance and discordance matrices, the two respective mechanisms for creating intuitive non-linearity and partial compensation. Figure 5-4 shows the concordance and discordance for the different types of harm criteria in SEVA-II.

Table 5-5: Thresholds of difference for various combinations of deductive nonlinearity, intuitive non-linearity and partial compensation (in all cases $q_i \leq p_i \leq v_i$)

	Intuitively Linear and Fully-Compensating	**Intuitively Non-Linear**		
		Full Compensation	**Full or Partial Compensation**	**Full, Partial or No Compensation**
Deductively Linear	**Type 1** H_{ik} $q_i=0$ $\max(H_{ik}-H_{ij})$ (k=1,n; j=1,n)$\leq p_i \leq v_i$	**Type 2** H_{ik} $q_i \geq \min\lvert H_{ik}-H_{ij}\rvert$ (k=1,n; j=1,n) $\max(H_{ik}-H_{ij})$ (k=1,n; j=1,n)$\leq p_i \leq v_i$	**Type 3** H_{ik} $q_i \geq 0$ $p_i < \max(H_{ik}-H_{ij})$(k=1,n; j=1,n)$\leq v_i$	**Type 4** H_{ik} $q_i \geq 0$ $p_i \geq 0$ $v_i \leq \max(H_{ik}-H_{ij})$(k=1,n; j=1,n)
Deductively Non-Linear	**Type 5** $H_i=f(I_1,I_2,\ldots)$ $q_i=0$ $\max(H_{ik}-H_{ij})$ (k=1,n; j=1,n)$\leq p_i \leq v_i$	**Type 6** $H_i=f(I_1,I_2,\ldots)$ $q_i \geq \min\lvert H_{ik}-H_{ij}\rvert$ (k=1,n; j=1,n) $\max(H_{ik}-H_{ij})$ (k=1,n; j=1,n)$\leq p_i \leq v_i$	**Type 7** $H_i=f(I_1,I_2,\ldots)$ $q_i \geq 0$ $p_i < \max(H_{ik}-H_{ij})$(k=1,n; j=1,n)$\leq v_i$	**Type 8** $H_i=f(I_1,I_2,\ldots)$ $q_i \geq 0$ $p_i \geq 0$ $p_i < v_i < \max(H_{ik}-H_{ij})$(k=1,n; j=1,n)

One of SEVA's (both SEVA-I and SEVA-II) strengths is that it does not require the conversion of harm criteria into a common scale. It is important to remember that the vulnerability matrix typically carries a collection of harm criteria of a very different nature and precision: continuous, discrete, ordinal and binary; climatic, physical, demographic and socio-economic. Clearly, no deductive arguments can be developed to guide aggregation of these criteria, ultimately because vulnerability is a social concept that is influenced by physical risk but not determined by it. Hence, the way harm criteria are combined to generate rankings ought to be influenced by normative judgements as well as 'hard' data that reflects exposure to risk. It is precisely through the thresholds of difference that such value judgements are systematically elicited in SEVA-I and SEVA-II at the data collection stage. For example, two measures of vulnerability in comparing two districts in a city may be the dollar value of likely damage to coastal infrastructures reflecting exposure to risk (harm criteria-1), and the percentage of population under 12 years of age (harm criteria-2) as a proxy for sensitivity or adaptive capacity. If one district is likely to sustain $30,000 less damage than another but has 20% more under 12 population, how do we determine which one is more vulnerable? In SEVA-II, through the thresholds of difference, the question is divided into 5 parts:

1. What is the importance of the dollar value of any likely damage relative to the percentage of under 12 population (reflected by relative importance factors w_1 and w_2)?
2. How significant is a difference of $30,000 (reflected by q_1 and p_1)?
3. How significant is a difference of 20% in the number of under 12 population (reflected by q_2 and p_2)?
4. Is there a threshold of difference in values of damage beyond which the difference in vulnerability between the two districts is considered decisive, regardless of their performances on other harm criteria (reflected by v_1)?
5. Is there a threshold of difference in the % of under 12 population beyond which the difference in vulnerability between the two districts is considered decisive, regardless of their performances on other harm criteria (reflected by v_2)?

Three observations can be made here. First, thresholds of difference and relative importance factors must emanate from some knowledge of the community under study and its values, and must be determined through a consultative process involving experts and stakeholders. Second, the approach allows some vagueness, expected to be present, in the stakeholders judgments. Third, the smaller the geographical scale under study, the more likely for the processes generating vulnerability to be well defined and for the thresholds of difference and relative importance factors to be faithful reflections of the community and its values. In other words, SEVA-II formalises an observation about vulnerability assessment that has already been made in the literature, namely that indicator based assessments are more likely to be meaningful at smaller rather than larger scales (Füssel 2007; Hinkel 2011).

Figure 5-5 shows the overall architecture of SEVA-II while Figure 5-6 depicts all the different steps in building a vulnerability model using the SEVA-II framework.

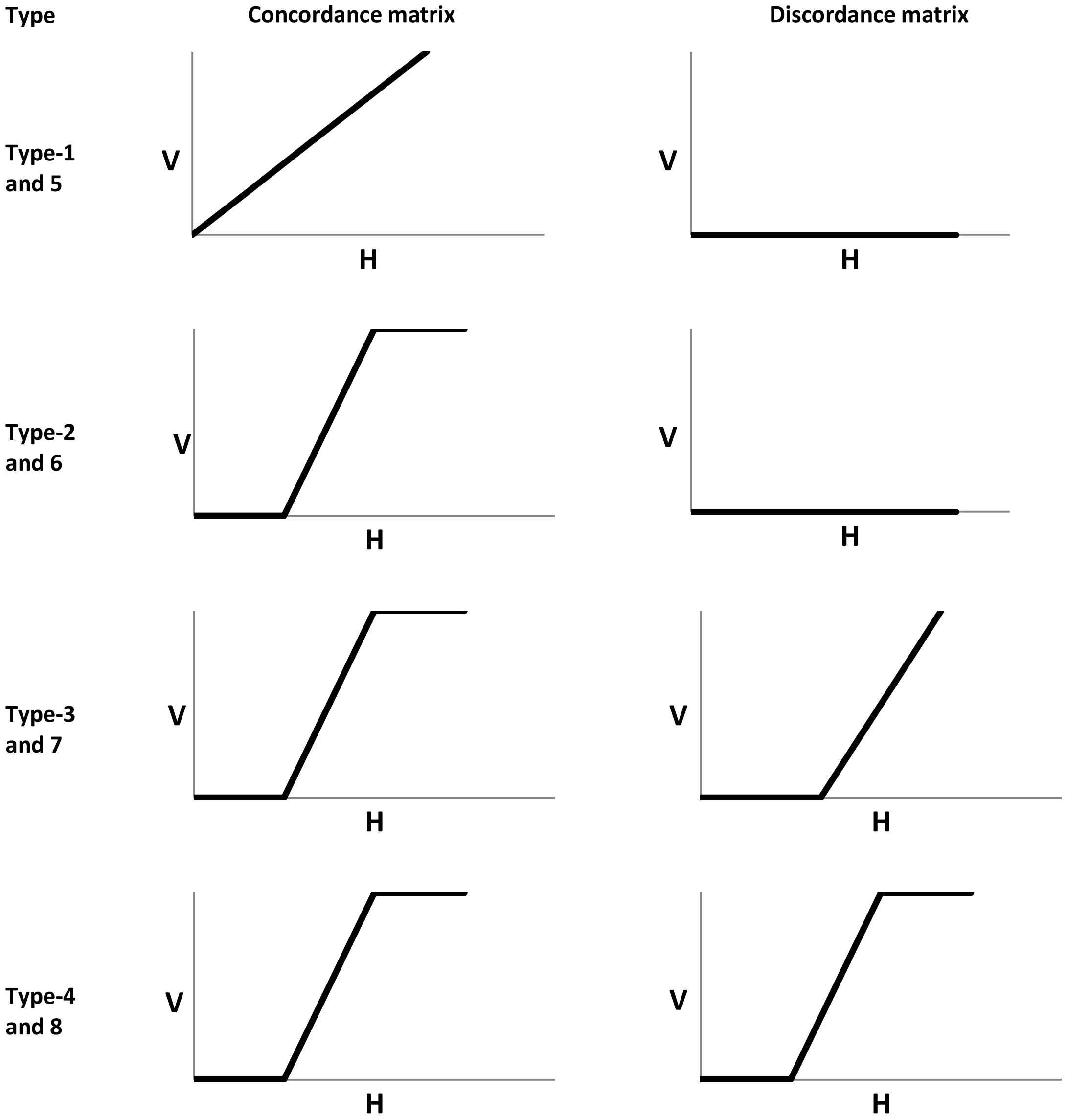


Figure 5-4: Definition of concordance and discordance in different types of harm criteria in SEVA-II

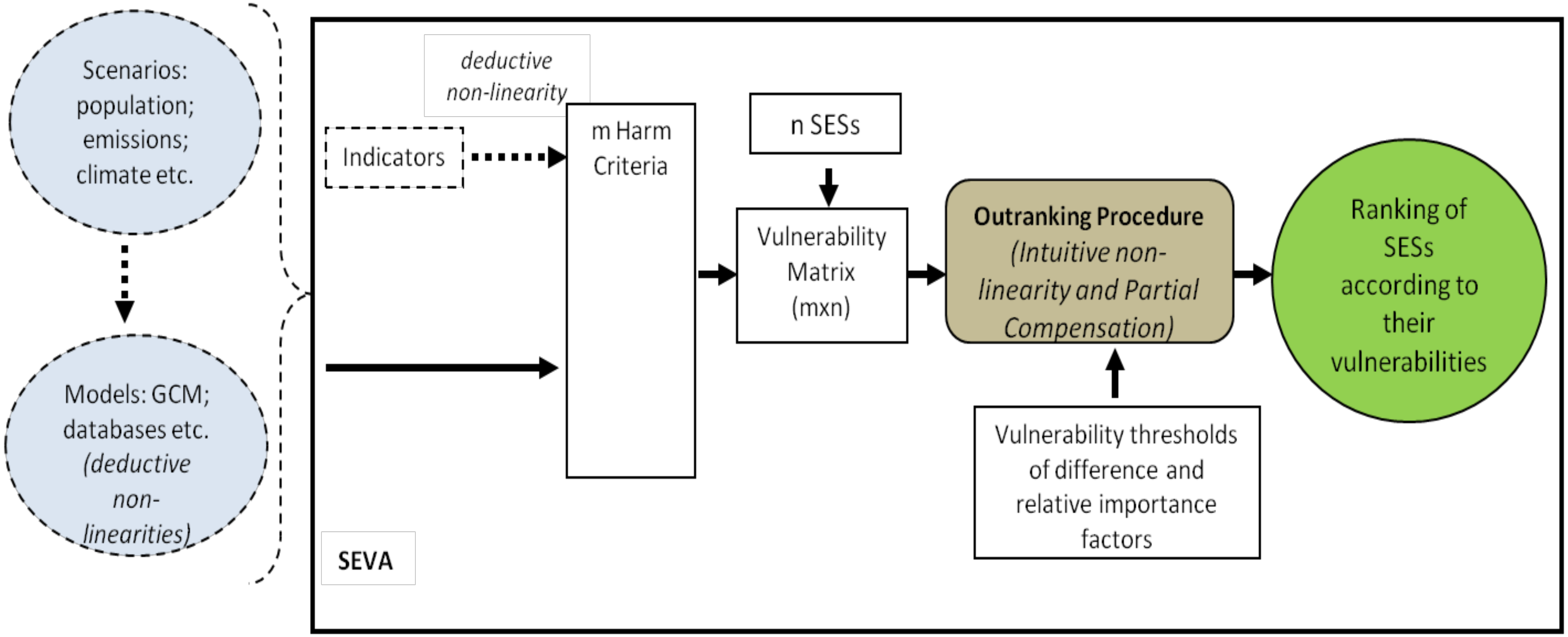


Figure 5-5: Overall architecture of SEVA-II

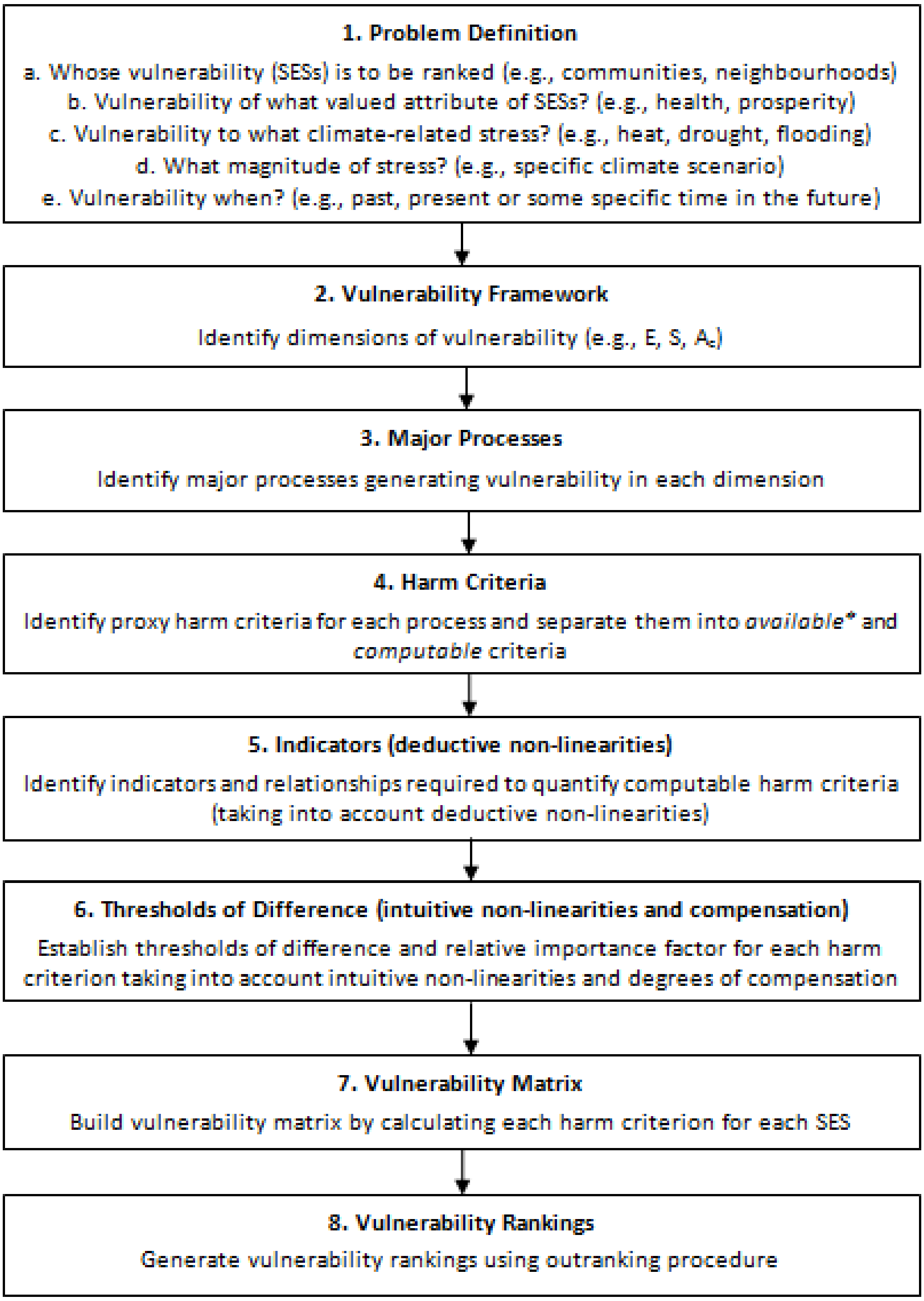


Figure 5-6: SEVA-II Step-by-Step Vulnerability Ranking Procedure

*available harm criteria are ones whose values for all the SESs under consideration can be found from available databases, or as output from climate or other models, without further computation.

5.6 An illustrative Example: Assessment of Vulnerability to Heat Stress using SEVA-II

Table 5-6 shows the results of SEVA-II analyses conducted on the model shown in Table 5-2 and Table 5-3. The SESs in this case are four hypothetical city districts of similar scales. Vulnerability of the well being of residents to the effects of temperature is assumed to be adequately reflected by the four harm criteria shown in Table 5-2. Starting from a scenario where all relationships are linear and full compensation between harm criteria is available (case 1), new scenarios are generated (cases 2 to 5) by gradually introducing different forms of intuitive and deductive non-linearity and partial compensation. This is done to illustrate the effects of different non-linearities on the rankings of vulnerabilities. Scores and votes in all 5 cases are the same. However, thresholds of differences are changed between cases. Case 5 represents the full non-linear model as presented in Table 5-2 and Table 5-3. In all analyses it is assumed that all four harm criteria have a relative importance factor of one. A SEVA-II analysis is conducted for each case to generate rankings for the four SESs. Although not shown here, in all cases, a large number of additional analyses have also been conducted to assess the sensitivity of the ranking outcomes to small changes (±5%) in harm criteria scores, thresholds and relative importance factors. The results generated by SEVA-II have been found to be robust.

It can be seen in Table 5-6 that in **case 1** where all the harm criteria are of type 1, SES3 is the most vulnerable district because it performs worst on all but one of the 4 harm criteria (median income). SES4 is found to be least vulnerable primarily because of its low percentages of over 65 and a built-up land cover. SES2 is more vulnerable than SES1 according to harm criteria 1 and 4, but vice versa judging by harm criteria 2 and 3. The analysis ranks them equally. In **case 2**, the type of H3 is changed from type 1 to type 2 by the introduction of an indifference threshold of q_3=$90. This change cancels the mean income advantage of SES4 over SES1 because the difference in median income between the two is $80, now considered insignificant as an indicator of difference in vulnerability, because it is less than q_3. Likewise, the advantage of SES1 over SES2 derived from harm criterion 3 is now inconsequential because the difference is $75. Hence, the overall effect of introducing the indifference

Table 5-6: Five sample scenarios and effects of nonlinearity and degrees of compensation on rankings using SEVA-II (rankings: 1:most vulnerable; 4:least vulnerable; all thresholds of difference correspond to harm criteria not indicators; cases 2, 3 and 4 are modifications of case 1 with the change highlighted in bold characters; in all intuitively linear relationship q_i=0 and p_i=max(H_{ik}-H_{ij}), k=1,n; j=1,n)

Cases	Description	Harm	Units	Indicator	Dir [a]	Type [b]	q_i	p_i	v_i	w_i	SES1	SES2	SES3	SES4
Case 1	All harm criteria are intuitively and deductively linear and fully-compensating[3]	H_1	%	N/A	↑	1	0	8	N/A	1	35%	29%	38%	25%
		H_2	%	N/A	↑	1	0	14	N/A	1	43%	48%	52%	38%
		H_3	$	N/A	↓	1	0	200	N/A	1	$875	$800	$1000	$955
		H_4	counts	I_4	↑	1	0	75	N/A	1	87	50	125	113
						Vulnerability Ranking					**2**	**2**	**1**	**4**
Case 2	Intuitive non-linearity present only for H_3 with full compensation between all harm criteria	H_1	%	N/A	↑	1	0	8	N/A	1	35%	29%	38%	25%
		H_2	%	N/A	↑	1	0	14	N/A	1	43%	48%	52%	38%
		H_3	**$**	**N/A**	**↓**	**2**	**90**	200	**N/A**	**1**	$875	$800	$1000	$955
		H_4	counts	I_4	↑	1	0	75	N/A	1	87	50	125	113
						Vulnerability Ranking					**3**	**2**	**1**	**3**
Case 3	Intuitive non-linearity and partial compensation present only for H_3	H_1	%	N/A	↑	1	0	8	N/A	1	35%	29%	38%	25%
		H_2	%	N/A	↑	1	0	14	N/A	1	43%	48%	52%	38%
		H_3	**$**	**N/A**	**↓**	**4**	**90**	**100**	**110**	**1**	$875	$800	$1000	$955
		H_4	counts	I_4	↑	1	0	75	N/A	1	87	50	125	113
						Vulnerability Ranking					**1**	**2**	**2**	**4**
Case 4	Deductive non-linearity introduced for H_4	H_1	%	N/A	↑	1	0	8	N/A	1	35%	29%	38%	25%
		H_2	%	N/A	↑	1	0	14	N/A	1	43%	48%	52%	38%
		H_3	$	N/A	↓	1	0	200	N/A	1	$875	$800	$1000	$955
		H_4	**counts**	**I_4**	**↑**	**5**	**0**	**25**	**N/A**	**1**	**100**	**107**	**125**	**113**
						Vulnerability Ranking					**3**	**2**	**1**	**4**
Case 5	Full model of Table 2 with all relevant non-linearities and degrees of compensation present	H_1	%	N/A	↑	1	0	8	N/A	1	35%	29%	38%	25%
		H_2	%	N/A	↑	1	0	14	N/A	1	43%	48%	52%	38%
		H_3	**$**	**N/A**	**↓**	**4**	**90**	**100**	**110**	**1**	$875	$800	$1000	$955
		H_4	**counts**	**I_4**	**↑**	**8**	**15**	**20**	**25**	**1**	**100**	**107**	**125**	**113**
						Vulnerability Ranking					**2**	**1**	**3**	**4**

a: Dir= Direction: ≤(≤) indicates that vulnerability increases (decreases) with increasing harm

b: Type refers to the different relationship shown in Table 5-5 threshold for H_3 is that SES1 and SES4 are now ranked equally in third place. **Case 3** shows the effect of introducing partial compensation for H_3 (type 4), with p_3=\$100 and v_3=\$110. Hence, the advantage that SES3 carries over SES2 in terms of median income has become decisive: SES3 can no longer be more vulnerable than SES1, regardless of its performance on other harm criteria. Note that the newly introduced dominance threshold also affects the comparison between SES2 and SES4, with SES4 carrying a decisive income advantage. However, in this case SES2 had already been found to be more vulnerable than SES4 in case 1. Overall, in case 3, SES1 is found to be most vulnerable and SES4 least. The non-linear relationship between mortality and temperature is introduced into the model in **case 4** by making H_4 as type 5**.** It is clear that a linear relationship between temperature and mortality (with an assumption of H_4 being type 1, in case 1) underestimates mortality for SES1 and SES2. Introducing the non-linear relationship hence leads to poorer performance of both SES1 and SES2 on harm criterion H_4, relative to case 1, with average daily mortality increasing from 87 and 50 to 100 and 107, respectively. In other words, SES2 is much worse off in case 4 compared to case 1, with its average mortality increasing by 67, while that of SES1 increases by 13. The introduction of this non-linearity does not change first and last ranks but it does push down SES3 to third rank. In **case 5,** all non-linearities and degrees of compensation are present. SES2 is found to be the most vulnerable district and SES4 the least. Note that the introduction of a relative vulnerability threshold p_4 for H_4, affects the analysis by capping the extent to which a difference in values of the harm criterion for two SESs translates into a difference in vulnerability.

Next, the effects on the analyses outcomes of a 100% change in the relative importance factors are assessed. To this end, four additional analyses for case 5 were conducted, after changing one relative importance factor from 1 or 2 each time, while keeping all the others constant at 1. All rankings remained the same in all four additional analyses and, therefore the results are not shown here.

Hence, the illustrative example has demonstrated the following:

1. the proposed SEVA-II framework allows a combination of non-linear and partial compensation effects to be incorporated in vulnerability assessments;
2. non-linearity and partial compensation do have an effect on the rankings of vulnerability;

3. the SEVA-II assessment appears to be robust to small changes in scores and thresholds up to 100% changes in relative importance factors.

It is clear from the above discussion that SEVA-II offers analytical added-value in climate change vulnerability assessments, relative to more conventional approaches based on multiple-attribute utility theory (MAUT).

5.7 Conclusions

Assessments of vulnerability to climate change can help in developing adaptation policies. In particular, sound resource allocation may require the ranking of different socio-ecological systems according to the vulnerability of a valued attribute to a climate related stress. Given the multi-dimensional nature of vulnerability as a construct reflecting physical and socio-economic components of risk, assessments inevitably require aggregation of data from different knowledge domains. This chapter has expanded SEVA-I and developed a new formulation of an outranking framework, SEVA-II which achieves two objectives:

a. It incorporates different forms of non-linearity and degrees of compensation that are obtained in vulnerability assessments,
b. It incorporates a methodology based on outranking methods to rank the vulnerabilities of a set of comparable socio-ecological systems, while taking into account a heterogeneous set of indicators which are not necessarily commensurate with each other.

The framework is flexible enough to accommodate a wide range of data types and, as stated earlier, rankings generated by the framework are robust. A useful extension of this work is the application of the framework to a real life vulnerability assessment exercise. This would make it possible to assess the ease with which the framework can be implemented, especially in relation to establishing thresholds of difference. Chapter 7 and 8 will report such an application of SEVA-II for assessing vulnerability to the sea level rise of a set of coastal communities in Sydney, and also will discuss lessons learnt from the exercise.

The next chapter will scrutinize the possible impediments of conducting an IBVA for assessing vulnerability of infrastructure to sea level rise (SLR) specifically the non-linear interaction of multiple infrastructure systems and embed a system dynamics (SD) model, as a specific form of deductive non-linearity within SEVA-II.

Chapter 6

An infrastructure interdependency model for IBVA using a system dynamics approach

6.1 Synopsis

Some methodological challenges of IBVA have been identified and addressed through a new outranking based mathematical formulation and framework (SEVA-II). This chapter conducts two simultaneous developments: First, it briefly discusses different forms of infrastructure systems and their interdependency at a local scale and develops a system dynamics model to represent such interdependencies. Second, it demonstrates how this model can be used within an IBVA framework to assess the vulnerability of infrastructure systems to sea level rise and its associated processes (e.g., increased flooding during a storm event).

6.2 Introduction

It has been estimated that the global mean sea level may rise between 0.18m and 0.59m by 2100 (Meehl et al. 2007) with recent studies predicting even higher levels (e.g., 0.5m to 1.4m by 2100 according to (Rahmstorf 2007). Of the 63 most populated cities of the world (with 5 million or more inhabitants in 2011), 72 per cent are located on or near the coast (United Nations 2012). SLR may accelerate the erosion of coastal margins, threatening surrounding land, property, and infrastructures. Rising seas may also lead to an increase in coastal flooding, either by providing a higher base and therefore increasing the height of storm surges, or by acting as a higher seaward barrier restricting the escape of flood waters caused by excessive runoff (Walsh et al.

2004). Therefore, many coastal councils around the world have included climate change adaptation as part of long-term infrastructure and environmental planning.

Coastal Local Government Areas (LGAs) usually harbour infrastructure systems, or parts thereof, that provide vital services to population centres, such as transportation, energy, telecommunication, water, and solid and liquid waste disposal (Jacob et al. 2000; Rinaldi 2004). Often individual components in these systems are highly interdependent and any disruption of services to one component can impact other components, propagate through the whole system and produce a compound effect on users. This phenomenon is well known in the literature as infrastructure interdependency (Rinaldi 2004; Rinaldi et al. 2001; Min et al. 2007; UNEP 2001). In addition, the life spans of some of these infrastructures are long enough for SLR and associated processes to affect them (Walsh et al. 2004). Therefore, the development of adaptation actions for infrastructures by quantifying risk and vulnerability is crucial.

The infrastructure interdependency literature is characterised by studies conducted mainly from a national security perspective which aims to identify critical infrastructure at regional and national, rather than local, scales (Pederson et al. 2006; Min et al. 2007; Rinaldi 2004; Rinaldi et al. 2001; Briguglio 1995). One approach, prevalent in the climate change impact assessment literature is termed integrated assessments (IA) and aims to find the cross sectoral (water resource, transport, energy demand etc) impact of climate change. There have been several in-depth IAs conducted in urban areas (e.g., (GovernmentOfSamoa 2013; WorldBank 2010; ICCAI 2011; Konidari and Mavrakis 2007; Ringius et al. 1998; Greening and Bernow 2004; Vincent 2004). As an example, Vincent (2004) identified climate impacts on multiple sectors (e.g., health, water resources, transport, etc) of the Boston metropolitan area and assessed how the impact on one sector can translate into impact on another. Greening and Bernow (2004) identified cross sectoral interactions between four major sectors (agriculture, bio-diversity, coasts and floodplains, and water resources) driving change in the landscape in East Anglia, UK. However, these studies were mostly conducted at a city scale and identified broader cross sectoral impacts on infrastructure systems (e.g., a summer heat wave increases the energy demand and cooling water demand of a city which might cause an energy shortage in the transport sector). Such an approach is important for higher-level adaptation decision-making.

At local scales it can provide useful information to local councils, but it is not sufficient because the decision-making contexts at these two geographic scales are different. Local council need to:

a) specifically identify the public infrastructure systems and components that are at risk (e.g., a specific road or an electrical sub-station may be very close to the coast and has the potential to be damaged by long term erosion or increased coastal flooding).

and,

b) understand how disruption of those at-risk public infrastructure systems can affect its residents.

Such information can help a council in identifying its critical infrastructures and design adaptation action plans to safeguard them. Very little has been done so far in the literature to model service inter-dependency among infrastructure systems at a local council level, and even less to identify how disruption of some public infrastructure during a natural disaster event might affect households. This chapter is mainly concerned with this problem and aims to develop a system dynamics model that can capture such complex infrastructure service dependencies and measure the overall performance of the infrastructure network of a council during a disaster event.

The second aim of this chapter is to show how an SD model can be used within an IBVA framework to capture deductive non-linearities of an infrastructure system. In this regard, an IBVA framework has been developed specifically for the vulnerability of infrastructure and its users to SLR by embedding the developed system dynamics model in the SEVA-II mathematical formulation (which was developed in the previous chapter).

6.3 Development of a system dynamics model (SEVA-SD)

The system dynamics (SD) model proposed in the following section is a general interdependency model for the infrastructure systems of any SES exposed to a hazard. In the final section of this chapter the SD model is applied to the coastal infrastructure systems subjected to sea level rise.

6.3.1 Objectives

Sydney Environmental Vulnerability Assessment using System Dynamics (SEVA-SD) was developed with an objective of measuring the system performance (e.g., performance of water supply system, wastewater transport, etc) of a council during a possible disaster scenario (e.g., increased coastal flooding due to SLR). The performance of such an infrastructure system is dynamic, i.e. it can change over time. SD concepts were used to attain two objectives:

a) identify the effects of the failure of one infrastructure component as they propagate through the system(s) and
b) measure the performance of the infrastructure components over time.

The first objective can be achieved by modelling different nodes of a given infrastructure system and identifying their linkages and dependencies (see Figure 6-1). The second objective can be achieved by using the system dynamics concepts of stock and flow. The following sections define urban infrastructure systems and their dependencies at a local scale. Here local scale refers to the geographical extent of the analysis and in this research, it is considered to be the lowest level of administrative boundary within an urban context (e.g., council, county); the Australian term Local Government Area (LGA) is employed.

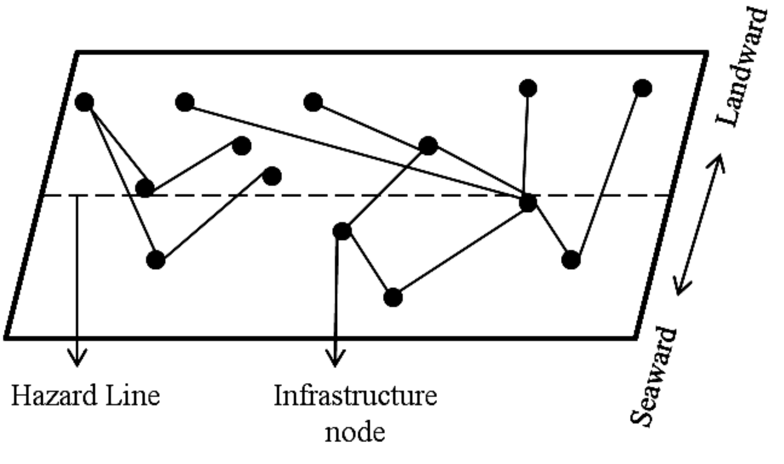


Figure 6-1: Schematic representation of infrastructure interdependency concept in the context of SLR

6.3.2 Infrastructure interdependency at a local scale

6.3.2.1 Urban infrastructure systems

A local council houses multiple infrastructure systems to serve its residents. Table **6-1** shows some examples of that. However, this table is not a complete representation of the infrastructure systems relevant to an LGA and it can be expanded to include other infrastructure systems such as natural gas supply systems, health care infrastructures, and emergency response services, etc. SEVA-SD can model any number of infrastructure systems. Each of these services (sewerage, water supply, and roads, etc) rely on multiple infrastructure components (e.g., water mains, rising mains, pipe networks, pumping stations, etc) to function. Following convention, these individual components are referred to as *"infrastructure nodes"*, a set of connected nodes providing a service as an *"infrastructure system"* (e.g., water supply infrastructure system), and multiple systems (e.g., water supply, power supply, transportation etc) as *"infrastructure network"* (Rinaldi et al. 2001; Pederson et al. 2006).

Table 6-1: Some examples of infrastructure systems and components

Examples of infrastructure system	Examples of infrastructure components (relevant for a local council)
Electricity supply	Substation, distribution network
Water treatment and supply	Treatment plant, water mains, trunk mains, pipe networks
Waste water transport	Pumping station, gravity main, rising main
Telecommunication (e.g., cellular and land phones, internet)	Telecom base stations, towers, transmission stations, underground fibre optics cable
Road network	Roads, traffic control systems

6.3.2.2 Dependency and interdependency of the infrastructure

An infrastructure node is said to be *dependent*, if its serviceability (i.e. its ability to fulfil its function) depends on that of another infrastructure node within the same infrastructure system. As an example, the serviceability of a downstream water main depends on its neighbouring upstream water main. On the other hand, if such a dependency exists between two nodes from a different infrastructure system (e.g., power supply from one specific station influencing the serviceability of a connected water pump), it is called *interdependency* (Figure 6-4).

6.3.2.3 System boundary and scale

A given infrastructure system (e.g., water supply system) of a coastal council (LGA) may contain some nodes that are far away from the coast or even outside the geographical boundary of the LGA but are an essential part of the whole system (e.g., water reservoir dams may be located outside the boundary of the council). Figure 6-2 shows a diagram of the concept using the example of water supply system. A similar demonstration is possible for other systems (e.g., electricity used in the LGA might be produced away from the coast). This model (SEVA-SD) is concerned with the disruption of performance of infrastructure nodes located at or near the coast due to climatic stresses that are associated with SLR on the coast of the given LGA only (dotted line in Figure 6-2). Performance reduction of the system due to any disruption of upstream nodes (e.g., nodes located outside the boundary of the LGA) due to any given stresses (associated with SLR or not) are not considered here. For example, a reduction in electricity services delivered to the LGA as a result of disruption to electricity production system upstream of the LGA, is not captured by this model. This is justified by the overall objective of the model: to aid in identifying adaptation measures to be undertaken by the local council, and upstream systems do not usually fall within the jurisdiction of the local council. However, the boundaries of the model, thus defined, do impose a limitation on its scope, since it cannot capture local effects of concurrent disruptions to systems located at the beach (within its boundary) and those away from the coast (outside the boundary).

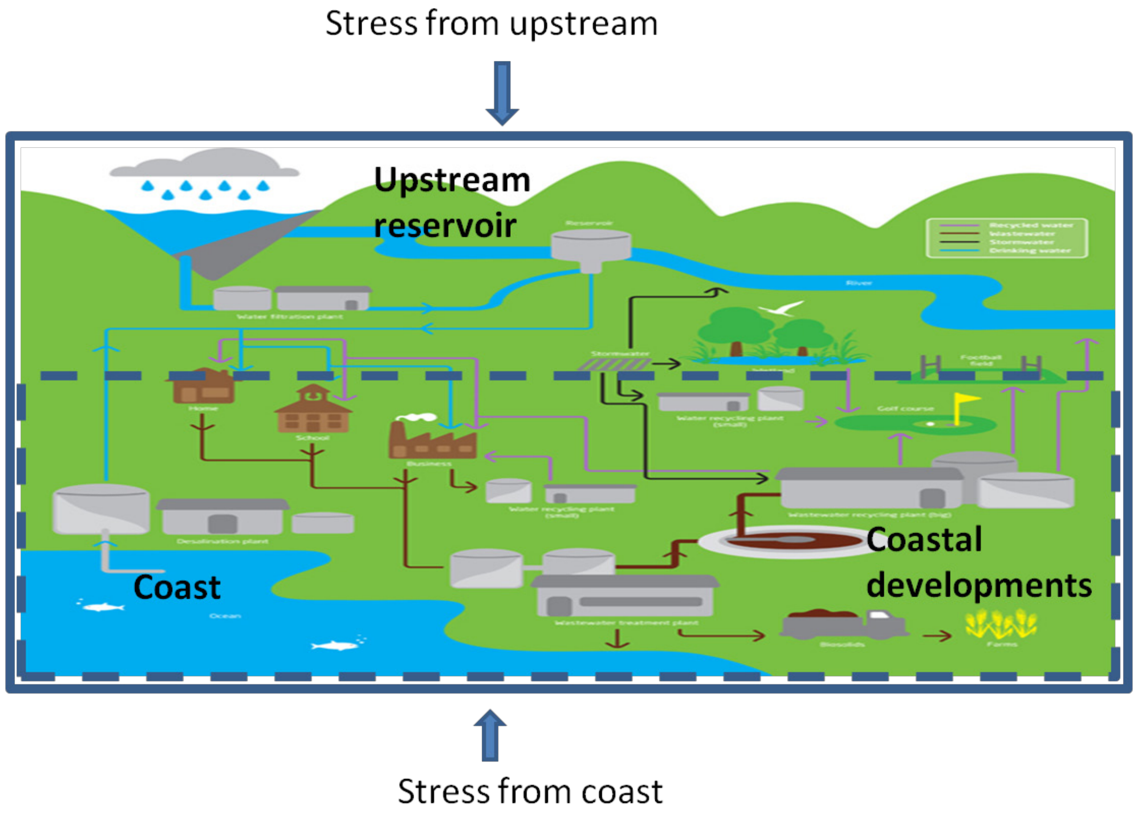


Figure 6-2: System boundary (example for water supply system)

6.3.3 Classification of dependencies and interdependencies

Four types of infrastructure interdependencies and dependencies were identified by Rinaldi et al. (2001): physical (output of one node is an input to another), cyber (infrastructures are connected via information links), geographic (possibility of disruption due to proximity of location), and logical (dependent on factors related to human decisions and actions). It is possible to incorporate all four concepts but, in this thesis, only physical interdependencies and dependencies are considered.

6.4 Modelling interdependency using system dynamics

System Dynamics has been widely used to model the dynamic behaviour of a complex system by simulating complex feedback systems. Stocks (the accumulation of resources in a system), flows (the rates of change that alter those resources), controls (variable that control the flow) and feedback are the central concepts in this methodology. Min et al. (2007) argued that SD simulations can offer insights into important causes and effects that may result in a better understanding of the dynamic and evolutionary behaviour of a system. Other modeling approaches such as agent-based or Bayesian network approach can also be considered for modeling interdependency. However, use of these approaches will require a greater detail of data, which might be difficult to obtain.

6.4.1 Model structure

For system dynamics modelling, the language used for building SEVA-SD is STELLA from “isee systems”. A STELLA computer model consists of three “layers” (Figure 6-3). The “top” layer is a map containing the input and output devices (graph, tables, etc) that are designed to make the model easy to use. The model itself is developed in the “middle layer” which contains icons for stocks and flows, and the connections between them. The initial conditions, parameter values, and functional relationships are specified within each of these icons and listed in the “bottom layer”. This layer contains a set of solution algorithms to solve equations simultaneously for each period of time, and to carry over values for stocks, flows etc, from one period of time to the next.

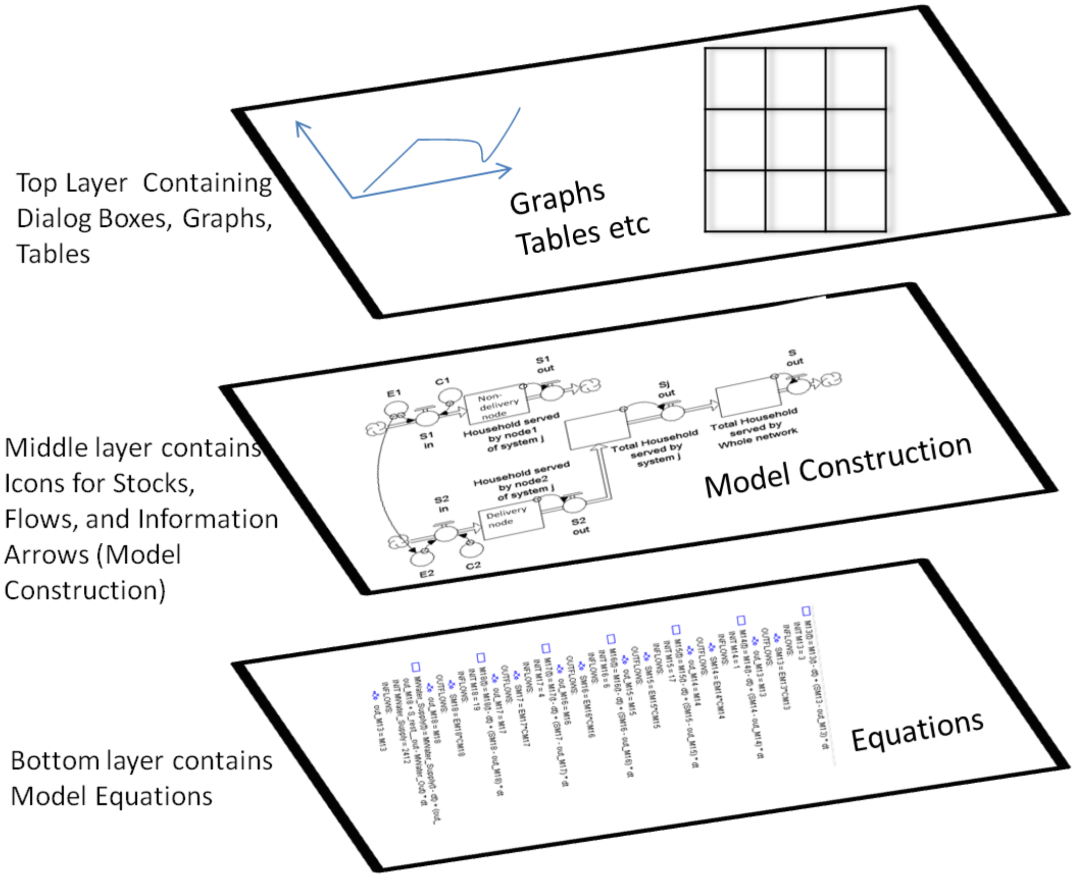


Figure 6-3: STELLA model structure for SEVA-SD

6.4.2 Conceptual model

Modelling and conceptualization of urban infrastructure systems using SD concepts are conducted through two diagrams: (i) causal-loop diagrams, and (ii) stock-and-flow diagrams. Figure 6-4 is a causal loop diagram that shows the concept of higher levels of interdependency (among systems). Stock and flow diagrams are developed in the following sections to model the dependency between nodes both within and across systems.

6.4.3 Causal loop diagram

Figure 6-4 shows a diagram of interdependencies which, though not universal, is typical of coastal infrastructure systems. The assumption being made here is that the entire urban infrastructure system delivers its service to buildings. This assumption is directly true for most of the systems (e.g., power supply, water supply, sewerage, telecommunication etc) and indirectly true for the rest (e.g., roads, rain and storm water system, etc). Although indirectly linked systems such as roads and storm water systems do not serve buildings directly, one of their main objectives is to enhance urban facilities for the population living in the buildings. Physical interdependency (the output of one infrastructure influencing the service of another) is evident in all the links from the power supply with the systems that serve buildings directly (e.g., water supply, sewerage, telecommunication, etc). On the other hand, roads often house components of other infrastructure (e.g., water and wastewater pipes, power

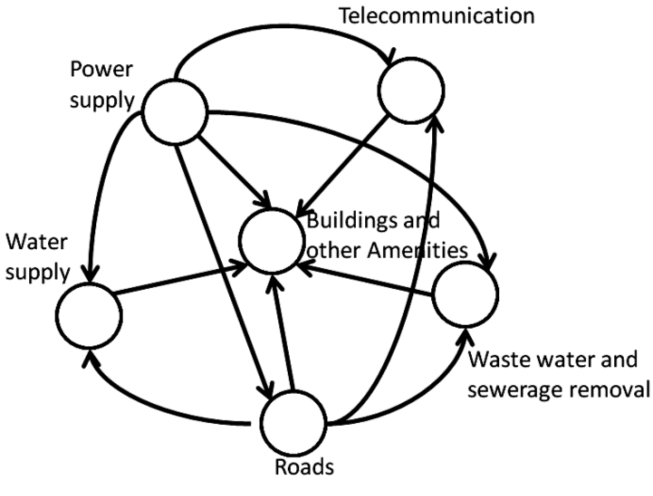


Figure 6-4: Infrastructure inter-dependency

cables) and therefore the latter are geographically dependent on roads. As mentioned before, the SD model to be developed in the following section is concerned with physical interdependency only, hence it can measure the performance of the systems that serves buildings directly (e.g., water supply, sewerage, power supply, telecom etc).

Two sources of complexity are evident here. The first is obviously the need to clearly articulate dependencies and interdependencies in order to simulate the overall performance of the system. The second is to do with the fact that the performance of each system with different types of dependencies and interdependencies is measured by incommensurable variables which are therefore hard to compare. As an example, the serviceability measure of a physically dependent systems (e.g., a water supply system) can be the number of buildings it serves at a certain point in time. However, such a measure of performance is not useful for a geographically dependent system such as road networks which do not serve buildings directly. This is because, as mentioned before, traffic generated by a road is composed of both direct use (local residential/commercial building access) and indirect use (non-residential traffic). Therefore, comparing performance measures of systems becomes a problem of incommensurability. An SD model integrated within an outranking SEVA framework addresses both issues.

The following sections describe the development of SEVA-SD using the stock and flow diagrams.

6.4.4 Stock and flow diagram

STELLA was used to build the conceptual framework of the stock and flow diagram. Here the basic unit of analysis is the number of households served, although the total number of the population can also be used. The service provider of the infrastructure (e.g., water supply authority) can usually supply this data.

6.4.4.1 Problem definition

The fluctuation of services can be measured by comparing between a No Stress (NS) scenario (e.g., baseline of no disruption) and an Under Stress (US) scenario (e.g., when the system loses one or more of its nodes). Which nodes lose some or all of their functionality is clearly related to the nature and magnitude of the hazard. The maximum difference in population served between these scenarios over a period of time for a given SES will be calculated as the variable H_{max}. This variable represents the sensitivity of an infrastructure network under stress and can be used as a harm criterion for a sea level rise IBVA model. For an example of such a model please see the following chapter which develops an IBVA model for the Shoalhaven council and uses H_{max} to measure the performance of Shoalhaven water supply and sewerage infrastructure network while under stress.

The following assumptions are made in the model:

a) under a no-stress scenario the number of households served per unit of time for the whole system is constant (hence, ignoring routine technical difficulties that might cause fluctuation in this number).
b) the adaptive capacity is measured by the differential ability of the Council to repair and restore different infrastructure systems under stress.

6.4.4.2 Model: general equation to measure system performance

This section describes the development of a general equation to measure an infrastructure node's performance at any given time taking into account dependencies and interdependencies.

If m infrastructure systems (e.g., water supply, power supply, wastewater transport) are physically interdependent and have comparable measures of performance (e.g., number of households served), then it is aimed to measure such performance over a period of time using an SD concept (Tonmoy and El-Zein 2013b).

The number of households served by a specific infrastructure node is considered as a flow that accumulates in a stock (for each infrastructure node i). The rate of this flow is the number of households served per unit of time. The flow is regulated by two control variables applied to each node: capacity and efficiency (Figure 6-5). Capacity refers to the number of households node i is designed to serve and efficiency is the degree to which the node is able to deliver its service at the design

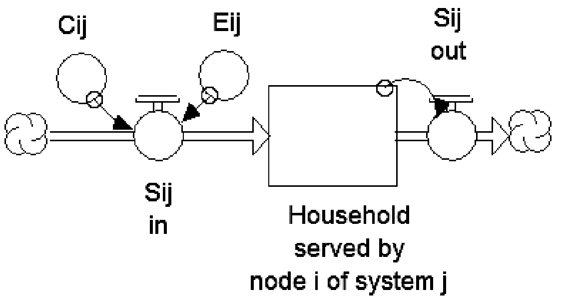


Figure 6-5: SD model for a single node i of system j

capacity.The capacity of a node is often constant as the infrastructure is designed to serve a specific unit (e.g., gallons of water supply, KW of power supply etc) with an objective to serve a specific number of households. Efficiency, on the other hand is not, and may be affected by the stress under consideration. Therefore, the serviceability of a node is time-dependent and can be described by:

$$S_{ij}(t) = C_{ij} * E_{ij}(t) \tag{6-1}$$

where S_{ij} is the serviceability of node i of system j, i.e. the number of households served at a given point in time; C_{ij} is the design capacity of node i of system j; E_{ij} is the efficiency of node i in system j defined as the degree to which the node is able to deliver its service at the design capacity ($0 \leq E_{ij} \leq 1$, where $E_{ij} = 0$ for complete failure and $E_{ij} = 1$ for full function).

If any physical dependency between nodes is present, a distinction is made between node efficiency as determined by its own physical integrity ($E_{ij}(t)$) and the overall efficiency of the node as determined by its own physical integrity AND, the efficiencies of its mother nodes $\bar{E}_{ij}(t)$ (see Figure 6-6). Here, mother nodes refer to the nodes that influence the performance of a given node through service dependency. Hence:

$$\bar{E}_{ij}(t) = E_{ij} \prod_{k=1\ (k \neq i)}^{N_n} \{[\bar{E}_{kj}(t) - 1]D_{ki} + 1\} \tag{6-2}$$

where N_n is the total number of nodes in the entire network; D_{ki} is the degree of dependence of node i on node k ($0 \leq D_{ki} \leq 1$; D_{ki}=0: no dependence; D_{ki}=1: complete dependence). Note that the term inside multiplication operator of equation 6-2 is 1 if

D_{ki}=0 (no dependence) and $\bar{E}_{kj}(t)$ if D_{ki}=1 (complete dependence). (A mother node k for node i is one for which D_{ki}>0).

Clearly, the overall efficiency of the node must be used in equation (6-1) rather than its efficiency, and therefore the general equation for the serviceability of any node i of a system j at any point in time t, taking dependencies into account, is as follows:

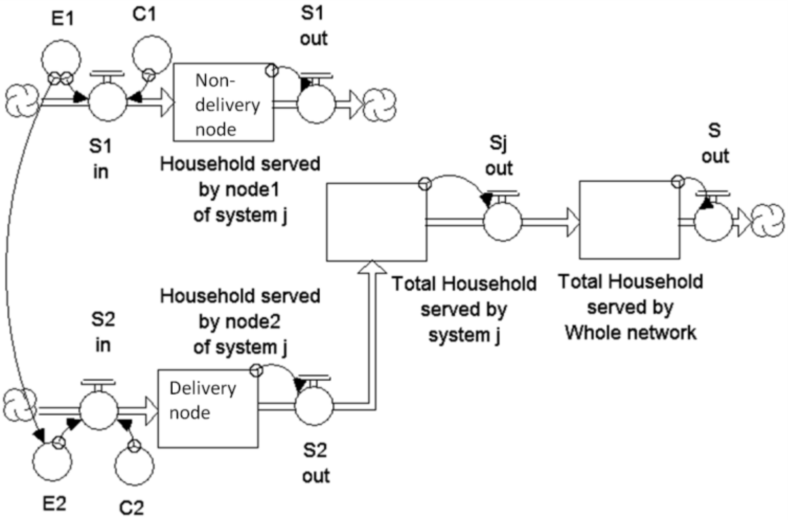


Figure 6-6: Interdependency of SEVA-SD

$$S_{ij}(t) = C_{ij}E_{ij} \prod_{k=1\ (k\neq i)}^{N_n} \{[\bar{E}_{kj}(t) - 1]D_{ki} + 1\} \qquad \textbf{6-3}$$

Equation (6-3) may conceivably be nested (i.e. two nodes are directly or indirectly mutually dependent) in which case an iterative scheme would be needed to evaluate $S_{ij}(t)$.

Now, the direction of the flow of the service (to the households or from the households) varies among infrastructure systems. As an example, water supply system has a service flow that is directed from water source (treatment plant) to households. On the other hand, sewerage system's service flow direction is the opposite (e.g., it transports household produced sewerage to an ocean or river outlet through a pump station). Nodes that are at the end of the service flow path are called delivery or system boundary nodes (S_{ij})d. The overall system serviceability is the summation of the serviceability of all the system boundary or delivery nodes:

$$S_j(t) = \sum_{i=1}^{n_d} (S_{ij}\,(t))_d \qquad \textbf{6-4}$$

where n_d is the number of system boundary nodes in a system. Finally, the serviceability of the whole infrastructure network can be measured by:

$$S(t) = \sum_{i=1}^{m} S_j\,(t) \qquad \textbf{6-5}$$

(m, defined earlier, is the number of systems in the network).

6.4.4.3 Measuring system performance under stress (US)

Using equations 6-1 to 6-5 it is now possible to measure the serviceability of an infrastructure system (e.g., the number of household it serves) at any given time. As per the model assumption, at its full efficiency (i.e. under no stress, NS), the serviceability of any node is constant at S_{NS}. Let’s assume that a storm event affects the infrastructure network of an SES under consideration. The fluctuation in serviceability is given by:

$$H(t) = S_{NS} - S(t) \qquad \textbf{6-6}$$

It is now possible to measure the sensitivity of the infrastructure network of the SES as H_{max}, the *maximum equivalent number of households* experiencing a single service interruption at any point in time in the period T_R, between the beginning of the event and the point in time at which all services have been restored to full baseline capacity (see Figure 6-7). It is also possible to measure the sensitivity of the infrastructure system through H_{av} (equation **6-7**).

$$H_{av} = \frac{1}{T_R} \int_0^{T_R} H(t)dt \qquad \textbf{6-7}$$

In this case, sensitivity is measured as the *average equivalent number of households* experiencing interruption (shaded area of the curve in Figure 6-7, normalized relative to T_R). In the reminder of the thesis, H_{max} will be used rather than H_{av}.

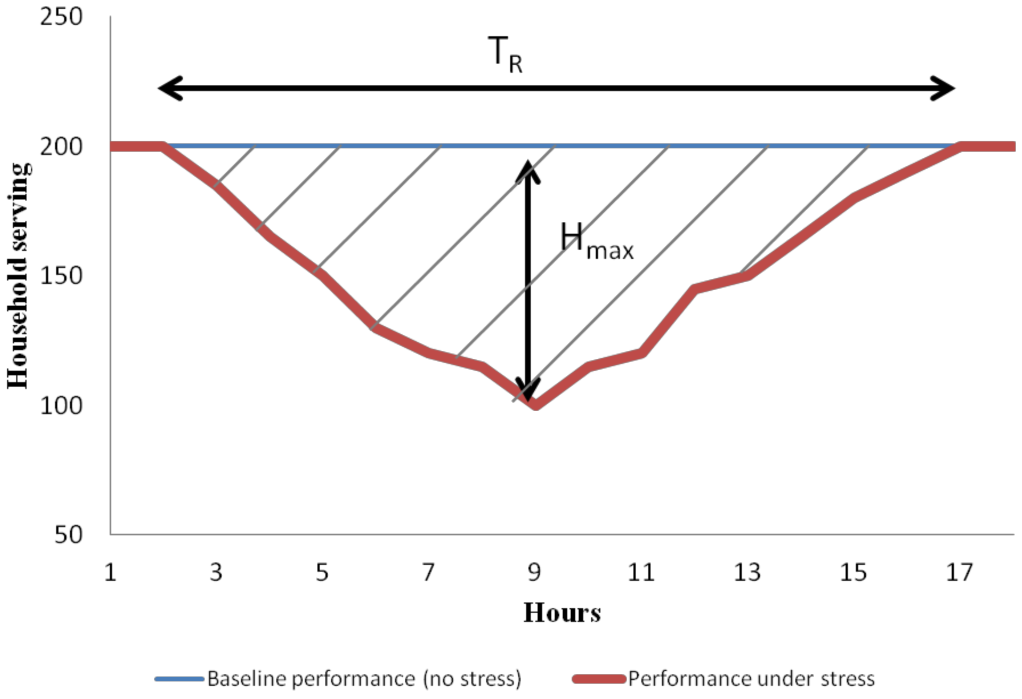
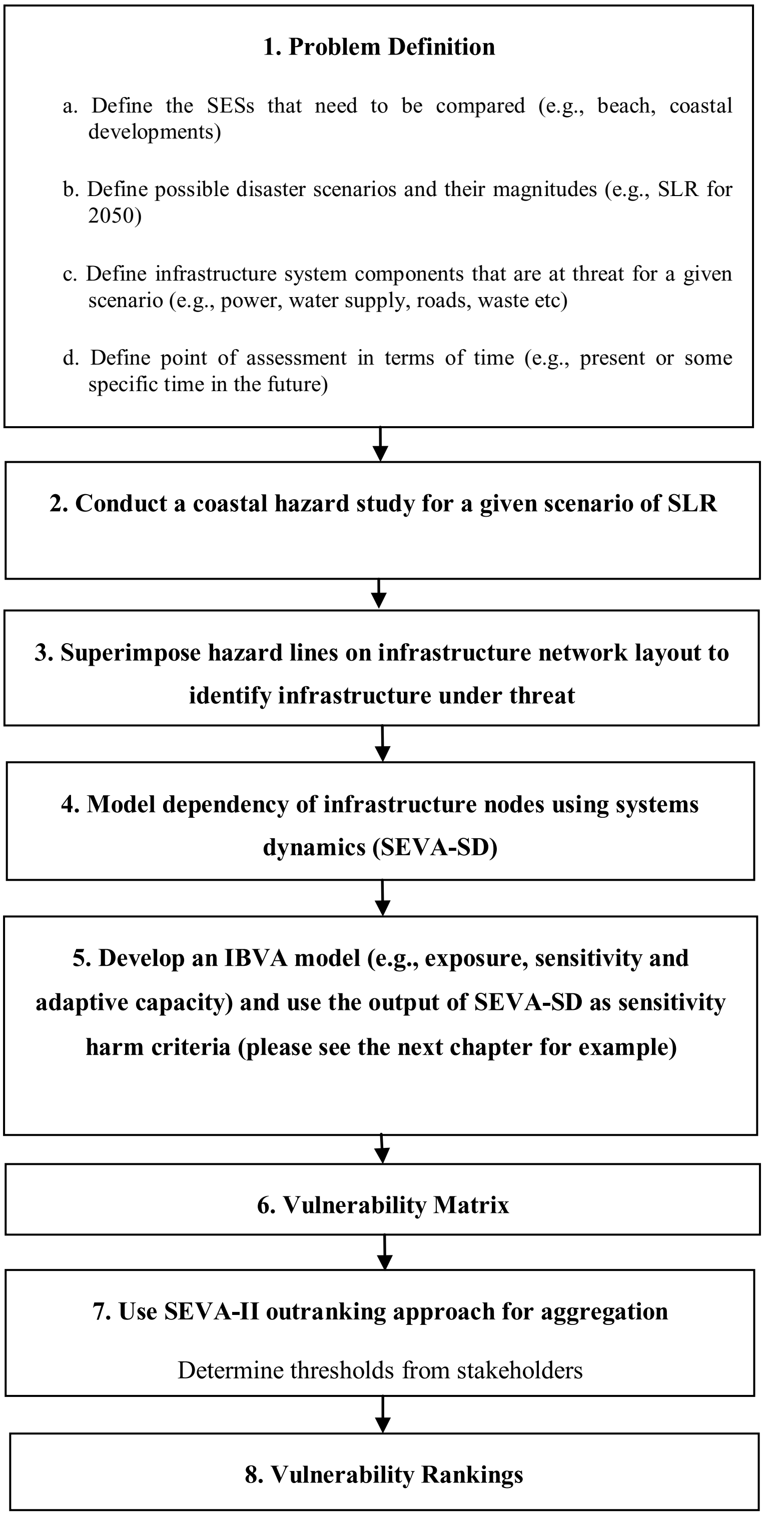


Figure 6-7: Illustrative example of System Dynamics model output

6.5 Development of SEVA-III

The overall architecture of the framework is shown in (Figure 6-8) This framework is general in scope and can be used for any local council for assessing its vulnerability to rising sea levels and its associated processes. However, steps 5 and 6 of the framework require the development of models (e.g., a system dynamics model for infrastructure interdependency and IBVA models by identifying appropriate harm criteria that represent all major processes generating vulnerability) that need to be tailor made for the council in question.

The complex service dependence of multiple infrastructures is a form of deductive non-linearity that is generally present in SLR vulnerability assessment problems associated with infrastructures. Output of SEVA-SD (Hmax) can now be used as a harm criterion (as discussed in Chapter 5) in IBVA models of SEVA-III. As a result, it is possible to address the deductive non-linearities of the infrastructure systems by integrating the SD model within an IBVA methodology.



1. Problem Definition

a. Define the SESs that need to be compared (e.g., beach, coastal developments)

b. Define possible disaster scenarios and their magnitudes (e.g., SLR for 2050)

c. Define infrastructure system components that are at threat for a given scenario (e.g., power, water supply, roads, waste etc)

d. Define point of assessment in terms of time (e.g., present or some specific time in the future)

2. Conduct a coastal hazard study for a given scenario of SLR

3. Superimpose hazard lines on infrastructure network layout to identify infrastructure under threat

4. Model dependency of infrastructure nodes using systems dynamics (SEVA-SD)

5. Develop an IBVA model (e.g., exposure, sensitivity and adaptive capacity) and use the output of SEVA-SD as sensitivity harm criteria (please see the next chapter for example)

6. Vulnerability Matrix

7. Use SEVA-II outranking approach for aggregation

Determine thresholds from stakeholders

8. Vulnerability Rankings

Figure 6-8: Overall architecture of the framework for assessing SLR vulnerability of infrastructure systems (SEVA-III)

Now, IBVA model for infrastructure may include the performance of multiple infrastructure systems as harm criteria ($H_{max}1$, $H_{max}2$......$H_{max}n$). As discussed in section 6.4.3, these performance measures of multiple infrastructure systems can be incommensurable while these criteria (performance measures of multiple systems) are important for estimating the sensitivity of the infrastructure systems to the hazard, they do not carry all the information required by a local authority to prioritize adaptation actions. As mentioned earlier, vulnerability of users of the infrastructure systems depends on, in addition to sensitivity, some measure of adaptive capacity and this again results in the problem of compensation and aggregation (discussed in Chapter 4). Therefore, aggregation of this information using SEVA-II outranking mathematical formulation (developed in chapter 5) offers a sound approach for generating vulnerability rankings of SESs (step 7 and 8 of Figure 6-8)

6.6 Conclusion

This chapter presented an infrastructure vulnerability assessment framework in the context of SLR (and its associated processes) that can be used at a local scale. The framework combines an outranking approach that can incorporate partial compensation and a system dynamics model that incorporates the non-linearity of the service dependencies of infrastructure components and systems. The SD model measures the system performance under stress which can be used as a sensitivity harm criterion of a sea level rise IBVA model. In the next chapter (Chapter 7), an IBVA model will be developed for the Shoalhaven council to assess the vulnerability of its infrastructure systems and their users to sea level rise and its associated processes. Chapter 8 will use SEVA-III framework and the developed IBVA models (Chapter 7) to rank eight beaches of Shoalhaven as per their relative vulnerability to SLR.

Chapter 7

Assessment of vulnerability to sea level rise of eight beaches in Shoalhaven: I. Model development

7.1 Synopsis

This chapter and the following one aim to apply the methodological developments discussed earlier to a real life IBVA problem, an assessment of the vulnerability to a rise in sea levels of eight beaches in a local council called Shoalhaven. This chapter starts with a description of the study area and its potential climatic hazards that are associated with SLR, and presents the methodology that the study follows. Starting from the IPCC definition of vulnerability, two IBVA models, specific to the Shoalhaven context, were developed through consultation with the stakeholders and experts of council. One focused on the vulnerability of the infrastructure systems of Shoalhaven beaches by considering their dependencies and interdependencies, while the other considered the well being of the residents living at the beach. The chapter also shed some light on the stakeholder consultation process that took place throughout this study.

7.2 Introduction

The world's population is growing rapidly along the coasts, especially around coastal conglomerations. Australia, with more than 60 per cent of its population living in coastal settlements in six State capital cities, is likely to be affected by future climatic impacts such as sea level rise and extreme flooding (ABS, 2003; Gurran and Blakely, 2007). Specifically, exposure to long-term and short-term beach recession due to sea level rise as well as an increased frequency of inundation or flooding is likely to significantly affect these urban concentrations. Coastal councils are responsible for the sustainable management of the coast in Australia. They are charged with identifying present and future coastal risks in order to prioritize action and base any risk management and resource allocation decisions they make on evidence-based science. As a result, coastal councils traditionally commission expert coastal studies in order to identify current and future coastal hazards.

Shoalhaven City Council is responsible for the sustainable management of 165 kilometres of open coast, the longest of any local government area in New South Wales. In order to prepare a comprehensive coastal zone management plan, the Council investigated present and expected future coastal risks on its beaches. Detailed studies identified eight beaches where coastal hazards would significantly impact private properties and public infrastructures. In order to help decision makers prioritise management actions for the eight areas, an analytical tool was needed that would not only quantify the physical risks to infrastructure but would also integrate social and environmental considerations towards a holistic assessment of the vulnerability of each beach area.

While the SLR vulnerability literature is rich with multi-dimensional focus (Ozyurt and Ergin 2009; Viehhauser et al. 2006; Abuodha 2010; Clark et al. 1998; Harvey and Woodroffe 2008; Yoo et al. 2011; Kelly and Adger 2000), studies on vulnerability to SLR of infrastructure systems and their users appeared to have given very little consideration to the social and institutional dimensions of risk, especially at local- government level. Most coastal vulnerability assessment studies in the literature that focus on infrastructure have either been conducted at city, regional, or national scales, have not attempted to include both the physical and socio-economic dimensions of risk, or have not considered the cascading impacts of the failure of inter-dependent infrastructures (Karvetski et al. 2011; Alves et al. 2007; Hemer 2009; Ozyurt and Ergin 2009; Duriyapong and Nakhapakorn 2011; Chu-Agor et al. 2011; Lambert et al. 2011). Jacob et al. (2000), conducted a study assessing the vulnerability to SLR of infrastructures around the Metropolitan East Coast of the United States by focusing on possible economic losses. Sahin and Mohamed (2009) conducted a spatiotemporal analysis of SLR vulnerability of the infrastructure on the Gold coast, Australia. But neither of these studies took the infrastructure interdependency or social dimensions of risk into account. Gornitz et al. (2001) conducted a study to identify the impact of sea level rise and its associated processes on New York City shorelines and relevant communities. Kirshen and Ruth (2004) developed detailed climate change impact scenarios for different infrastructure components (e.g., water demand, transport, and energy demand, etc) in Boston city and analysed different adaptation plans. However, both studies were conducted at a city scale and did not look at the physical inter-dependency of infrastructure components.

Therefore, the usefulness of those vulnerability models and frameworks for developing local government adaptation decision making has remained somewhat limited because coastal councils must make decisions that:

a) are local in nature;
b) take into account all the dimensions of the risk and not just the bio-physical ones, including institutional capacity and resilience;
c) are based and communicated on the basis of scientific evidence and community consultation, including a multiplicity of value judgements; and
d) take into account the interdependency of connected infrastructure systems.

Bearing these facts in mind, the general framework SEVA-III developed in the previous chapter was specifically designed for assessing the vulnerability of infrastructures and its users to sea level rise by considering measures of bio-physical, socio-economic and institutional risks, as well as the infrastructure interdependencies at a local council level. As mentioned in the previous chapter, this framework (with its eight steps) is general in scope and can be applied to assess the SLR vulnerability of any council (see Figure 6-7). However, steps four and five of the framework required the development of system dynamics and IBVA models, respectively, that are specific to the council in question. This chapter describes the development of these coastal vulnerability assessment models tailored to Shoalhaven City Council.

7.3 Study area

Shoalhaven City is located on the south coast of New South Wales, about 163 kilometres south of Sydney (Figure 7-1). The City encompasses a total land area of about 4,561 square kilometres, including substantial areas of national park, state forest, bushland, beaches and lakes. Most of the population is concentrated along the coastal fringe, in major centres and numerous small settlements. In addition to its permanent residents, this area has attracted a significant amount of tourists over the years, and is currently the most visited LGA in NSW outside of Sydney (Kaly 1999). The population grew from about 29,000 in 1971 to nearly 100,000 in 2013 with a forecast of 37.05% growth in next 23 years. Rural land of Shoalhaven is mainly used for dairy farming and agricultural activities. The main sectors of employment within the Shoalhaven are manufacturing, government (including Defence), community services, retail and tourism.

The council develops and maintains a number of public infrastructures around the coast to provide basic services to its residents. Figure 7-2 shows private properties and public infrastructure around Mollymook beach (one of its most densely developed beaches) at Shoalhaven. “Shoalhaven Water” is responsible for managing water and waste water infrastructure worth over 1 billion AUD that include 218 sewerage pumping stations, 1,229 kilometre of waste water pipes, 1,621 kilometres of water pipe lines and 1,500 water mains among other (ShoalhavenWater 2012). In terms of transportation, the council maintains 1637 kilometre of roads which are crucial from Shoalhaven’s business and economic perspectives (StrategicPlanning&InfrastructureGroup 2012).

This study focused on the eight beaches of Shoalhaven that were identified by a council-commissioned hazard study (Nielsen and Varley 2004) as most at risk among other beaches from long term erosion and inundation. These beaches are Callala Beach, Shoalhaven Heads, Culburra Beach, Currarong Beach, Collers Beach, Mollymook Beach, Warrain beach and Collingwood Beach (Figure 7-1). The study has the following two goals:

a) rank these eight beaches of the Shoalhaven council in terms of their vulnerability to sea level rise, as input into the process of prioritizing the response action by the council.

and

b) help understand the underlying reasons that make households or public infrastructures in some beaches more vulnerable to sea level rise than others under consideration.

It is important to point out here that, since the unit of analysis in this study is a beach community, the IBVA models and analyses will not capture differences in vulnerability at a smaller scale, i.e. within a given beach.

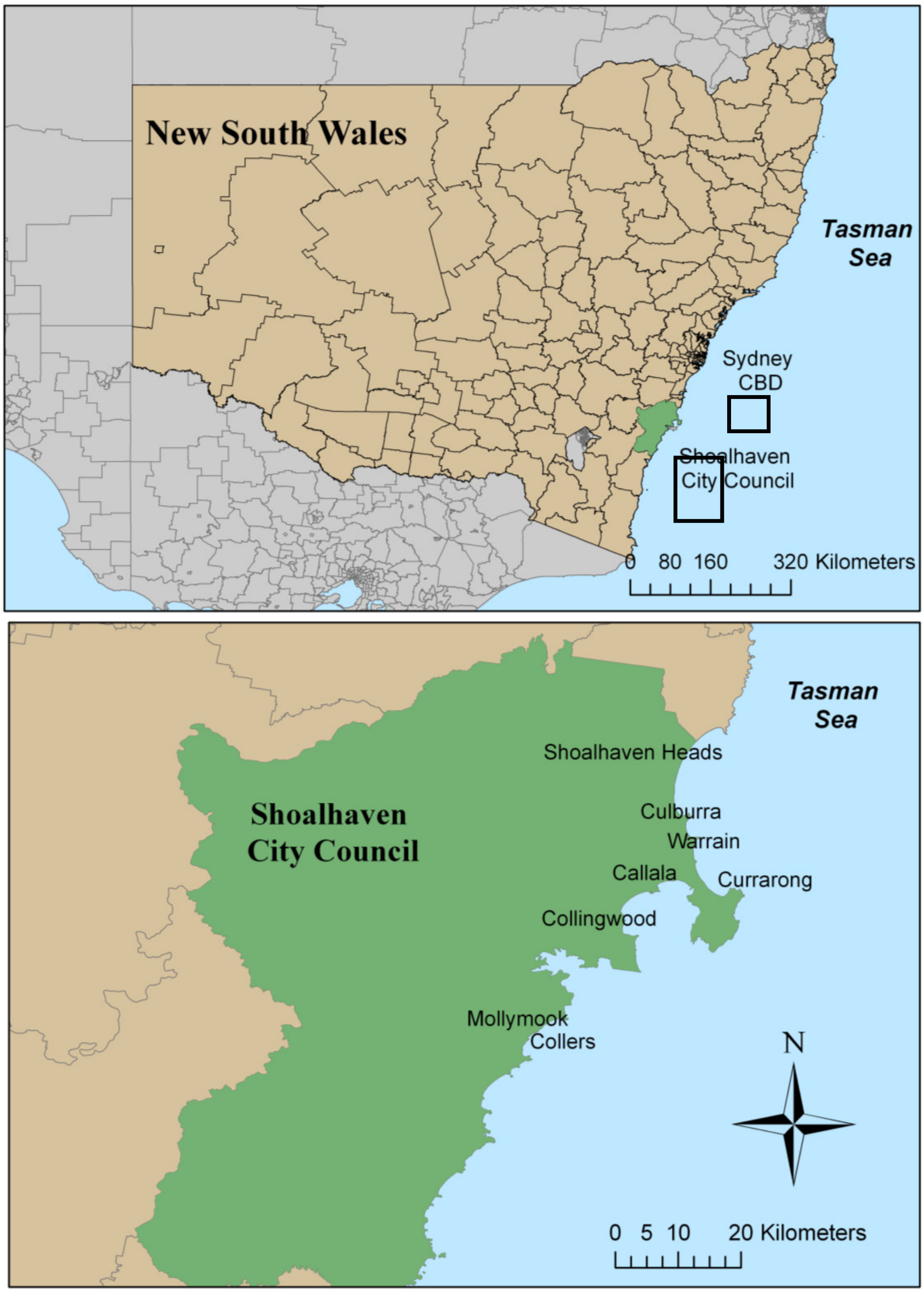


Figure 7-1: Study Area

Figure 7-2: 2050 SLR hazard line for Mollymook beach at Shoalhaven (Adamantidis et al. 2009)

7.4 Coastal hazards of Shoalhaven beaches due to a rise in the sea level

There are past histories of extreme events at the Shoalhaven coast, mostly in the form of coastal storms, inundation and flooding. Historical flood records are available since 1860 and the largest floods occurred in 1870, 1860, 1873, 1891, 1916, 1925, and 1978 (UNDP 2013). More recent significant floods occurred in August 1974, June 1975, October 1976 and March 1978 (Figure 7-3). One of the factors associated with floods and storm surges of NSW coasts is *East Coast Lows* (an intense low pressure system) and historically significant flooding and beach erosion events along the Shoalhaven coastline (occurred in 1974, 1978, 1986 and 1998) are associated with major *East Coast Low* storms (Hough et al. 2010). On the other hand, most of the climate models (studies conducted specifically for NSW coasts) project an annual increase in the frequency of such low pressure systems (Refsgaard et al. 2007). Rising seas may compound the problem either by providing a higher base and therefore increasing the height of storm surges, or by acting as a higher seaward barrier restricting the escape of flood waters caused by excessive runoff (Walsh et al. 2004). Apart from coastal flooding, SLR may accelerate the erosion of coastal margins, threatening surrounding land, property and infrastructures.

Figure 7-3: Shoalhaven Heads-extreme event 1978 (Webb, 2008)

Keeping these factors in mind, the following principal hazards induced by coastal processes pertinent to the Shoalhaven beaches are included in this study (Adamantidis et al. 2009):

- short-term coastal erosion including that resulting from severe storms, the behavior of estuary entrances and slope instability;
- long-term coastline recession including that resulting from imbalances in sediment budget, such as aeolian sand transport, climate change and beach rotation;
- oceanic inundation of low-lying areas.

7.5 Vulnerability Assessment Methodology

This section outlines the methods implemented to assess the vulnerability of public infrastructure systems and the well being of residents of Shoalhaven beaches to the hazards discussed in the previous section.

7.5.1 Framework

SEVA-III, developed specifically for assessing vulnerability of infrastructure systems and their users to SLR (chapter six) at a local scale, was used as the assessment framework of this study. The framework was tailored for Shoalhaven by specifying the basic definitions of this study (e.g., SESs, SLR scenario, etc) and developing IBVA models (SEVA-INFRA-SD, SEVA-HOUSE) for Shoalhaven (step 5). The process of consultation of stakeholders and experts of the council for this purpose is discussed in the following section.

7.5.2 Stakeholder consultation and information flow process

The process flow diagram, shown in the Figure 7-4 was developed to demonstrate the flow of information in this study. The process started with a preliminary discussion with experts from the environmental planning department of the council regarding the goal, objectives and methods to be used in the study. Reviewing previously conducted hazard studies of Shoalhaven beaches as well as relevant literature, a conceptual model of the vulnerability of Shoalhaven beaches was developed. Following this conceptual model, a list of harm criteria were proposed to the stakeholders of the council for further consultation (1st phase of consultation), who then selected those that are most relevant in the context of Shoalhaven. Harm criteria were proposed for two separate IBVA models. Starting from the IPCC definition of vulnerability, SEVA-INFRA-SD (Sydney Environmental Vulnerability Assessment of Infrastructures using System Dynamics) was developed with a focus on the vulnerability of the infrastructure systems of Shoalhaven beaches to sea level rise, as well as its associated processes (e.g., long-term erosion, increased flooding, and inundation, etc) by considering the bio-physical, socio-economic and institutional dimension of risk, as well as the interdependency of the infrastructure. On the other hand SEVA-HOUSE (Environmental Vulnerability Assessment of Households) was developed with a focus on the vulnerability of the well-being of the beach residents. In order to select the most relevant set of harm criteria for Shoalhaven from the proposed set following stakeholders from the Council were consulted in the 1st phase.

- Shoalwater (responsible for developing and managing water supply and sewerage infrastructure of Shoalhaven);
- Transportation division of the council (responsible for managing the roads);

- Environmental and coastal planning division (responsible for long term coastal planning)
- Tourism department
- Asset management department

Total number of participants of this decision making exercise were 10. The list included 2 water supply engineers, 2 transportation engineer, 3 coastal planners, 2 asset management specialists and one tourism specialist. After deliberation with the Council it was decided to limit shareholders to Council experts and managers, for three reasons. First, it was important from the Council's point of view that, prior to wider community consultation, necessary analytical assessment be conducted internally by way of preparation. Second, second step involving the wider community was beyond the time and logistics scope of this thesis project. Third, testing some of the ideas proposed in the thesis (outranking, thresholds of difference) is better conducted in the first instance, with a narrow set of stakeholders.

Once finalized, the scores for each harm criteria of each beach were estimated in order to populate the vulnerability matrix. This was done in collaboration with the engineers and experts from respective departments of the council (2nd phase of the consultation). This phase of consultation also identified the interdependencies and dependencies of the Shoalhaven infrastructure systems. The 3rd phase of consultation was conducted through two consecutive workshops, in order to generate the thresholds of differences and votes. Details of this process will be discussed in the following chapter. During the last two consultation stages, a number of questions came up which can be seen as matters of community preferences and value judgment for the Council stakeholders and Shoalhaven community at large. Those deemed likely to have strong influence on the outcome of the analyses were identified and multiple scenarios were built representing these preferences. These will be discussed in more detail in the following chapter. After testing the robustness of the analyses, the final results were discussed with the Council. The following sections describe the two conceptual models as well as the harm criteria that were finally selected.

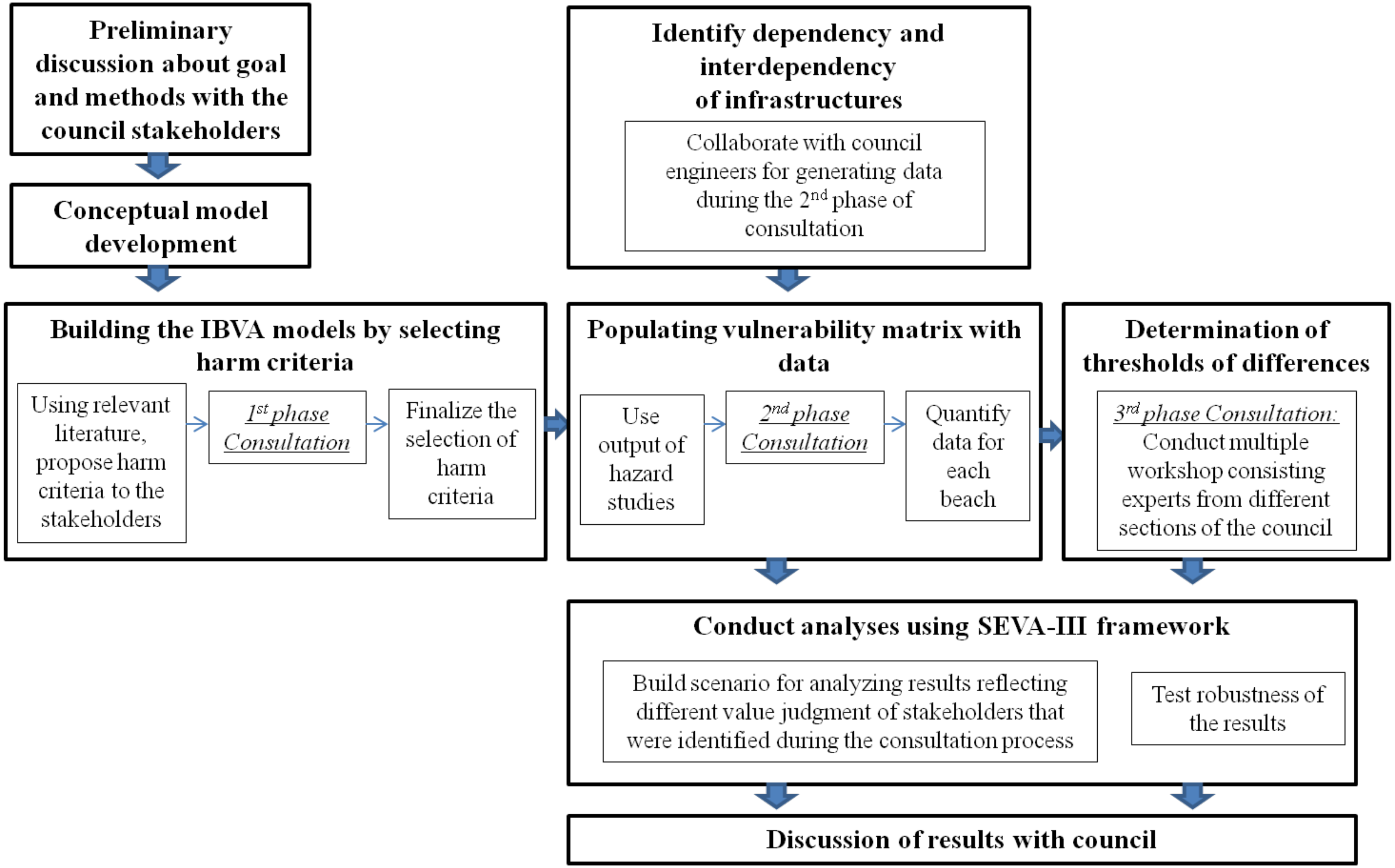


Figure 7-4: Process flow diagram of the study

7.5.3 Conceptual Model

A general conceptual model for coastal vulnerability is shown in Figure 7-5. Climatic events (e.g., storm surge, flooding and inundation, sea level rise, etc) pose certain hazards in the coastal areas (coastal forcing). Their impact depends on the characteristics of the coast (e.g., geomorphology and coastal structures, etc). The social, institutional and financial resources that the community has access to are considered as a reflection of its adaptive capacity. This is based on the concept presented in Preston B.L et al. (2008).

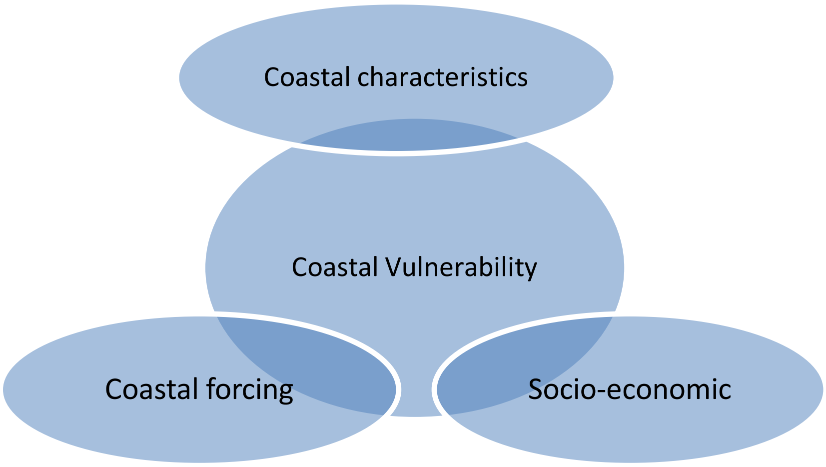


Figure 7-5: Conceptual model of coastal vulnerability

The first step in building the most basic vulnerability model, as shown in step one of the SEVA-III framework (see Figure 6-7), was to define the problem at hand by answering some basic questions (e.g., which socio-ecological system (SES) is the object of the study, the vulnerability to which climate related stress(es) or hazard(s) is to be assessed, the vulnerability of which valued attribute(s) of this SES(s) is to be assessed, at what point of time is the assessment to be done, what SLR scenario is under consideration, which components of the infrastructure are relevant for the council, etc). In the following section, the answers to these basic questions are discussed in the context of this study.

7.5.4 Problem definitions

As mentioned before one of the main objectives of this study was to rank a given set of beaches of Shoalhaven in terms of their relative vulnerability to SLR and its associated processes. Therefore, a **beach (**coastal developments near to the coast**)** was taken as a socio-ecological system which needs to be ranked. A plausible **sea level rise** and associated processes (discussed earlier) are the hazards under consideration, with a 2050 scenario at the NSW coast being adopted for the analysis.

Two valued attributes were considered separately through two different models:

a) The well being of households living at or near the beach (SEVA-HOUSE);

b) The integrity of the public infrastructures at or near the beach and the well being of its users, whether they live at the beach or not (SEVA-INFRA-SD).

The reason behind building two separate models is that, despite some similarities, the processes that determine vulnerability are quite different for households and infrastructure and its users. For example, the adaptive capacity of households is mainly governed by socio-economic factors such as income, employment, access to social capital, and access to information, etc. On the other hand, the vulnerability of the users of a given infrastructure is partly determined by the extent to which the service it provides is critical, and the ability of the Council and/or the users to deploy an alternative to the disrupted service. In addition, while a disruption of beach infrastructure services may well impact beach households, the effects may not be confined to beachside residents, especially if infrastructure dependency and interdependency are taken into account.

In consultation with the council, three systems were identified as important in determining Shoalhaven council’s ability to maintain public service: water supply, waste water transport, and roads. In addition, Shoalhaven earns high revenue from its tourism activities and therefore other public amenities (e.g., the golf course, the surf club, and the car park near a tourist spot, etc) are important and were included in the model. The electrical grid and telecommunication systems were left out of the analysis because of the unavailability of suitable data.

Two separate timeframes could be used in the model, both of which are based essentially in the **present**. In the first time frame, the beaches can be ranked according to their present vulnerability to recent and present coastal flooding and erosion of beaches. This timeframe is called TF1. In the second time frame (TF2), the analysis can answer the following question: if the projected future (e.g., the year 2050 or 2100) sea level rise and associated processes of erosion and inundation *were to happen today*, which of the beaches included in the study would be most vulnerable? This means that, in both cases, the impact of specific scenarios of plausible sea level rise on the *present* land use, taking into account the *present* adaptive capacity of the given Council and Council beach households is assessed. Placing the analyses in the present time allows the model to avoid uncertain, and often controversial, projections into the future of patterns of land use as well as demographic, institutional, and technological change. On the other hand, the analyses will lay the foundation for subsequent attempts at making such projections, by allowing the analyst to assess the sensitivity of the vulnerability rankings to specific changes in these assumptions.

In the following sections, the conceptual models underlying SEVA-INFRA-SD and SEVA-HOUSE are discussed in detail. For the sake of conciseness, it should be noted that, this thesis describes the models and conducted the analyses that are associated only with TF2 (the TF1 models are identical, except for the patterns of the hazard).

7.5.5 Vulnerability of infrastructure and its users (SEVA-INFRA-SD)

A conceptual model for infrastructure vulnerability to sea level rise was developed for this project and is shown in Figure 7-6. In this model, the sea level rise and severe storm events were taken as the main driving forces impacting the Shoalhaven coast. A design storm equal in intensity to the storm that hit the NSW coast in May 1974 and that has a 5% probability of being exceeded over a 50-year period was adopted for this analysis. A sea level rise of 0.4m by 2050 was assumed, as specified in the guideline of the NSW Sea Level Rise policy statement (NSW 2009). A design storm causes short-term erosion and inundation in the coastal areas while a rise in sea level contributes to long term beach erosion as a result of change in the sediment budget. These processes were judged to be the more significant ones when it comes to the Shoalhaven beaches in studies recently commissioned by the councils (Adamantidis et al. 2009; Fletcher 2011). Exposure to these climatic hazards might impact the infrastructure at or around the beach. Any disruption to the infrastructure due to this will affect its users, whether they live at, near, or away from the beach. These can be termed the bio-physical impacts of a climate hazard. On the other, hand the capacity of government institutions (local, state, and federal government) to counter and/or mitigate these impacts and the collective and/or individual capacities of populations to cope with and diminish the impacts is referred to as the adaptive capacity of the SES. The overall infrastructure vulnerability of the beach was determined by the physical impact on its infrastructure and the sensitivity of its users to the impacts, minus the capacity of the council and individuals to cope with those impacts, as shown in Figure 7-6. A summary of the definitions underlying the model are given in Table 7-1.

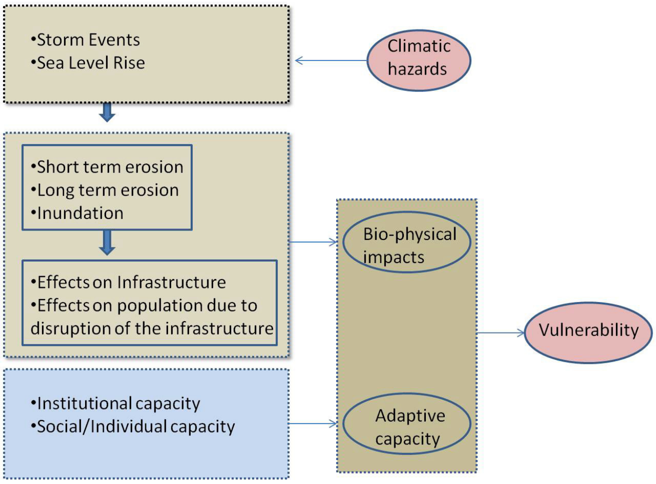


Figure 7-6: Conceptual model of vulnerability of beach infrastructure to sea level rise (SEVA-INFRA-SD)

Table 7-1: SEVA-INFRA-SD: How vulnerable is the public infrastructure network and its users to sea level rise (SLR) and coastal processes associated with it, namely beach erosion and inundation (collectively called SLRAP)

Information Type	Description
Socio-Ecological System (SES)	The beach defined as the coastal State Suburb Level (SSL) which is a lower statistical unit in Australia.
Valued attribute of concern (VA)	All public infrastructures and the well-being of their users
Climatic stress	SLRAP (sea-level rise as predicted for 2050 + design storm with same magnitude as 1974 NSW storm)
Time	Present-day vulnerability to SLRAP
Exposure of infrastructure to hazard	Extent to which public infrastructure systems are exposed to SLRAP
Sensitivity of infrastructure to the impacts of hazard	1. Extent to which the well-being of the community of users of the public infrastructure is likely to suffer as a result of disruption to service; 2. Extent to which, and speed with which, relevant public authorities are able to repair damaged infrastructure components and restore disrupted services to users or offer substitute services
Adaptive capacity of users	Extent to which, and speed with which, users are able to substitute, or do without, disrupted services, without help from government institutions

7.5.6 *Vulnerability of households (SEVA-HOUSE)*

A conceptual model for household vulnerability to sea level rise was developed for this project and is shown in Figure 7-7. In this model, the climatic hazards are similar to those of SEVA-INFRA-SD, but this model focused on the impact of those hazards on beach residents, including damage to their properties, and the effects on their well-being of disruption to services as a result of damage to the infrastructure. This model is called SEVA-HOUSE. A summary of the definitions underlying this model are given in Table 7-2.

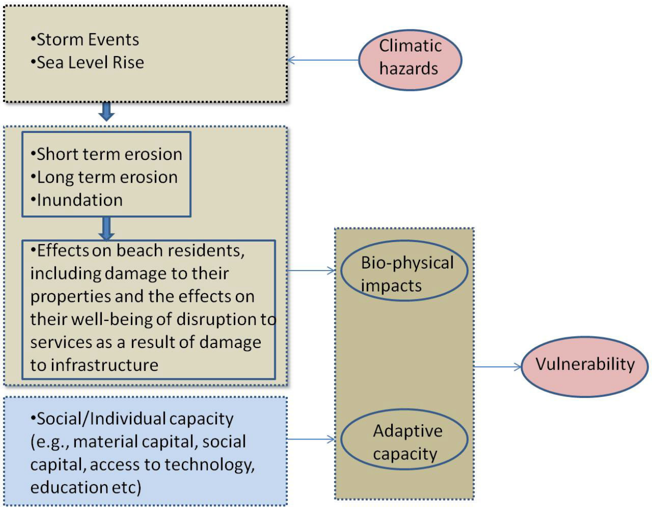


Figure 7-7: Conceptual model of vulnerability of beach resident households to sea level rise (SEVA-HOUSE)

Table 7-2: SEVA-HOUSE: How vulnerable is the well being of the beach private residents to SLRAP

Information Type	**Description**
Socio-Ecological System (SES)	The beach defined as the coastal State Suburb Level (SSL) which is a lower statistical unit in Australia.
Valued attribute of concern (VA)	The well-being of all households at the beach
Climatic stress	SLRAP (sea-level rise as predicted for 2050 + design storm with same magnitude as 1974 NSW storm)
Time	*Present-day* vulnerability to SLRAP
Exposure	Extent to which houses and households are exposed to SLRAP
Sensitivity	Extent to which the well-being of residents at the beach is likely to suffer as a result of that exposure, due partly, but not exclusively, to physical damage to houses and infrastructure services
Adaptive Capacity	Extent to which households can adapt to, and mitigate, the impact on their well-being of exposure to SLRAP.

7.5.7 Selection of harm criteria

The next phase was to identify the harm criteria through which SEVA-HOUSE and SEVA-INFRA-SD could be made operational, i.e. used as a basis for ranking vulnerabilities. The previous chapter discussed the general characteristics of harm criteria and their relationship with indicators in detail. The harm criteria proposed for the two vulnerability models are described in the next sections. The selection was conducted in collaboration with experts from the Shoalhaven council. Harm criteria had to satisfy the following requirements: a) to capture the most significant processes driving the vulnerability of Shoalhaven's coasts, and b) be readily available or can be measured with reasonable confidence. In presenting the harm criteria (Table 7-3 to Table 7-13), the following conventions were used:

"C"	: continuous variable (e.g., monetary value of an asset; length of a shoreline)
"D"	: discrete variable (e.g., population numbers; number of properties at the beach)
"O"	: ordinal variable (e.g., degree of importance on an increasing scale of 1 to 5)
"+"	: vulnerability increases with an increase in the value of the harm criterion
"-"	: vulnerability decreases with an increase in the value of the harm criterion
"N/A"	: not applicable

7.5.8 Harm criteria for SEVA-INFRA-SD

Present replacement costs of damage to infrastructure inflicted by an event in a do-nothing scenario were selected as the harm criteria of exposure for SEVA-INFRA-SD (Table 7-3). The damage cost was deemed to reflect the extent of exposure and can be estimated through hazard studies. These studies downscaled the output of climate models and combined them with local coastal, geomorphologic and hydrodynamic models, in order to develop hazard lines and identify long term coastal erosion, as well as possible flooding during a storm event. Hazard studies conducted for Shoalhaven beaches will be briefly discussed in the following chapter. Infrastructure systems of Shoalhaven that are likely to be affected by SLRAP were divided into four categories: sewerage, water supply, roads, and public buildings and other infrastructures (e.g., golf course, surf club, car park, etc) for the reasons discussed above. However, it is always possible to expand this model in order to make it usable by other councils by including other categories such as the power supply, telecommunications or any other relevant infrastructure system.

Table 7-3: SEVA-INFRA-SD Harm criteria of Exposure (7 harm criteria)

Public infrastructures and services	Code	$value of Affected	Variable Type	Unit	D_a	Scale	Source
Sewerage	H1	pumping stations	C	$	+	N/A	Hazard studies
	H2	rising main					
	H3	gravity main					
Water supply	H4	supply main					
	H5	trunk main					
Roads	H6	roads					
Public buildings and other infrastructures	H7	other affected infrastructure (e.g., car park)					

D_a = Direction: + (-) indicates that vulnerability increases (decreases) with increasing indicator.

The sensitivity dimension of the model is represented by a set of measures that quantify a) the impact of the disruption of public infrastructures on households and b) the capacity of authorities to replace or restore the service (Table 7-4). A more intuitive approach would be to include point b in the adaptive capacity dimension. However, through discussion with Council stakeholders and experts, it became clear that, in eliciting some quantitative measure of expected impacts on users it was difficult to separate it from Council's ability to replace/repair the service. H_{max} as discussed in the previous chapter is an example of this; because the extent of disruption to households depends on the duration that the Council is required for fixing or restoring the service under stress. Hence, the model lumped the two together. Adaptive capacity as will be discussed below was then defined as the ability of users to do without the service, i.e. it measures how critical the service is, which is clearly distinct from the ability to repair by the council.

The sensitivity of roads was quantified through two impact categories (e.g., direct and indirect impacts). Disruption of traffic (during a disaster event, e.g., storm) leading to loss of direct access to any private properties was regarded as direct impact (R1). On the other hand, an indirect impact R2, measured disruption based on traffic volume and service category (e.g., arterial, collector or local road). The sensitivity of public amenities was represented by R3, which is a relative measure (on a predefined scale) of the number of affected population (if the amenity in question is disrupted). Details of these variables (R1, R2, and R3) are discussed in the following tables. On the other hand, the system dynamics model presented in a previous chapter allowed for the development of sensitivity indicators which reflected the dependent and dynamic nature of the infrastructure components of a given infrastructure system or multiple infrastructure systems. This is relevant to sewerage and water supply and the indicator in question H_{max} is the maximum number of households affected by the disruption of a single service (derived in Chapter 6). It measures the collective service performance of the components of the above-mentioned infrastructures when under stress, as well as the capacity of the public authority to maintain the service (consistently with the definition of sensitivity in Table 7-1.

Table 7-4: SEVA-INFRA-SD harm criteria of sensitivity (5 harm criteria)

Public infra-structures and services	**Code**	**Nodes**	**Harm criteria**	**Variable type**	**Unit**	**D_a**	**Scale**	**Source**
Sewerage	H8	pumping stations rising main gravity main	(H_{max})waste	D	NH/hr	+	N/A	Shoal-water database
Water supply	H9	supply main trunk main	(H_{max})water					
Roads	H10	roads (direct impact)	R1	O	NH	+		Roads database
	H11	roads (indirect impact)	R2	O	NA	+	Table 7-5	
Public buildings and other infra-structures	H12	other affected infrastructure	R3	O	NA	+	Table 7-6	Expert estima-tion

NH: Number of households; NH/hr: Number of household served per hour; Hmax: maximum number of household affected by disruption of service per unit time-output of SEVA-SD; R1: Number of households affected by the service disruption of the system; R2: Impact on passing traffic based on a predefined scale (Table 7-5); R3: Relative measure of Number of affected population measured on a predefined scale (Table 7-6); D_a = Direction: + (-) indicates that vulnerability increases (decreases) with increasing indicator.

Table 7-5: Scale used for H11 (developed in consultation with the experts of Council)

Scale for importance (indirect impact)	**Scale**
arterial roads	3
collector roads	2
local roads	1

Table 7-6: Scale used for H12 (developed in consultation with the experts of Council)

Number of affected population	Scale
>200	5
75-200	4
51-75	3
26-50	2
No affected population	1

Finally, the adaptive capacity of users was captured by expert and stakeholder judgement about the degree to which the disrupted service is critical, i.e. the extent to which it serves a vital function (e.g., the water supply is more vital than a car park at a beach). In other words, adaptive capacity in this case is reflected by the extent to which users can do without the service in question. The harm criteria are shown in Table 7-7.

Table 7-7: SEVA-NFRA-SD harm criteria of adaptive capacity (7 harm criteria)

Public infra-structures and services	Code	How critical is the affected infrastructure?	Variable type	Unit	D^a	Scale	Source
Sewerage	H13	pumping stations	O	NA	+	Table 7-8	Stakeholder Consultation
	H14	rising main			+		
	H15	gravity main			+		
Water supply	H16	supply main			+		
	H17	trunk main			+		
Roads	H18	roads			+	Table 7-9	
Public buildings and other infra-structures	H19	other infrastructures (e.g., car park)			+	Table 7-10	

D^a: Direction: + (-) indicates that vulnerability increases (decreases) with increasing indicator.

Table 7-8: Scales used for water and Sewerage infrastructure (H17 to H21)

Description	Scale
Extremely Critical - asset failure is unacceptable. The consequences are so serious that they cannot be tolerated under any circumstances	3
Critical - The consequences of failure may be tolerated provided the risk of failure is as low as reasonably practicable.	2
Non - Critical - Consequences of asset failure are acceptable	1
No infrastructure affected	0

Table 7-9: Scale used for H18 (developed in consultation with the experts of Council)

Scale for adaptive capacity of direct impact	Scale	Scale for adaptive capacity of indirect impact	Scale
Alternative service cannot be provided	2	No alternative access available	3
Alternative service can be provided	1	Alternative access is available but reroute length is long	2
		Alternative access is available	1
		No Indirect impact	0

Assigned values of direct and indirect impacts were added to generate overall over all adaptive capacity score of a given road.

Table 7-10: Scale used for H19 (developed in consultation with the experts of Council)

Description	Scale
Users have no capacity to avail similar service with alternative options.	3
Users have alternative options to ***partially*** avail similar service with minimum effort	2
Users have alternative options to ***completely*** avail similar service with minimum effort	1

The scales presented here were developed during the 1st phase of stakeholder consultation. This choice of scales was influenced by the extent of the availability of data. As an example, a more refined scale based on a value of 1 to 5 was proposed for the scale presented in Table 7-8 (with further divisions in category such as moderate critical). However, consultation with experts from the council revealed that available data do not justify such a refined categorization; hence, a scale of 1-3 was adopted instead.

7.5.9 Harm criteria for SEVA-HOUSE

The following tables (Table 7-11, Table 7-12 and Table 7-13) show the selected SEVA-HOUSE harm criteria for exposure, sensitivity, and adaptive capacity, respectively. The exposure of a household living at or near the beach to SLRAP was assumed to occur through the exposure of its property (be it owned or rented). Sensitivity was measured by the number of people affected by property damage and disruption to infrastructure services, but unlike the sensitivity of SEVA-INFRA-SD, *only including those living at or near the beach* (direct impacts). Finally, the adaptive capacity was captured through a set of socio-economic indicators for the whole beach. Existing literature identified cultural beliefs, norms, and lack of access to resources and political power as important determinants of the capacity to adapt to a certain risk. Some of the key papers in this field (Blaikie P 1994; Cutter 1996; Hewitt 1997;

Cutter et al. 2000; Clark et al. 1998; B 1997) demonstrated that some key demographic and housing characteristics such as age, gender, race, income, education, and living conditions are important in amplifying or reducing the overall vulnerability to hazards (Wu et al. 2002). Following the concepts illustrated in Wu et al. (2002) a list of adaptive capacity criteria was presented to the council and only those that are relevant to the context of Shoalhaven were finally selected (Table 7-13). The total number of harm criteria for SEVA-HOUSE is 10.

Table 7-11: SEVA-HOUSE: Harm criteria of exposure dimension (2 harm criteria)

Properties and infra-structures	**Harm criteria**				
	Code	**Description**	**Variable type**	**Unit**	**Direction**
Residential properties	H20	$ value of all affected residential properties	C	AUD	+
Commercial properties	H21	$ value of all affected commercial properties	C	AUD	+

Table 7-12: SEVA-HOUSE: Harm criteria of sensitivity dimension (3 harm criteria)

Properties and infra-structures	**Harm criteria**				
	Code	**Description**	**Variable type**	**Unit**	**Direction**
Residential properties	H22	all affected residential properties	D	Capita	+
Commercial properties	H23	all affected commercial properties	D	Capita	+
Public infra-structure and services	H24	all affected public infrastructure	D	Capita	+

Table 7-13: SEVA-HOUSE: Harm criteria of adaptive capacity dimension (5 harm criteria)

	Harm criteria				
	Code	**Description**	**Variable type**	**Unit**	**Direction**
Demographic profile of the beach	H25	% of population attending secondary education	D	Capita	+
	H26	% of population under 19	D	%	-
	H27	% of population over 60	D	Capita	+
	H28	% of single-parent household	D	Capita	+
	H29	Median weekly household income	D	Capita	+

7.5.10 Modelling and Aggregation of harm criteria

The next step in the SEVA-III framework was to build the vulnerability matrix by establishing the scores of the harm criteria for each beach (step 6 of figure 6-7). The columns of the matrix represent the beach and the rows represent the harm criteria. The SEVA-II outranking formulation (developed in Chapter 5) was then applied using this matrix to generate the vulnerability rankings of the beaches. However, this requires the thresholds of differences to be elicited from the stakeholders. These steps will be discussed in the next chapter.

7.6 Applicability and Validation

7.6.1 Applicability

The SEVA computer tool, developed in Chapter 4, can be applied to any indicator-based assessment of vulnerability of any SES to any hazard or combination of hazards. The SEVA-SD interdependency models, developed in chapter 6, are general in scope and can be used for measuring the performance of an infrastructure system under any given climatic stress(es). On the other hand, the framework (SEVA-III) proposed in the previous chapter was specifically targeted at the vulnerability of beaches to sea level rise and associated processes, at local scales. The IBVA models (which are parts of SEVA-III) developed in this chapter were customized for Shoalhaven Council (e.g., in the selected infrastructure categories and the specific harm criteria used) but they can be adjusted for other councils looking at vulnerability assessment at similar scales by including other relevant infrastructure systems or demographic information. However, a key element in these models is that they need to be customized through consultation with local stakeholders so as to ensure their relevance to the local context. (e.g., "% of non-English speaking population" in each SES, often used in the literature as an inverse proxy of adaptive capacity, was found to be irrelevant in the context of Shoalhaven and dropped from the models).

In summary, the key strengths of these models are:

1. they are designed and populated at a local scale, in collaboration with local stakeholders and experts; as a result, their outcomes are more likely to be relevant to local decision-making;
2. they combine biophysical and socio-economic components of risk, while using an aggregation procedure (outranking) that recognizes the absence of deductive arguments for combining the harm criteria and avoids the use of global utility functions;
3. they allow the use of partial and non-compensation which makes it easier to reflect preference structures of local stakeholders;
4. they incorporate a system dynamics model for infrastructure dependencies.

7.6.2 Validation

The IBVA frameworks and models cannot be validated in a conventional, engineering sense. This is because, as discussed in chapter 2, vulnerability is not a measurable entity but a social concept which depends on both biophysical and socio-economic factors. Therefore, the IBVA frameworks and models developed in this thesis did not aim to "measure" vulnerability. Rather, they aimed to function as an aid to decision makers, helping them to structure their thought processes regarding vulnerability and elicit the logical implications of specific preferences. Therefore, the validity of the analyses depends not so much on their ability to replicate a measurable reality; but on the extent to which they are found to be useful and relevant by the decision-maker.

On the other hand, the robustness of the rankings generated by the outranking analyses in SEVA-II and SEVA-III can be seen as an additional criterion of validity. Robustness can be defined as the relative insensitivity of the rankings to small changes in analysis parameters. In the case of outranking methods, the indifference and preference thresholds cushion the analyses against small differences in scores.

However, sensitivity to thresholds of difference and votes, as well as rank reversal, still need to be assessed as a measure of robustness. Both relevance to the decision-maker and robustness will be discussed in chapter 8 when the results of the analyses are presented.

Finally, the SD models are clearly mechanistic in nature and can therefore be validated. However, this requires disaster data (failure of multiple infrastructures during a storm event) which was not available in the context of Shoalhaven.

7.7 Limitations of the Analyses

7.7.1 Epistemic and Conceptual Limitations

First, the models developed in this chapter are limited to sea-level rise and associated processes (SLRAP). In reality, other climate and non-climate hazards and stresses may combine with SLRAP and affect the well-being of the beach communities under study. For example, the effects of a storm event on a beach community may be experienced very differently depending on whether it occurs against the background of economic prosperity or hardship (Neil Adger 1999).

Second, an IBVA model should capture all significant processes that generate vulnerability of a system. In this project, these processes were identified through a) existing literature on coastal hazards, b) hazard studies conducted specifically for Shoalhaven and c) consultation with Shoalhaven Council stakeholders and experts. Nevertheless, it is possible that significant processes, either biophysical or socio-economic, may have been overlooked in the SEVA-III framework and/or in the hazard studies that were its starting point.

In addition, the harm criteria selected to represent these processes may be inadequate, insufficient or operate in a more complex way, not captured by the model. As an example, values of exposed properties are used as a harm criterion for exposure in SEVA-HOUSE. However, it could be argued that higher property values also indicate higher adaptive capacity (community has more to lose but its ability is more to cope with the loss). On the other hand, the use of outranking procedures is justified in part by this epistemic deficiency, since these procedures are especially suitable for systems characterised by incomplete data and imperfect knowledge.

Third, SEVA assumes that the 3 dimensions of vulnerability, exposure, sensitivity and adaptive capacity, are largely independent. This is an analytically useful, albeit inaccurate, assumption. For example, adaptive capacity can be seen as dependent on the extent of exposure (Luers 2005b). As an example, it is widely recognized that beyond a threshold of sea level rise, the adaptive capacity of small island states will be overcome and no increase in that capacity can protect the island residents and their built environments from devastating damage. In such a case, adaptive capacity of the residents of the small islands can be seen as a function of their exposure.

7.7.2 Methodological Limitations

First, the proposed framework generates relative rankings rather than absolute indices of vulnerability. One consequence of this is that, while this approach allows a comparison of vulnerabilities of different SESs to be made, it cannot be used to provide some measure of the reduction in vulnerability as a result of adaptation, as indices would.

Second, the temporal framework of the models combines current socio-economic and geo-morphological data with a 2050 climate projections. This is useful in avoiding added uncertainty to the analyses (e.g., by attempting demographic and socio-economic projections into 2050). However, an inconsistency is hence introduced in the model.

Finally, some limitations pertain specifically to the infrastructure system dynamics model. Only four types of infrastructure systems were included because no data was available for power supply and telecommunication infrastructure. Hence, any cascading effect of the disruption to the power supply cannot be captured by the model—although anecdotal evidence from Council stakeholders suggest that no major power supply substations are situated near the hazard lines.

The SD models do not take into account any service disruption of dependent upstream infrastructure nodes. Details of this limitation have been discussed in the previous chapter (section 6.3.2.3). In the context of Shoalhaven, this limitation is evident only in water supply systems as the eight beaches considered in this analysis receive water from two upstream dams. However, these dams are located within the boundaries of Shoalhaven and located away from the coast and are therefore unlikely to be affected by an SLR-associated hazard. The sewerage systems model does not suffer from this limitation as there is no dependence on the upstream or downstream nodes, outside the domains of the analyses in the case of the 8 Shoalhaven beaches.

Chapter 8

Assessment of vulnerability to sea level rise of eight beaches in Shoalhaven: II. Results

8.1 Synopsis

The previous chapter developed the IBVA models for assessing the vulnerability of eight beaches of the Shoalhaven council. This chapter describes the process of data collection (e.g., harm criteria, thresholds of differences, votes etc) and presents and discusses the results of the analyses.

8.2 Introduction

The analyses in this chapter aimed to answer the following research questions.

1. How do the 8 beaches of Shoalhaven rank in terms of their relative vulnerability to SLR; why and how are they different across different vulnerability dimensions?
2. How different are the results of outranking procedures compared to more conventional additive MAUT-based approaches?
3. What effect on vulnerability rankings does the inclusion of an SD model have?
4. What effect do different community preference scenarios have on the rankings?

8.3 Data collection processes

This section describes the data collection process that was conducted in collaboration with the council experts. Previously conducted studies, existing asset database of the infrastructure-maintaining authorities, demographic profile of the beach communities and expert opinion are the main sources of the data.

8.3.1 Hazard studies

Council authorities commissioned a council-wide hazard study in 2004 to identify beaches most at risk from coastal hazards (Nielsen and Varley 2004). Eight beaches were hence singled out. Based on this report, the Council commissioned further individual hazard studies for each of the eight beaches, over the last few years. These individual hazard studies are taken as the starting point of the data collection process for this study. These studies developed hydrodynamic models for individual beaches and conducted detailed analyses as follows. Erosion-demand volume for each beach was estimated for the first two of the three hazards that this study is concerned with (e.g., short-term and long-term erosion). Erosion demand volume of a beach is the amount of sand that has the potential to be lost during a certain time duration. Short-term erosion demand of the beaches was estimated by using a storm erosion volume equivalent to a 1974 storm (which is estimated to have 5% risk of being exceeded over the next 50 years). This was done by analyzing pre- and post-storm historical photogrammetric data. Long-term erosion demand was estimated by combining historical long-term erosion (through historical photogrammetric analysis) with the future possible beach recession due to sea level rise using Bruun rule (Faber and Stewart 2003). On the other hand, inundation hazard at the beaches was estimated through calculation of the wave run-up level by simulating a design storm with equivalent properties (e.g., wave height, wave period etc) of the 1974 storm and combining it with the rise in sea level. Two scenarios of SLR were considered, 0.4 meter rise by 2050 and 0.9 meter by the year 2100. The simulation was tailored for each beach considering their individual bathymetric properties. For the details of these studies, the reader is referred to Adamantidis et al. (2009).

Outputs of these studies are hazard lines for each beach under two scenarios of sea level rise: year 2050 and 2100. Hazard lines show on a map the region along the coast that has the potential to be affected by the coastal hazards under question. After discussion with the Council experts, results of the 2050 scenario were used for this study. This choice was mainly guided by Council's interest in developing mid- to long-term adaptation plans.

8.3.2 Populating the model with data

The vulnerability matrix of the model developed for Shoalhaven in the previous chapter has been populated in consultation with the Council experts and stakeholders listed in Chapter 7. Infrastructure layout maps of the eight beaches were overlaid with the corresponding hazard lines in a Geographic Information System (GIS) software. This allowed the identification of the public infrastructure (SEVA-INFRA-SD) and private properties (SEVA-HOUSE) of a given beach that are located inside the hazard line. Figure 8-1 shows an example of the superimposed hazard lines and infrastructure layout for Collingwood beach. Similarly, Figure 8-2 shows an example of the water and sewerage infrastructure layer of a part of the Mollymook beach that falls inside the hazard lines. Infrastructure components and properties thus identified have been labeled "at risk" and are listed in Table 8-1 to Table 8-8.

Figure 8-1: 2050 SLR hazard line for Collingwood beach at Shoalhaven (Adamantidis et al. 2009)

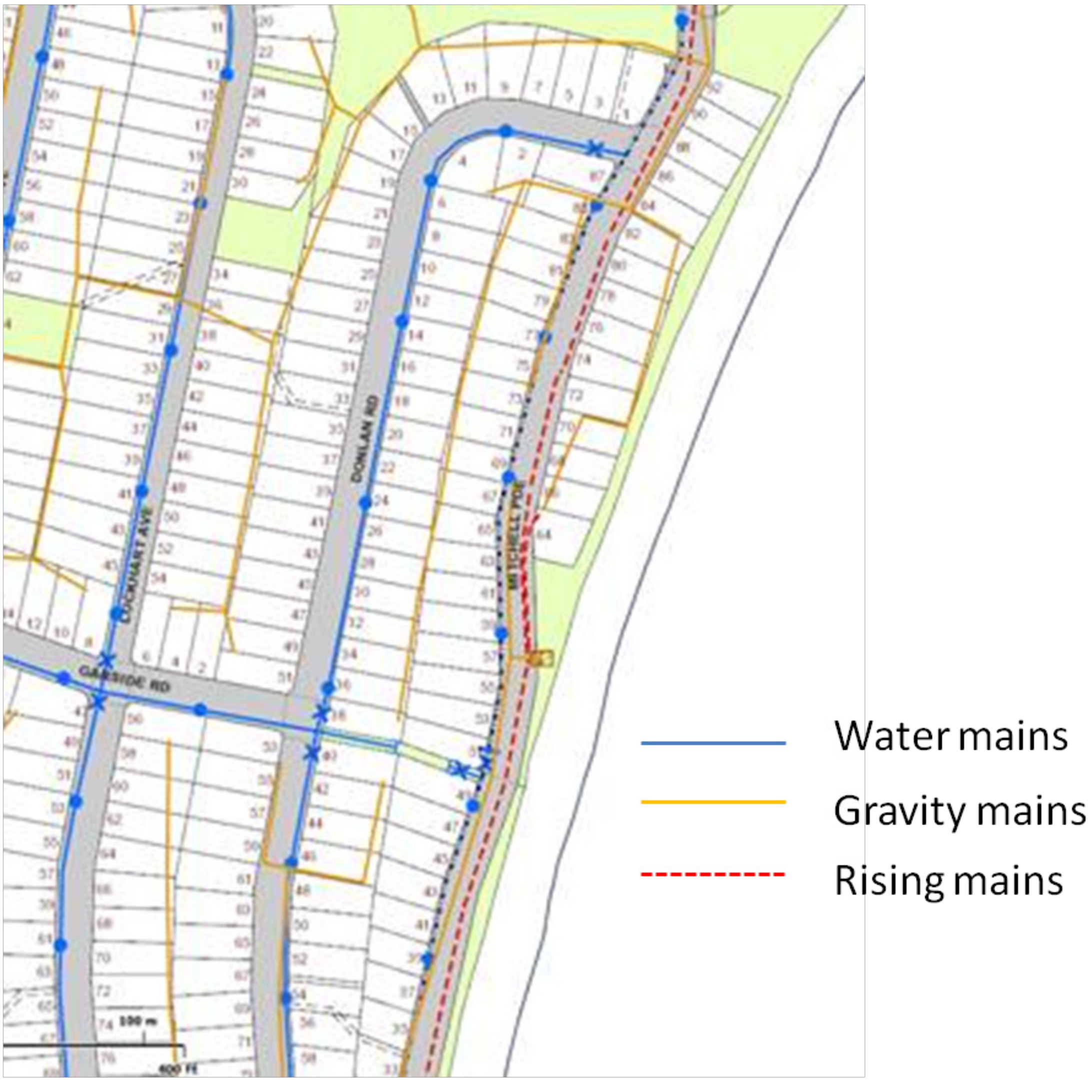


Figure 8-2: Infrastructure layer of a part of Mollymook beach

8.3.2.1 SEVA-INFRA-SD

Exposure harm criteria

Exposure harm criteria for SEVA-INFRA-SD (H1 to H7 of Table 7-3) are the current replacement cost of the "at risk" public infrastructure in a "do nothing" scenario and are estimated using the asset register of the Council which is based on "NSW Ref Rates Manual 2012" (Table 8-1 to Table 8-8). Table 8-9 shows the exposure matrix of SEVA-INFRA-SD.

Table 8-1: At risk water supply and sewerage infrastructure of Mollymook beach. Set-01 are located inside the hazard lines. Set-02 are not located inside the hazard lines but their performance depend on set-01 infrastructure

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity* (Number of Households)
Set-01	**Sewerage Infrastructure**							
	M1	Pump Station south end	unit	1	1,200,000	N/A	0.25	186
	M2	Pump station north side of bridge	unit	1	760,000	M1, M6	0.25	269
	M3	Beach Road 100mm rising main	meter	345	46,286	M2	1.00	39
	M4	Beach Road 150mm gravity main	meter	270	63,013	M3, M19	0.50	39
	M5	North End Mitchell Parade 150mm Gravity main	meter	715	168,777		0.50	60
	M6	Mitchell Parade 250mm Rising Main	meter	14	4,410		1.00	269
	M7	Mitchell Parade 150 mm Gravity Main	meter	215	50,910	M2	0.50	10
	M8	375mm rising main around golf club	meter	230	107,525	M1	1.00	186
	M9	Pump Station Z6 (Mitchell Parade)	unit	1	300,000	M20, M2, M1, M6	0.25	20
	M10	Mitchell Parade 100mm Rising Main	meter	83	12,729	M20, M2, M1, M6	1.00	20
	M11	Mitchell Parade 250mm Rising Main	meter	840	129,663	M10, M20, M2, M1, M6	1.00	116
	M12	Mitchell Parade 150mm Gravity Main	meter	340	71,576	M9, M20, M2, M1, M6	0.50	20
	Water Supply Infrastructure							
	M13	Golf Avenue 100mm water main	meter	65	5,401	M14	1.00	3
	M14	Ocean Street 100mm water main	meter	51	4,609	M13	1.00	1
	M15	Beach Road 100mm water main	meter	190	16,135	M16, M17	1.00	17
	M16	Mitchell Road 250mm trunk main	meter	230	37,994	M17	1.00	6
	M17	150m water main 300mm trunk (Mitchell Parade - north blackwater creek)	meter	150	36,751	N/A	1.00	4
	M18	Mitchell Parade 250m trunk main	meter	505	8,3401	N/A	1.00	19
Set-02	**Sewerage Infrastructure**							
	M19	Pump Station Z3 (Northern end of Beach Road)	unit	1		M20, M2, M1, M3	0.25	39
	M20	Pump station Z2 (Mitchell Parade)	unit	1		M2, M1, M6	0.25	950
	M21	Pump Station X2 (Ocean Street)	unit	1		M1	0.25	116
	M22	Pump Station X4 (Maisie Williams Drive)	unit	1		N/A	0.25	99
	M23	Pump Station Z8 (Clifford Cl)	unit	1		M20, M2, M1,	0.25	26

*Numbers shown here are the direct capacity (households that are located downstream of the infrastructure). However, 2133, 2017, 1067 and 80 more households located upstream are dependent on M1, M2, M20 and M22 respectively

Table 8-2: At risk roads and other public infrastructure of Mollymook beach

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Roads**							
	M24	Bridge on Mitchel Avenue	meter	176	278,960	N/A	N/A	0
	M25	Golf Avenue	meter	75	33,000	N/A	N/A	0
	M26	Ocean Road	meter	40	17,600	N/A	N/A	0
	M27	Beach Road	meter	200	88,000	N/A	N/A	17
	M28	Mitchell Parade	meter	360	158,400	N/A	N/A	22
	Public building and other infrastructure							
	M29	Golf club	meter^2	2072	4,817,400	N/A	N/A	N/A
	M30	SLSC (Surf Club)	meter^2	324	727,380	N/A	N/A	N/A
	M31	SLSC Car park	meter^2	1002	80,160	N/A	N/A	N/A

Table 8-3: At risk public infrastructure of Callala beach

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Roads**							
	Cal 1	Greenway Road	meter	530	233,200	N/A	N/A	32
	Public building and other infrastructure							
	Cal 2	Tennis club house	unit	1	600,000	N/A	N/A	N/A
	Cal 3	Car park at tennis club	meter^2	300	24,000	N/A	N/A	N/A
	Cal 4	Toilet block in front of tennis club	unit	1	100,000	N/A	N/A	N/A
	Cal 4	Car park on Callala Beach Road	meter^2	320	25,600	N/A	N/A	N/A

Table 8-4: At risk public infrastructure of Collingwood beach

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Sewerage Infrastructure**							
	Col 1	pump station (SPS 9)	unit	1	400,000	Col 1, Col 3	0.25	81
	Col 2	150mm Gravity main southern end of Elizabeth Street	meter	730	169,797	Col 3	0.50	81
	Col 3	225mm rising main southern end along Elizabeth Street	meter	1420	394,522	Col 6	1.00	3500*
	Col 4	450mm gravity main along Susan Street	meter	47	32,606	Col 5, Col3	0.50	454
	Col 5	450mm gravity main Montague Street	meter	67	47,208	Col3	0.50	470
	Col 6	225mm rising main Berry Street	meter	92	26,668	Col3	1.00	3500*
	Water Supply Infrastructure							
	Col 7	Illfracombe Avenue 100mm water main	meter	460	41,458	N/A	1.00	22
	Roads							
	Col 8	Ilfracombe Avenue	meter	460	202,400	N/A	N/A	24
	Col 9	Susan Street (East of Elizabeth Dr)	meter	30	13,200	N/A	N/A	1
	Col 10	Berry Street (East of Elizabeth Dr)	meter	20	8,800	N/A	N/A	2
	Col 11	Montague Street (East of Elizabeth Dr)	meter	25	11,000	N/A	N/A	2
	Col 12	Public cycle way	meter	2000	100,000	N/A	N/A	N/A

*Rising main pipeline carries effluent of the entire Huskisson/Vincentia area form the treatment plant to the ocean outfall

Table 8-5: At risk public infrastructure of Collers beach

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Water Supply Infrastructure**							
	CB 1	150 mm gravity main	meter	48	10,638	N/A	0.50	1

Table 8-6: At risk public infrastructure of Warrain beach

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Water Supply Infrastructure**							
	War 1	Farrant Avenue 150mm gravity main	meter	190	44,998	N/A	0.50	56
	Public building and other infrastructure							
	War 2	SLSC (Surf Club)	unit	1	1,000,000	N/A	N/A	N/A
	War 3	Car park	unit	1	102,000	N/A	N/A	N/A

Table 8-7: At risk public infrastructure of Culburra beach

	ID	Name of the infrastructure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Water Supply Infrastructure**							
	Culb 1	150mm Gravity main near Allerton street	meter	100	23,514	N/A	0.50	29
	Culb 2	150mm Gravity main near Haven street	meter	48	10,815	N/A	0.50	16
	Roads							
	Culb 3	Allerton street	meter	100	44,000	N/A	N/A	5
	Culb 4	Haven street	meter	30	13,200	N/A	N/A	1
	Public building and other infrastructure							
	Culb 5	Part of Allerton street car park	unit	40	3,200	N/A	N/A	N/A
	Culb 6	Large car park at northern end	unit	2,000	160,000	N/A	N/A	N/A

Table 8-8: At risk public infrastructure of Shoalhaven Heads

	ID	Name of the infra-structure	Unit	Quantity	Estimated value (AUD)	Performance dependent on	Recovery time (estimated) Days	Capacity (Number of Households)
SET-01	**Sewerage Infrastructure**							
	SH 1	150mm gravity main along mcintosh street	meter	101	23,848	N/A	0.50	0
	Water Supply Infrastructure							
	SH 2	100 mm Reticulation Mcintosh street	meter	167	14,915	N/A	0.50	0
	Public building and other infrastructure							
	SH 3	All of the surf club	unit	1	1,000,000	N/A	N/A	N/A
	SH 4	Surf club car park	meter^2	1,500	120,000	N/A	N/A	N/A

Table 8-9: Vulnerability matrix of exposure (SEVA-INFRA-SD)

Public infra-structures and services	Code	Harm criteria	Mollymook	Collingwood	Callala	Currarong	Warrain	Culburra	Shoalhaven Heads	Collers
Sewerage	H1	$ value of affected pumping stations	2,260,000	400,000	-	-	-	-	-	-
	H2	$ value of affected rising main	300,614	421,190	-	-	-	-	-	-
	H3	$ value of affected gravity main	354,277	249,611	-	-	44,998	34,329	23,848	10,638
Water supply	H4	$ value of affected water main	26,145	41,458	-	15,000	-	-	14,915	-
	H5	$ value of affected trunk main	158,147	-	-	-	-	-	-	-
Roads and bridges	H6	$ value of affected roads	575,960	335,400	233,200	224,400	-	57,200	-	-
Public buildings and other infra-structures	H7	$ value of other affected infrastructure (e.g., surf club, car park)	5,624,940	-	649,600	-	1,102,000	163,200	1,120,000	-

Sensitivity and adaptive harm criteria of roads

Direct impacts (H10) were calculated by overlaying the road network of a beach on the hazard lines and counting the number of houses that use the said road for direct access to their households (Table 8-10). On the other hand, the calculation of indirect impacts (H11) of a road disruption event was more complicated. This is mainly because indirect impacts depend on multiple factors: the functional category of the road, the traffic volume of the road, the availability of alternative routes, to name a few. These factors were considered and scales were developed for both sensitivity (H11) and adaptive capacity (H18) in consultation with the transportation experts of the council (Table 8-10). At-risk roads were classified and scores were allocated based on these scales and again, maximum value was adopted for the beach.

Sensitivity harm criteria of sewerage and water supply systems

Two sets of values are calculated for sewerage and water supply infrastructure, one without system dynamics and the other with it. Values for the former were quantified by overlaying infrastructure layer with the hazard lines (Table 8-11). On the other hand, values for the latter were obtained by building a SEVA-SD model for individual beaches (Table 8-13). The following section describes the quantification technique used for H8 (sewerage) and H9 (water). Only models for Mollymook beach are shown here as this beach has the maximum number of at-risk infrastructure with dependencies. A similar technique was used for Collingwood. Other beaches either do not have at-risk sewerage/water supply infrastructure or at-risk infrastructures are remote and their disruption does not have effects on services in other parts of the beach.

The conceptual model of SEVA-INFRA-SD (Table 7-1) defined sensitivity of the infrastructure to the impacts of the hazard as follows.

1. Extent to which the well-being of the community of users of the public infrastructure is likely to suffer as a result of disruption to service;
2. Extent to which, and speed with which, relevant public authorities are able to repair damaged infrastructure components and restore disrupted services to users or offer substitute services

For both H8 and H9, point 1 was attained by building a system dynamics model of the infrastructure systems of the beach. This was achieved by identifying dependencies among the nodes of a given system of a beach and modeling them using SEVA-SD (developed in Chapter 6). There is no service interdependency between the sewerage and water supply systems of Shoalhaven beaches as they function as separate individual infrastructure layers. However, both sewerage and water supply systems have multiple components (or nodes) within the system that are mutually dependent. As an example, the sewerage system of Shoalhaven beaches collects waste water from source (e.g., households, other public facilities) through gravity mains, and transports it through rising mains to a treatment plant, and finally discharges the treated waste to an ocean outlet using a pump station. Therefore, these components (e.g., gravity main, rising main, treatment plant and pumping stations) are dependent on each other, i.e. a disruption in one node has the potential to disrupt the operation of the whole sewerage system of the beach.

Dependencies (for both sewerage and water supply system) were identified for Shoalhaven beaches (listed in Table 8-1 to Table 8-8) in collaboration with the concerned engineers of Shoalwater and were modeled using SEVA-SD. It should be mentioned that only at-risk infrastructure nodes (set-01) were considered for SEVA-SD modeling as the aim of the model was to identify how the disruption of all at-risk infrastructure components (or nodes) affects the overall serviceability of the given system of the beach. However, if the serviceability of any *not* at-risk node (e.g., node that is located outside the hazard line) is dependent on an at-risk node, then those were identified and listed as set-02 infrastructure. Such characterization allows the model to identify the cascading effects of failure that goes beyond the beach (i.e. to the surrounding suburbs). Only the sewerage system of the Mollymook beach has been found to have set-02 infrastructure. Figure 8-3 shows the SEVA-SD model of Mollymook sewerage system.

On the other hand, point 2 (previous page) requires information on the capacity of the relevant authority to manage disruption. In order to build such information, a hypothetical storm event (with an increased wave run-up due to SLR) has been considered along the Shoalhaven coast and all of the at-risk infrastructure nodes have been assumed to be disrupted. In consultation with the engineers from Shoalwater,

Table 8-10: At risk roads of Shoalhaven and possible impact of their disruption

	Sensitivity					Adaptive Capacity			
	Direct Impact (access to property)	Indirect impact (passing traffic)			Value adopted for the beach [e]	Direct impact [c]	Indirect impact [d]	Combined capacity (Sum of the two)	Value adopted for the beach [e]
Name of the at risk roads	No. of households	Functional type of the road	AADT [a]	Importance [b]					
Mollymook									
Golf Avenue	0	Collector	1,395	2	2	2	1	3	4
Ocean Street	0	Collector	1,085	2		2	1	3	
Beach Road	17	Local	700	1		2	0	2	
Mitchell Parade, south of Tallwood Ave	22	Collector	5,766	2		2	2	4	
Bridge on Michelle parade	0	Collector	9,765	2					
Collingwood Beach									
Ilfracombe Avenue	24	Local	525	1	1	2	0	2	2
Susan Street (East of Elizabeth Dr)	1	Local	150	1		2	0	2	
Berry Street (East of Elizabeth Dr)	2	Local	75	1		2	0	2	
Montague Street (East of Elizabeth Dr)	2	Local	100	1		2	0	2	
Callala Beach									
Greenway Road	32	Local	550	1	1	2	0	2	2
Currarong Beach									
Warrain Crescent (eastern end)	14	Local	200	1	1	2	0	2	2
Warrain Crescent (western end)	9	Local	250	1		2	0	2	
Culburra Beach									
Allerton St	5	Local	450	1	1	2	0	2	2
Haven Street	1	Local	450	1		2	0	2	

a. AADT= Annual Average Daily Traffic; for b, c and d please see the following table; e: maximum value of the roads of a given beach was adopted as the value for the beach

b. Scale for importance (indirect impact)	
arterial roads	3
collector roads	2
local roads	1

c. Scale for adaptive capacity of direct impact	
Alternative service cannot be provided	2
Alternative service can be provided	1

d. Scale for adaptive capacity of indirect impact	
No alternative access available	3
Alternative access is available but reroute length is long	2
Alternative access is available	1
No Indirect impact	0

Table 8-11: Vulnerability matrix of sensitivity without SD (NH/Hr: Number of Household/Hour; NH: Number of Household; N/A: Not Applicable)

Public infrastructures and services	Code	Harm criteria	Unit	Mollymook	Collingwood	Callala	Currarong	Warrain	Culburra	Shoalhaven Heads	Collers
Sewerage	H8	pumping stations	NH/Hr	475	81	0	0	0	0	0	0
		rising main		630	2178	0	0	0	0	0	0
		gravity main		129	1005	0	0	56	45	0	1
Water supply	H9	water main		21	22	0	10	0	0	0	0
		trunk main		29	0	0	0	0	0	0	0
Roads and bridges	H10	roads (direct Impact)	NH	39	29	32	23	0	6	0	0
	H11	roads (indirect Impact) [a]	N/A	2	1	1	1	1	1	1	1
Public buildings and other infrastructures	H12	other affected infrastructure (e.g., surf club, car park) [b]		5	1	1	1	5	4	5	1

a: based on scale shown in Table 8-10; b: based on scale shown in Table 8-12

Table 8-12: Scale used for identifying sensitivity of public infrastructures categorized as others (H12)

Scale for other infra (e.g., surf club, car park)	Number of affected population	Scale
	>200	5
	75-200	4
	51-75	3
	26-50	2
	No affected population	1

Table 8-13: Vulnerability matrix of sensitivity with system dynamics (SEVA-INFRA-SD)

Public infra-structures and services	Code	Harm Criteria	Unit	Mollymook	Collingwood	Callala	Currarong	Warrain	Culburra	Shoalhaven Heads	Collers
Sewerage	H8	Hmax (waste)	NH/Hr	5,855	3500	0	0	56	45	0	1
Water supply	H9	Hmax (water)		50	22	0	10	0	0	0	0
Roads and bridges	H10	roads (direct Impact)		39	29	32	23	0	6	0	0
	H11	roads (indirect impact)[a]	N/A	2	1	1	1	1	1	1	1
Public buildings and other infra-structures	H12	other affected infrastructure (e.g., surf club, car park) [b]	N/A	5	1	1	1	5	4	5	1

a: based on scale shown in Table 8-10; b: based on scale shown in Table 8-12; NH/Hr: Number of household served per hour estimation was then made for the service restoration time (listed in Table 8-1). Actual restoration time will depend on the type of the actual damage and may vary from case to case. However, experts from the Council suggested that if the damage is *not* associated with a complete replacement of the equipments, then the estimated times can be considered as reasonable assumptions. It was found that the rising mains of the sewerage system would take maximum time to restore (1 day) as generally these are under pressure and require installation of service valves. Restoration of pumping stations, on the other hand, requires minimum duration (a quarter of a day) assuming that the failure is associated with the disruption in power supply on site.

Restoration information was then included in the SEVA-SD model prepared for the Mollymook sewerage system (Figure 8-3) in order to calculate H_{max} which is the maximum number of households at any point in time, affected by the drop in the serviceability. The model was run with a response time (T_R) of 48 hours in two different scenarios (no stress and under stress). This choice of T_R was made because experts of Shoalwater suggested that if the disruption does not require complete reconstruction of the node, then there is a high possibility that all of the disrupted at-risk nodes can be restored within this time frame.

Figure 8-4 shows the serviceability curve generated by the model under both scenarios. Base case scenario (no stress) serves 6,562 households of Mollymook and its surrounding area. However, when the model was run in an under-stress scenario (with restoration information in place), a change was observed (non-linear in time) in the serviceability curve with a maximum drop (H_{max}) after 6 hours of the storm event with a value of 5,816 sewerage service disrupted households. The system was restored at normal capacity after 24 hours. A similar model was developed for Mollymook's water supply system (Figure 8-5 and Figure 8-6) and Collingwood's sewerage system (Figure 8-7).

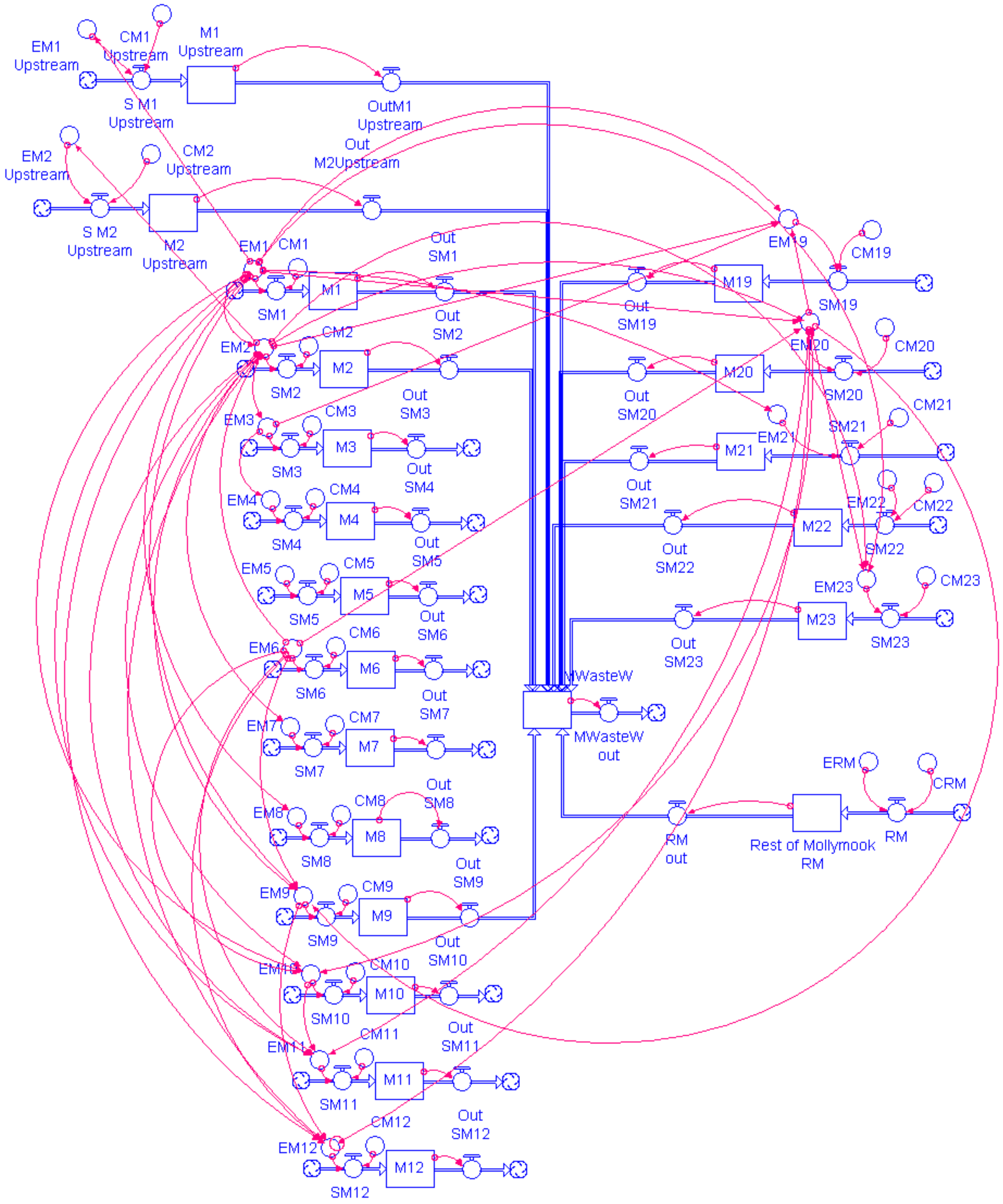


Figure 8-3: SEVA-SD model for Mollymook sewerage system

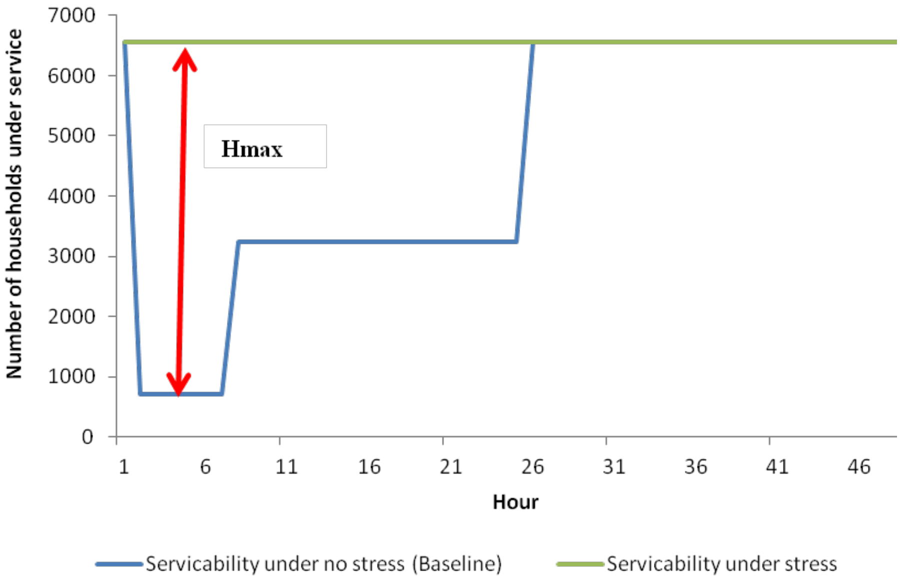


Figure 8-4: Serviceability curve of Mollymook sewerage system under two scenarios

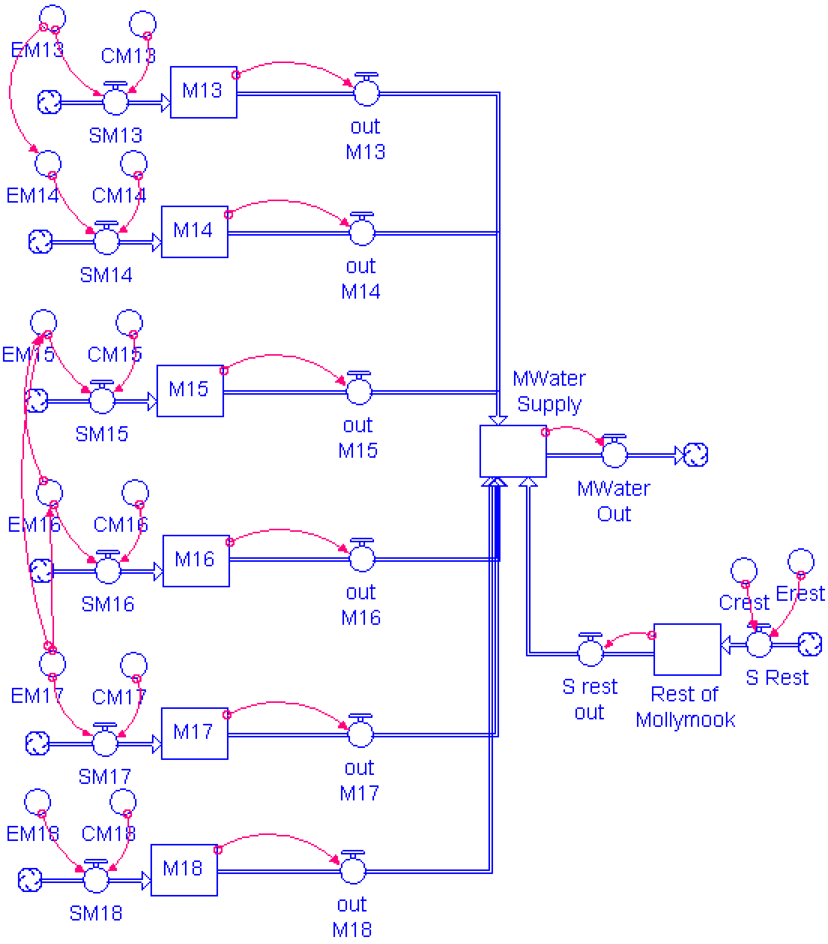


Figure 8-5: SEVA-SD model for Mollymook water supply system

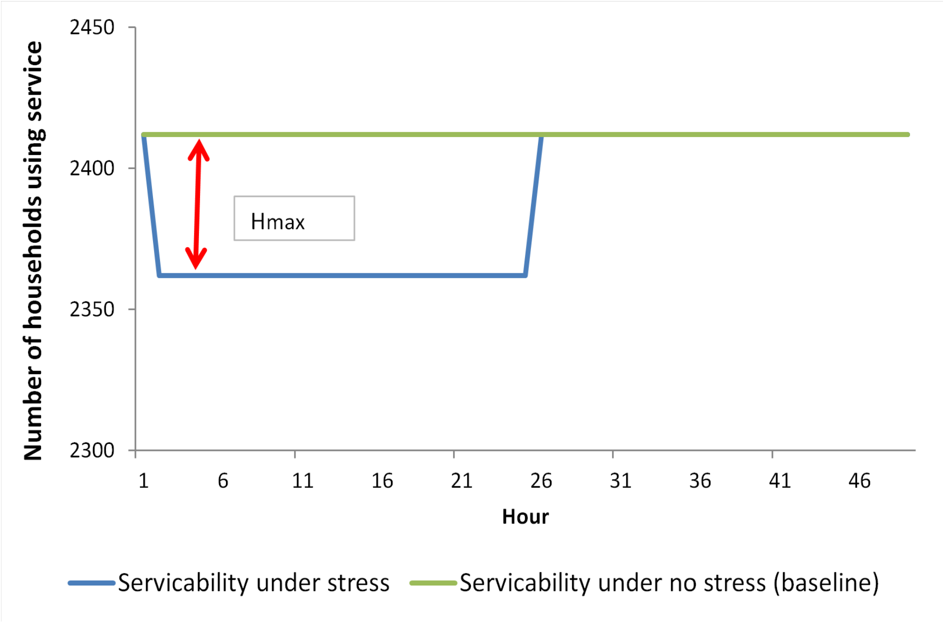


Figure 8-6: Serviceability curve of Mollymook water supply system under two scenarios

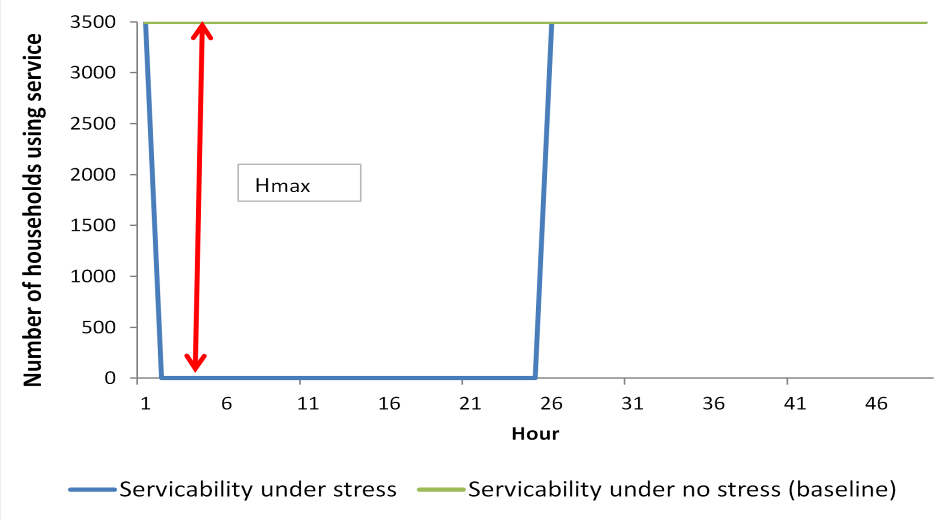


Figure 8-7: Serviceability curve of Collingwood sewerage system under two scenarios

Adaptive capacity harm criteria for sewerage and water supply system

The conceptual model of SEVA-INFRA-SD (Table 7-1) defined adaptive capacity harm criteria as "extent to which, and speed with which, users are able to substitute, or do without, disrupted services, without help from government institutions". It is reasonable to assume that the user's ability to substitute the disrupted service reflects the "importance" of the service that the infrastructure provides. As an example, the service of a given water main serving a hospital is more vital than a similar capacity water main serving a number of private households. Therefore, this concept was operationalized by categorizing the identified at-risk infrastructures based on the importance of the service that they provide (Table 8-14). For this purpose, one scale was developed by consulting with the relevant experts from the council (Table 8-15) and used for both the sewerage and water supply system. Each at risk infrastructure node (of sewerage and water supply system) was allocated a value using this scale. Finally the infrastructure node which had the maximum value (within a given system of a given beach) was identified and its value was adopted as the harm criterion of the whole beach. This approach ensures that each beach is as vulnerable as its weakest links. It must be borne in mind here that, consistently with our outranking framework, the scale aims to compare the performance of different beaches for a given harm criterion; NOT compare the importance of different harm criteria.

Adaptive capacity of "other infrastructure"

Adaptive capacity of "other infrastructure" was perceived as the ability of the users of the infrastructure to avail similar service by any other available alternative means. Again value for this harm criterion was measured using a predefined scale, developed in consultation with the Council experts (Table 8-16).

8.3.2.2 SEVA-HOUSE

Hazard lines were overlaid with properties layer of the beaches and at-risk properties were counted and used as a sensitivity harm criteria (Table 8-17). A median property value of the beaches was obtained from the Australian Property Monitor (APM) and used to calculate the total present value of at-risk properties which yielded our exposure harm criteria (Table 8-18). This data was based on the last 12 months median property sale value of each individual beach. Adaptive capacity harm criteria (which are selected measures of the demographic profile of the beach shown in Table 8-19) were obtained from the Australian Bureau of Statistics (ABS, 2011) using data for State Suburbs Level (SSL) which corresponds roughly with the beach community.

Table 8-14: Vulnerability matrix of adaptive capacity (SEVA-INFRA-SD)

Public infra-structures and services	Code	Harm criteria	Unit	Mollymook	Collingwood	Callala	Currarong	Warrain	Culburra	Shoalhaven Heads	Collers
Sewerage [a]	H13	pumping stations	N/A*	3	2	0	0	0	0	0	0
	H14	rising main		2	2	0	0	0	0	0	0
	H15	gravity main		2	2	0	0	2	2	1	1
Water supply [a]	H16	water main		1	1	0	1	0	0	1	0
	H17	trunk main		1	0	0	0	0	0	0	0
Roads and bridges [b]	H18	roads		4	2	2	2	0	2	0	0
Public buildings and other infra-structures [c]	H19	other affected infrastructure (e.g., surf club, car park)		3	0	0	0	3	2	2	0

a: based on scale shown in Table 8-15; b: based on scale shown in Table 8-10; c: based on scale shown in Table 8-16; *N/A Not Applicable

Table 8-15: Scales used for water and sewerage infrastructure (H13 to H17)

Extremely Critical - asset failure is unacceptable. The consequences are so serious that they cannot be tolerated under any circumstances	3
Critical - The consequences of failure may be tolerated provided the risk of failure is as low as reasonably practicable.	2
Non - Critical - Consequences of asset failure are acceptable	1
No infrastructure affected	0

Table 8-16: Scale used for identifying adaptive capacity of public buildings and other infra-structures (H19)

Users have no capacity to avail similar service with alternative options.	3
Users have alternative options to ***partially*** avail similar service with minimum effort	2
Users have alternative options to ***completely*** avail similar service with minimum effort	1
Beach was assigned the highest value for its affected other public infrastructure	

Table 8-17: Vulnerability matrix of sensitivity (SEVA-HOUSE)

	Code	Harm Criteria	Mollymook	Collingwood	Callala	Currarong	Warrain	Culburra	Shoalhaven Heads	Collers
Residential properties	H22	No of affected residential properties	46	104	81	10	8	86	0	0
Commercial properties	H23	No of affected commercial properties	1	0	0	0	0	0	0	0
Public infra-structure and services	H24	Number of properties at the beach affected by possible failure in public infrastructure*	1323	3315	32	33	56	51	0	1

* These are the households that are located at the beach (not in neighboring suburb)

Table 8-18: Vulnerability matrix of exposure (SEVA-HOUSE)

	Code	Harm Criteria	Mollymook	Collingwood	Callala	Currarong	Warrain	Culburra	Shoalhaven Heads	Collers
Residential properties	H20	$ value of affected residential properties *	20,240,000	35,360,000	27,540,000	4,300,000	3,440,000	28,552,000	0	0
Commercial properties	H21	$ value of affected commercial properties	4,817,400	0	0	0	0	0	0	0

* rates are based on the last 12 months median property sale value data from Australian Property Monitor	**Mollymook**	**Collingwood**	**Callala**	**Currarong**	**Warrain**	**Culburra**	**Shoalhaven Heads**	**Collers**
	$440,000	$340,000	$340,000	$430,000	$430,000	$332,000	N/A	N/A

Table 8-19: Vulnerability matrix of adaptive capacity (SEVA-HOUSE)

	Code	**Harm Criteria**	**Unit**	**Mollymook**	**Collingwood**	**Callala**	**Currarong**	**Warrain**	**Culburra**	**Shoalhaven Heads**	**Collers**
Demographic profile of the whole beach*	H25	% of population attending secondary education	%	23	21	21	17	26	26	21	23
	H26	% of population under 19		20	20	23	21	20	20	18	22
	H27	% of population over 60		37	37	39	36	38	38	41	36
	H28	% of single-parent household		16	13	18	9	18	18	14	14
	H29	median weekly household income	AUD	791	935	724	845	757	757	691	816

*source of these data is the ABS demographic profile 2011. Demographic profile of Warrain is not available separately, rather in ABS data, it is included with Culburra. Therefore demographic profile of Culburra was adopted for Warrain. Again, demographic profile of Collers beach is not separately available. However, there is a data in ABS that includes most of the collrs beach. It is named as Mollymook with code SSC11570. This was used for Collers.

8.3.2.3 Thresholds of difference and votes

As discussed earlier in the thesis, thresholds of difference control the extent of intuitive nonlinearity in the relationship between vulnerability V and a given harm criterion H, as well as degrees of compensation between different harm criteria. They can be derived through two types of reasoning, depending on the harm criterion in question:

1. from estimates by experts, in the absence of more precise articulations of the relationship V=f(H1,H2,…);
2. as a “value judgment” by stakeholders.

The first type can be illustrated by referring to the case of the $ value of damage to an infrastructure component (e.g., water main) as a harm criterion representing exposure (SEVA-INFRA, H1 to H7). To determine the indifference threshold for this harm criterion, Council engineers and financial managers were asked to provide a $ value below which the damage, or difference in damage to a component between two SESs, is considered insignificant. This can be based on the *modus operandi* of the Council and would mirror thought processes of these experts. An example of the second type is the degree of importance of, and ability to do without, a particular service provided by an infrastructure system to the community, as a harm criterion representing adaptive capacity (H13-H19). If the community chooses to single out one particular service as being indispensable, a veto threshold can be introduced to reflect this judgment.

It is important to keep in mind that the distinction between these 2 types of reasoning is not always clear cut: “estimates” by experts carry “value judgment” and “opinions” of stakeholders can also be partly based on “expertise”. Therefore, the distinction was useful in discussion with stakeholders in eliciting thresholds of difference; however, once these thresholds have been determined, it stopped having any effect on the SEVA analyses. Table 8-20 to Table 8-27 list the thresholds and votes generated by two consecutive workshops with the Council stakeholders.

Table 8-20: Average exposure thresholds for SEVA-INFRA-SD obtained from the responses of the stakeholders

Public infra-structures and services	Code	Harm Criteria	Unit	Average Thresholds			Expert thresholds*		
				q	p	v	q	p	v
Sewerage	H1	pumping stations	AUD	158,333	308,333	583,333	500,000	1,000,000	2,000,000
	H2	rising main		78,333	180,000	348,333	100,000	500,000	1,000,000
	H3	gravity main		71,667	139,167	236,667	100,000	300,000	500,000
Water supply	H4	water main		68,333	138,333	235,833	100,000	300,000	500,000
	H5	trunk main		73,333	180,833	348,333	100,000	500,000	1,000,000
Roads and bridges	H6	affected roads		57,500	133,333	262,660	25,000	250,000	575,960
Public buildings and other infra	H7	other infrastructure		75,000	185,000	310,000	75,000	185,000	310,000

*For sewerage and water supply, expert thresholds were provided by Shoalwater engineers and for roads by engineers of transportation department. However, these experts did not provide any thresholds for public and other buildings and therefore average threshold is used in this case.

Table 8-21: Average sensitivity thresholds for SEVA-INFRA-SD obtained from the responses of the stakeholders (used only for the scenario without SD)

Public infra-structures and services	Code	Harm Criteria	Unit	Average Thresholds			Expert threshold*		
				q	p	v	q	p	v
Sewerage	H8	pumping stations	NH	18	155	846	100	500	3,000
		rising main		17	112	1,759	100	500	3,000
		gravity main		21	97	1,046	100	500	3,000
Water supply	H9	water main		15	150	601	100	1000	4,000
		trunk main		14	151	598	100	1000	4,000
Roads and bridges	H10	direct impacts	N/A	4	17	41	3	8	23
	H11	indirect impacts		0	1	1	0	1	1
Other infra-structures	H12	other affected infrastructure		0	1	4	0	1	4

*For sewerage and water supply, expert thresholds were provided by Shoalwater engineers and for roads by engineers of transportation department. However, these experts did not provide any thresholds for public and other buildings and therefore and therefore average threshold is used in this case; NH: Number of Household

Table 8-22: Average sensitivity thresholds for SEVA-INFRA-SD obtained from the responses of the experts (Scenario with SD only)

Public infra-structures and services	Code	Harm Criteria	Unit	Expert threshold		
				q	p	v
Sewerage	H8	(Hmax)waste	NH/Hr*	100	500	3,000
Water supply	H9	(Hmax)water		100	1,000	4,000
Roads and bridges	H10	direct impacts	N/A	3	8	23
	H11	indirect impacts		0	1	1
Other infra-structures	H12	other affected infrastructure		0	1	4

*NH/Hr: Number of household/hour; As harm criteria H11 and 12 are based on ordinal scale, therefore 0 is taken as q, 1 as p and maximum difference in scores between two beaches in that harm criteria is taken as v

Table 8-23: Thresholds adopted for adaptive capacity (SEVA-INFRA-SD)

Public infra-structures and services	Code	Harm criteria	Unit*	q	p	v
Sewerage	H13	pumping stations	N/A	0	1	3
	H14	rising main		0	1	2
	H15	gravity main		0	1	2
Water supply	H16	water main		0	1	1
	H17	trunk main		0	1	1
Roads and bridges	H18	roads		0	1	4
Public buildings and other infra-structures	H19	other affected infrastructure		0	1	3

*N/A: Not applicable. As these harm criteria are ordinal and based on a scale, 0 is taken as q, 1 as p and maximum difference in scores between two beaches in that harm criteria is taken as v

Table 8-24: Average exposure thresholds for SEVA-HOUSE obtained from the responses of the stakeholders

Type of properties	Code	Harm Criteria	Unit	q	p	v
Residential properties	H20	residential properties	AUD	2,000,000	9,000,000	35,360,000
Commercial properties	H21	commercial properties		2,000,000	9,000,000	35,360,000

Table 8-25: Average sensitivity thresholds for SEVA-HOUSE obtained from the responses of the stakeholders

Type of properties and infrastructure	**Code**	**Harm criteria**	**Unit***	**q**	**p**	**v**
Residential properties	I22	residential properties	NH	6	28	126
Commercial properties	I23	commercial properties		0	1	1
Public infra-structure and services	I24	due to possible failure in public infrastructure		6	28	743

*NH: Number of households

Table 8-26: Average adaptive capacity thresholds for SEVA-HOUSE obtained from the responses of the stakeholders

	Code	**Harm criteria**	**Unit**	**q**	**p**	**v**
Demographic profile of the whole beach	H25	% of population passing year 12	%	19	35	73
	H26	% of population under 18		18	39	71
	H27	% of population over 60		18	40	70
	H28	% of single-parent household		19	38	72
	H29	median weekly household income	AUD	66	135	249

Table 8-27: Average votes obtained from the responses of the stakeholders

	Average of all participants			Average of the participated experts (sewerage, water and roads)		
	Exposure	Sensitivity	Adaptive Capacity	Exposure	Sensitivity	Adaptive Capacity
SEVA-INFRA-SD	1	1.8	2.5	1	1.5	2
SEVA-HOUSE	1	2.2	3.2	N/A	N/A	N/A

8.4 Development of community preference scenarios

As discussed in the previous chapter (section 7.5.2), during the last two stages of consultation with Council stakeholders, a number of questions came up which can be seen as matters of values and value judgment for the Shoalhaven community at large. The ones that were deemed important and could potentially have strong influence on the outcome of the analyses were identified and discussed below. Clearly, if the consultation is widened to include bigger section of stakeholders outside the Council, other preference issues might arise.

8.4.1 Respective infrastructure experts versus other Council stakeholders (Scenario-01)

As discussed in the previous chapter, multiple stakeholders from the Shoalhaven Council were consulted which include both experts from respective infrastructure authority (e.g., water, waste and roads) and experts from authorities which are responsible for overall coastal planning and management (e.g., tourism unit, coastal planning unit, asset management unit). In this thesis, the latter is referred to as other stakeholders. Thresholds of differences and votes of the vulnerability harm criteria (developed in the previous chapter) were generated from the responses of the stakeholders that attended the workshops. The question is, should priority be given to the vulnerability perspective of the respective infrastructure expert (e.g., opinion of water supply expert about the thresholds and votes related to water supply harm criteria) over the average opinion of all of the stakeholders or not? During consultation, it was observed that opinions about thresholds of differences and votes may differ significantly between, on the one hand, the experts on a specific infrastructure and, on the other hand, the remaining stakeholders (Table 8-20 and Table 8-21). Scenario-01 (Table 8-28) reflects this issue by giving preference to “all stakeholders” opinion over experts. The base case scenario, on the other hand, uses expert’s opinion.

8.4.2 Service value versus asset value of the infrastructure (Scenario-02)

The service value of the infrastructure refers to the extent to which the service that the infrastructure provides is critical, while the asset value refers to its monetary value (i.e. present replacement cost). An infrastructure can have comparatively low monetary value but still serve a critical service to the community and vice versa. As an example, a water main supplying water to a hospital or an aged care facility might have less asset value than a golf course or a surf club. However, the relative importance of the service is reversed. Therefore, the question arises, while conducting a vulnerability assessment that focuses on infrastructure, whether to give priority to the service value over the asset value of the infrastructure or vice versa. As an example, a surf club located at Warrain beach (War 2, Table 8-6), worth 1 Million AUD, is at risk. This is mainly used as a tourist amenity. On the other hand,

Table 8-28: Preference scenarios

	Expert vs All Stakeholders	**Service vs Financial Value**	**Sewerage vs Other IS***	**Public IS vs Private Properties**	**Residential vs Commercial Properties**
Base Case	Expert	Both similarly important	All similarly important	Public	Public
Scenario-1 Average stakeholder-preference scenario	All stakeholders	Both similarly important	All similarly important	Public	Public
Scenario-2 Service-preference scenario	Expert	Service more important	All similarly important	Public	Public
Scenario-3 Sewerage-priority scenario	Expert	Both similar important	Sewerage more important	Public	Public
Scenario-4 Private property preference scenario-a	N/A*	N/A*	All similarly important	Private	Separate criteria
Scenario-5 Private property preference scenario-b	N/A*	N/A*	All similarly important	Private	Combined in single criterion
How?	Using votes and thresholds of difference as the average of all stakeholders in scenario 1	Reducing the votes by half and disabling the dominance thresholds for H7, H12 and H19 in scenario 2	Doubling the votes and enabling dominance thresholds only for H1 to H3, H8 and H13 to H15 in scenario 3	Use SEVA-HOUSE instead of SEVA-INFRA-SD in scenario 4	Use SEVA-HOUSE instead of SEVA-INFRA-SD and lump H20, H21 together and H22, H23 together in scenario 5
Affected harm criteria	All harm criteria of SEVA-INFRA-SD except H7, H12 and H19**	H7, H12 and H19	H1, H2, H3, H8, H13, H14 and H15	H20 to H29	H20, H21, H22 and H23

*IS: Infrastructure systems; N/A: Not applicable;
**No expertise associated with these harm criteria

Mollymook beach has some water supply infrastructure at risk (M13 to M18 Table 8-1) whose present replacement cost is far less than the surf club at Warrain beach but affects the water supply of 50 households of Mollymook beach. In order to reflect such issues in the vulnerability rankings, a service preference scenario was developed (scenario-02) where importance of the service is determined by the service it provides rather than its financial value. In order to operationalize this concept, dominance thresholds of the harm criteria associated with "other infrastructure" (which consists of surf club, car park and other public buildings) were disabled (H7, H12 and H19). This was done to ensure that a beach whose vulnerability is generated by damage to "other infrastructure" does not get any advantage (i.e. seen as more vulnerable) over beaches with more damage to their water supply, sewerage system and roads. In the base case scenario, on the other hand, "service" and "financial" values were given equal treatment.

8.4.3 Sewerage system versus other infrastructure system (Scenario-03)

Shoalwater is responsible for managing Shoalhaven's water and sewerage infrastructure. During the consultation process, it became clear that the Shoalwater engineers give priority to problems associated with sewerage systems over the same-scale problems of water supply. This is because of the health hazard aspect of sewerage problems. In addition, the engineers were conscious of the potential adverse impact of a possible sewerage overflow on the nearby oyster farms. In order to test the impact of such preference (of sewerage system over water supply) on the vulnerability ranking, a sewerage-preference scenario (scenario-03) was developed. This provides priority to sewer systems over others and dominance thresholds were only used for the harm criteria that are associated with sewerage system. In the base case scenario, no such preference was given to sewerage systems.

8.4.4 Public infrastructures versus private properties (Scenario-04)

Shoalhaven beaches house both public infrastructure (e.g., water supply, sewerage, roads and other public amenities) and private properties. As discussed in the previous chapter, the processes that generate vulnerability of these two valued attributes are different. Therefore two different vulnerability models were developed (e.g., SEVA-INFRA-SD and SEVA-HOUSE). Both are important parts of Shoalhaven beaches. However, there some beaches in Shoalhaven have more public infrastructure at risk than private properties and vice versa. Again, the question arises whether to give more importance to private properties than public infrastructure or not. Scenario-04 was designed to test the effect on the vulnerability ranking of providing more importance to private properties by using SEVA-HOUSE instead of SEVA-INFRA-SD. (It should be noted that private properties include both commercial and residential properties and this scenario used separate harm criteria for them; H20 and H22 for residential and H21 and H23 for commercial).

8.4.5 Residential versus commercial properties (Scenario-05)

As mentioned before, in Shoalhaven beaches, along with residential properties, there are some business owned commercial properties which are at risk. Both are important. However, one beach might have more residential properties at risk in comparison with commercial ones and vice versa. In order to assess relative vulnerability of these beaches should equal priority be given to commercial and residential properties or not? In the context of the 8 beaches under study, Mollymook has a single, albeit large, commercial property: a golf club. In order to test whether this single asset is having significant influence over rankings, scenario-05, unlike base case, did not distinguish between the residential and commercial properties and added the values (H20 and H21) and numbers (H22 and H23) of the two under single criterion.

Table 8-28 lists these five scenarios. The purpose of building these scenarios is to assess how the change in stakeholder preferences may impact vulnerability rankings. Hence, starting from a base case, each of the 5 scenarios was built as a variation on a single preference issue. For detailed definitions and characteristics of these scenarios please refer to the table in appendix (Table A 7)

Apart from these five scenarios, two additional analyses were conducted. One was for testing the effect of using SD models (by comparing the vulnerability rankings generated with and without SD models) and the other was for comparing the results of outranking methods with the more conventional additive-weight approach. The results of all these analyses are presented in the following section.

8.5 Results

Harm criteria and thresholds of difference were entered into SEVA computer tool (developed in Chapter 4) to generate vulnerability rankings based on the outranking algorithm. Four sets of rankings were generated for each scenario: one for each dimension of vulnerability (exposure, sensitivity and adaptive capacity) and one reflecting the combined 3 dimensions (thereafter referred as combined ranking). Each ranking of a given scenario used its corresponding votes and thresholds of difference (as shown in Table 8-28 and Appendix (Table A 7). In discussing the results, the following conventions are adopted.

a) for exposure and sensitivity rankings, 1 is the most exposed/sensitive beach, while 8 is the least exposed/sensitive one.

b) for adaptive capacity ranking, 1 is the beach with least adaptive capacity, while 8 has the highest.

c) for combined ranking, 1 is the most vulnerable of the beaches, while 8 is the least.

In other words, 1 always reflects highest vulnerability and 8 lowest. For each scenario, spearman correlation factors (SCF) were also calculated. This is a measure of the differences in ranking from the base case (when SCF=1, the rankings generated by the base case and modified case are identical)

8.5.1 Base case

In the base case analysis, harm criteria selected for SEVA-INFRA-SD were used and respective votes and thresholds generated by averaging expert opinions were considered. Table 8-29 shows the rankings of this analysis. Mollymook had the highest possible damage cost of public infrastructure and was ranked as the most exposed beach. Although Warrain and Shoalhaven Heads do not have many roads, sewerage or water supply infrastructure at risk, both were ranked as the 2nd most exposed beach. This was mainly because of the high possible damage cost of the surf clubs located at these two beaches.

Table 8-29: Vulnerability rankings of Shoalhaven beaches: Comparison of rankings with and without system dynamics (Base case: rankings obtained using sensitivity harm criteria that were quantified without using SEVA-SD; Base case-SD: rankings obtained using sensitivity harm criteria that were quantified using SEVA-SD

Scenario	**Base Case**				**Base Case-without SD**			
Dimension	**Exposure**	**Sensitivity**	**Adaptive Capacity**	**Combined**	**Exposure**	**Sensitivity**	**Adaptive Capacity**	**Combined**
SCF	**1**	**1**	**1**	**1**	**1.00**	**0.98**	**1.00**	**0.88**
Mollymook	1	1	1	1	1	1	1	1
Collingwood	4	2	2	2	4	2	2	2
Callala	4	5	8	2	4	5	8	3
Currarong	6	7	6	7	6	6	6	7
Warrain	2	3	3	2	2	3	3	3
Culburra	6	6	4	5	6	7	4	6
Shoalhaven Heads	2	3	5	6	2	3	5	3
Collers	6	8	6	8	6	8	6	8

On the other hand, the sensitivity harm criteria were quantified by using the system dynamics models. As discussed before, SD models were developed only for Mollymook and Collingwood as these were the only two beaches that had at-risk infrastructure with dependencies. SD model for Mollymook captured this service dependency of the sewerage pumping stations and showed (as a form of H_{max}) that disruption to those has the potential to go beyond the beach and affect a large number of households (5,855). Table 8-11 shows, in the absence of the SD model, only 1,234 households were identified to be at risk of sewerage service disruption. However, the number increased to 5,855, when the SD model was introduced (Table 8-13). As a result, Mollymook became the most sensitive of all the beaches. A sewerage rising main of Collingwood (Col 3) carrying the treated waste water of the whole catchment (3500 households) to an ocean outlet is at risk. This makes this beach as the 2nd most sensitive beach. In this ranking (sensitivity), Warrain and Shoalhaven Heads position were lower (less sensitive) as they have lower number of affected household.

In terms of adaptive capacity, Mollymook had the least capacity to adapt as it has some major sewerage pumping stations (M1, M2) at risk. As mentioned before, the service provided by these two pumps goes beyond Mollymook and any disruption to these pumps has the capacity to affect other catchments of neighboring beaches and is therefore considered very critical. In the case of any major physical damage, at present, the Council has no capacity to maintain similar service with any alternative options. Apart from these sewerage pumping stations, another major infrastructure, a collector road (Mitchell parade) of Mollymook which has a high traffic volume (AADT) is at risk. Disruption to the at-risk portion of this road will not only cause losing direct access to 22 properties but also cause diverting a large volume of traffic to alternative route, putting extra pressure on them. This also contributed to Mollymook's overall high exposure and low adaptive capacity.

Finally, when these three dimensions (exposure, sensitivity and adaptive capacity) were combined, Mollymook's highest position in all three dimensions made it the most vulnerable of the beaches. Although Collingwood's exposure ranking was lower (4th), its high sensitivity (2nd) and lower adaptive capacity (2nd) made it as the 2nd most vulnerable of the beaches (in combined ranking). Warrain ranked as 2nd most vulnerable beach along with Collingwood. High damage cost of the surf club as well as its potential to affect a large number of people that use this facility contributed to this fact. Shoalhaven Heads, Currarong and Collers are the three least vulnerable beaches ranked 6th, 7th and 8th respectively. Minimum number of at-risk public infrastructure at these three beaches was one of the main reasons for such low vulnerability ranking. One notable feature of the rankings of the base case is Callala's variation in ranking in different dimensions. It came as 4th most exposed of the beaches (along with Collingwood), 5th most sensitive of the beaches and 8th in terms of adaptive capacity (indicating high adaptive capacity). However, when three dimensions were combined it came as the 2nd most vulnerable of the beaches along with Collingwood and Warrain. This is mainly because when all of 19 harm criteria from the three dimensions were combined, some of exposure and sensitivity harm criteria (e.g., H7, H11, H12) for Callala breached the dominance thresholds, when compared to Collingwood, which was ranked high in all 3 dimensions. This breach made Callala at least as vulnerable as Collingwood (2nd) in combined ranking.

8.5.2 Base Case-without SD

In this set of analyses, the sensitivity harm criteria were NOT quantified by using the system dynamics models, while harm criteria (as well as vulnerability rankings) of exposure and adaptive capacity remained unchanged. Sensitivity harm criteria and their values are shown in Table 8-11. As discussed before, SD models were developed only for Mollymook and Collingwood as these were the only two beaches that had at-risk infrastructure with dependencies. In base case SD models captured the compounding impact of service disruption of Mollymook sewerage system that goes beyond the beach and therefore it was ranked as the most sensitive beach. Removal of SD model for Mollymook reduced the number of affected household as it identified at-risk households located only at the beach. However, this change only affected two harm criteria (sewerage and water supply) of only two beaches (Mollymook and Collingwood), and was had only a small impact on the final rankings of the beaches (Table 8-29).

8.5.3 Base case with simple additive weight (SAW) approach

In this set of analyses the aggregation of harm criteria was done by using a MAUT based simple additive weight approach (SAW). Unlike the base case (where aggregation of harm criteria were done using an outranking approach), SAW does not use any thresholds for ranking, rather rank the beaches using normalized arithmetic mean of the harm criteria. This yields different rankings to the base case in all of the three dimensions as well as in the combined ranking. SAW ranked Collingwood as 2nd most exposed beach while the base case ranked it 4th. Similarly, Shoalhaven Heads

Table 8-30: Comparison of vulnerability ranking between base case and base case using simple additive weight (Here base case used SEVA-II outranking algorithm for aggregation of harm criteria while the other one used simple aggregated weight method.)

Scenario	**Base Case**				**Base case- Simple additive weight**			
Dimension	**Exposure**	**Sensitivity**	**Adaptive Capacity**	**Combined**	**Exposure**	**Sensitivity**	**Adaptive Capacity**	**Combined**
SCF	**1**	**1**	**1**	**1**	**0.85**	**0.80**	**0.87**	**0.59**
Mollymook	1	1	1	1	1	1	1	1
Collingwood	4	2	2	2	2	2	2	2
Callala	4	5	8	2	5	7	7	7
Currarong	6	7	6	7	6	4	6	6
Warrain	2	3	3	2	4	3	5	4
Culburra	6	6	4	5	7	6	3	5
Shoalhaven Heads	2	3	5	6	3	5	4	3
Collers	6	8	6	8	8	8	8	8

and Warrain, which were ranked jointly 2nd most exposed beaches in the base case were ranked 3rd and 4th respectively in SAW. These two beaches ranked higher (more exposed) than Collingwood in the base case because the difference with Collingwood on criteria H7 exceeded dominance thresholds. and the outranking algorithm ensured that these two beaches are ranked at least as high as Collingwood. Although Collingwood had higher damage cost than these two beaches in most of the remaining harm criteria, the differences were below the indifference threshold, which nullified their effects on ranking. Sensitivity ranking of SAW is substantially different than the base case with SCF reducing to 0.80. Although the topmost and the lowermost ranked beaches did not change, there were significant differences in the middle part of the rankings. Most notably Callala which was ranked 5th sensitive beach in the base case, was down to 7th in SAW. Again, the main reason for Callala being ranked higher in the base case is the effect of dominance threshold (in this case, for H12). Shoalhaven Heads, ranked 6th in the combined ranking in base case, was ranked 3rd in SAW. This is mainly because, high damage cost and relevant consequences (i.e. sensitivity and adaptive capacity) of surf club at Shoalhaven Heads compensated for its low damage cost and consequences in rest of the harm criteria in SAW, which was not possible in the base case because of outranking. Adaptive capacity rankings were quite similar in both of the analyses as the scores of adaptive capacity were based on ordinal scale and thresholds of differences had little effect on them. Similarly, combined rankings were also substantially different than the base case with an SCF of 0.59.

8.5.4 Combined analysis for SEVA-INFRA-SD and SEVA-HOUSE

In this set of analyses, harm criteria of two models (SEVA-INFRA-SD and SEVA-HOUSE) were combined in order to generate a new set of rankings. It should be noted that as discussed before, processes that generate vulnerability are quite different for infrastructure and households and that was the reason behind developing two separate models. Therefore, combining these models at this point may look contradictory to that concept. However, this set of analyses was done just to check whether the rankings deviate largely, if one instead of two separate models is built. Results shown in Table 8-31 suggested that rankings, based on each dimension, did deviate from the base case although not by a big margin. Combined rankings were almost similar to base case (where only SEVA-INFRA-SD was used) with an SCF of 0.99. The top and bottom of the ranking never changed. The maximum deviation was observed in the sensitivity rankings where Shoalhaven Heads and Culburra (3rd and 6th respectively in base case) swapped positions (6th and 3rd respectively). In the base case, sensitivity of Shoalhaven Heads was higher mainly because of the at-risk surf club. However, as this beach had no private or commercial properties at risk (while Culburra had a number of at-risk private properties), the sensitivity ranking of Shoalhaven Head in the combined model was reduced. In contrast, Culburra's ranking in sensitivity was higher.

Table 8-31: Comparison of rankings between base case (only SEVA-INFRA-SD) and the analyses where SEVA-INFRA-SD and SEVA-HOUSE harm criteria were combined and lumped into a single model

Scenario	Base Case				Combined SEVA-INFRA-SD and SEVA-HOUSE			
Dimension	**Exposure**	**Sensitivity**	**Adaptive Capacity**	**Combined**	**Exposure**	**Sensitivity**	**Adaptive Capacity**	**Combined**
SCF	**1**	**1**	**1**	**1**	0.97	0.78	0.86	0.99
Mollymook	1	1	1	1	1	1	1	1
Collingwood	4	2	2	2	5	2	2	2
Callala	4	5	8	2	4	5	7	3
Currarong	6	7	6	7	7	7	6	7
Warrain	2	3	3	2	2	4	5	3
Culburra	6	6	4	5	6	3	4	5
Shoalhaven Heads	2	3	5	6	2	6	3	6
Collers	6	8	6	8	8	8	7	8

8.5.5 Scenario-01

If the council prefers the vulnerability perceptions of the combined stakeholders (e.g., all of the participants of the workshop) over the expert opinion, then this value judgment was translated into vulnerability rankings by conducting the SEVA-III analysis using the average responses (votes and thresholds) of all participants (Table 8-20 and Table 8-21). Thresholds obtained from average stakeholder responses tended to be smaller than the same given by the experts. Therefore, smaller differences in harm criteria between the beaches became dominant. This was especially true for the beaches in the middle to bottom part of the ranking (e.g., Culburra, Currarong and Callala) as they had smaller differences in their harm criteria. Therefore stricter thresholds caused changes in the ranking of these beaches. Most notably, Callala (which was ranked 2nd in the combined ranking in base case) was ranked 4th. As mentioned before, this was a result of stricter threshold values.

8.5.6 Scenario-02

In this scenario, the importance of public property is judged more by the services it provides to the community that it's financial value. Warrain and Shoalhaven Heads were ranked 2nd most exposed beach in the base case, because of high financial value of their surf club, were ranked lower (4th) in scenario-02. In the base case, sensitivity ranking of Culburra was higher than that of the Warrain and Shoalhaven Heads. However, this advantage diminished once dominance thresholds were eliminated for "other infrastructure" and in scenario-02 these 3 beaches ranked equally sensitive. Collingwood, which had no "other infrastructure" at risk, was ranked 4th most exposed beach in base case. However, its exposure ranking rose to 2nd in scenario-02, because all of damage was associated with vital infrastructures.

8.5.7 Scenario-03

This scenario allocates more importance to sewerage systems, in comparison with other public infrastructure systems of Shoalhaven. This was done by using dominance thresholds only for harm criteria are associated with sewerage systems (e.g., H1, H2, H3, H8, H13, H14 and H15). Votes for those harm criteria were also doubled. These changes were done to ensure that any beach whose vulnerability was generated, partly or totally, by damage to sewerage systems was given priority. Callala was ranked 2nd most vulnerable beach in the combined ranking of the base case. However, this beach did not have any sewerage infrastructure at risk; therefore, scenario-03 ranked it 7. On the other hand, Shoalhaven Heads and Culburra's vulnerability rose in this scenario, compared with base case, as they had a substantial number of at-risk sewerage infrastructure.

8.5.8 Scenario-04

As mentioned before, this scenario gave preference to private properties over public infrastructure and therefore ranked the beaches using a different model (SEVA-HOUSE instead of SEVA-INFRA-SD). SEVA-HOUSE developed in the previous chapter was used along with the votes and thresholds generated by averaging the responses of all the workshop participants. Collingwood, with the highest number of at-risk private properties

Table 8-32: Vulnerability rankings of Shoalhaven beaches with scenario analysis (SCF: Spearman Correlation Coefficient; E: Exposure; S: Sensitivity; AC: Adaptive capacity; C: Combined ranking)

Scenario	**Base Case**				**Scenario-1** Average stakeholder-preference scenario				**Scenario-2** Service-preference scenario				**Scenario-3** Sewerage-priority scenario				**Scenario-4** Private property preference scenario-a				**Scenario-5** Private property preference scenario-b			
Dimension	**E**	**S**	**AC**	**C**	**E**	**S**	**AC**	**C**	**E**	**S**	**AC**	**C**	**E**	**S**	**AC**	**C**	**E**	**S**	**AC**	**C**	**E**	**S**	**AC**	**C**
SCF	**1**	**1**	**1**	**1**	**0.99**	**0.94**	**1.00**	**0.94**	**0.69**	**0.89**	**1.00**	**0.81**	**0.69**	**0.89**	**0.98**	**0.64**	**0.01**	**0.51**	**-0.13**	**0.82**	**-0.12**	**0.51**	**-0.13**	**0.82**
Mollymook	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	2	4	2	3	2
Collingwood	4	2	2	2	4	2	2	3	2	2	2	2	2	2	2	2	1	1	8	1	1	1	8	1
Callala	4	5	8	2	5	6	8	4	3	6	8	4	3	6	8	7	4	4	2	3	3	4	2	3
Currarong	6	7	6	7	6	6	6	7	4	7	6	7	4	7	7	6	5	6	7	7	5	6	7	7
Warrain	2	3	3	2	2	3	3	2	4	3	3	5	4	3	3	4	6	5	3	5	5	5	3	5
Culburra	6	6	4	5	6	5	4	6	7	3	4	3	7	3	3	3	2	2	3	3	2	2	3	3
Shoalhaven Heads	2	3	5	6	2	3	5	5	4	3	5	5	4	3	5	5	7	7	1	6	7	7	1	6
Collers	6	8	6	8	6	6	6	8	7	8	6	8	7	8	6	8	7	7	6	7	7	7	6	7

and with maximum possible damage cost (present value) was ranked as the most sensitive and most exposed of the Shoalhaven beaches. However, the adaptive capacity of this beach is relatively high (ranked 8th, suggesting the highest adaptive capacity compared to other 7 beaches) with higher median household income and lower % of single parent households. These socio-economic harm criteria may also be correlated with the median property value of Collingwood, which partly explain the high asset values of exposed properties. However, another reason of high vulnerability of Collingwood is their high number of houses under hazard line, which is, of course, unrelated with the median property price.

Mollymook, which was ranked as the most vulnerable beach in the base case (SEVA-INFRA-SD), was ranked 2nd after Collingwood in this scenario. Although Mollymook has a small number of at-risk private residential properties than Callala, the at-risk golf course of Mollymook (which is a commercial property) made it more exposed and sensitive than Callala. The adaptive capacity of the Shoalhaven Heads was the lowest, with the lowest median household income and the highest % of over 60 populations. However, as there is no at-risk private property at this beach, it was ranked 7th least exposed and sensitive of the beaches, with a 6th position when all of these dimensions were combined.

Scenario-05 was designed to test the effect of putting the residential and commercial properties as a single harm criterion (unlike scenario-04 where they were separate as H20 and H21). Mollymook was the only beach with at-risk commercial property (a golf course) and therefore had an advantage (i.e. seen as more exposed) in scenario-04. However, merge of residential and commercial property harm criteria (H20 and H21) eliminated this advantage and ranked Mollymook as 4th exposed beach (which was ranked 2nd in scenario-04).

8.6 Robustness of the results

Two types of robustness analyses were conducted for this study.

a) to test the sensitivity of rankings to changes in votes and thresholds of differences;
b) to test for rank reversal (discussed in chapter 4, page number 4-7)

Sensitivity of rankings to the changes in thresholds of differences was tested by changing the thresholds of differences (q, p and v) for each harm criterion by ± 5% from the base case, one criterion at a time. However, adaptive capacity harm criteria (H13 to H19) are ordinal variables and are quantified based on an ordinal scale and ±5% changes in these harm criteria not likely to make any difference. As an example, thresholds of difference of H13 are 0, 1 and 3 for q, p and v respectively (Table 8-23); a +100% change was made by making them 1, 2 and 4 respectively. Table 8-33 shows the SCF for each analysis (when SCF=1, the rankings generated by the base case and modified case are identical). Out of the 72 sets of analysis (14 for exposure, 10 for sensitivity, 14 for adaptive capacity and 38 for the combined ranking), rankings changed only in 10 cases. However, 9 out of these 10 changes were observed when adaptive capacity harm criteria were changed by ±100%. A ±5% change in exposure and sensitivity harm criteria only changed the ranking once (when H7 was changed). Apart from these changes, rankings were found to be insensitive to changes in thresholds.

In order to test the sensitivity of the rankings to votes, three sets of analysis were conducted, all of which starting from the "combined" analysis (i.e. where all harm criteria of all dimensions were included) (Table 8-34). In the 1st set, the votes of exposure harm criteria were increased 100% from the base case. A small change is observed in the ranking with an SCF of 0.88. The 2nd and 3rd set of analyses changed the votes of sensitivity and adaptive capacity harm criteria respectively by 100%. Again, the rankings were found to be largely insensitive to these changes (with an SCF of 0.98 and 0.99 for change in sensitivity and adaptive capacity respectively).

Table 8-33: Test of robustness: type-a (thresholds of differences)

Ranking Type	**Harm Criteria changed**	**SCF**				**Ranking Type**	**Harm Criteria changed**	**SCF**			
		"+" 5% change	**"-"5% change**	**“+100%” change [a]**	**“-100%” change [a]**			**"+" 5% change**	**"-"5% change**	**“+100%” change [a]**	**“-100%” change [a]**
Exposure	H1	1	1	NA	NA	**Combined**	H1	1	1	NA	NA
	H2	1	1	NA	NA		H2	1	1	NA	NA
	H3	1	1	NA	NA		H3	1	1	NA	NA
	H4	1	1	NA	NA		H4	1	1	NA	NA
	H5	1	1	NA	NA		H5	1	1	NA	NA
	H6	1	1	NA	NA		H6	1	1	NA	NA
	H7	1	1	NA	NA		H7	**0.99**	1	NA	NA
Sensitivity	H8	1	1	NA	NA		H8	1	1	NA	NA
	H9	1	1	NA	NA		H9	1	1	NA	NA
	H10	1	1	NA	NA		H10	1	1	NA	NA
	H11	1	1	NA	NA		H11	1	1	NA	NA
	H12	1	1	NA	NA		H12	1	1	NA	NA
Adaptive Capacity	H13	NA	NA	1	1		H13	NA	NA	1	1
	H14	NA	NA	**0.99**	1		H14	NA	NA	1	1
	H15	NA	NA	1	**0.96**		H15	NA	NA	**0.98**	**0.9**
	H16	NA	NA	**0.92**	**0.84**		H16	NA	NA	1	**0.67**
	H17	NA	NA	1	1		H17	NA	NA	1	1
	H18	NA	NA	1	1		H18	NA	NA	1	1
	H19	NA	NA	**0.99**	**0.92**		H19	NA	NA	1	1

*SCF: Spearman Correlation Factor; a: Adaptive capacity harm criteria are ordinal variable and are based on scale. Therefore, robustness of change in these criteria was tested by changing the thresholds one step up and down in the scale (+100% and -100% change respectively from the base case).

Table 8-34: Test of robustness: type-a (votes)

Type of ranking	Vulnerability dimensions where votes of the harm criteria were changed	Amount of change	SCF*
Combined ranking	Exposure	increased by 100%	0.88
	Sensitivity		0.98
	Adaptive Capacity		0.99

*SCF: Spearman Correlation Factor

The second test of robustness, the presence of rank reversal, was conducted by re-analyzing the combined rankings of the base case with one beach modified at a time by giving the same score as that of the least vulnerable beach (Collers). Rankings with compared to those of the base case (Table 8-35). This was conducted for all beaches except the most and least vulnerable in base case. The rankings were found to be reasonably robust, with the first and last beach never changing and an average spearman coefficient, relative to the base case, of 0.93. Where rank reversal did occur, it was around the middle ranks where the relatively small differences in scores between beaches made them more prone to instability. The most number of change occurred when Currarong, ranked 7th in the base case, was modified.

Table 8-35: Test of robustness: type-b (SCF: Spearman Correlation Factor)

	Base case	**SES removed and replaced by Collers, the least vulnerable SES of base case**						
		Collingwood	**Callala**	**Currarong**	**Warrain**	**Culburra**	**Shoalhaven Heads**	**% of change in relative position of rank in compared to base case**
SCF	**1**	**0.997**	**0.997**	**0.715**	**0.978**	**0.912**	**0.996**	
Mollymook	1	1	1	1	1	1	1	0%
Collingwood	2	7	2	3	2	2	2	20%
Callala	2	2	7	5	3	2	2	40%
Currarong	7	6	6	7	6	6	6	0%
Warrain	2	2	2	2	7	4	2	20%
Culburra	5	4	4	6	4	7	5	0%
Shoalhaven Heads	6	5	5	3	5	4	7	40%
Collers	8	7	7	7	7	7	7	0%

8.7 Discussion

Under the assumptions of the study, the following observations can be made:

1. Mollymook and Collingwood are the most vulnerable among the 8 beaches analyzed. Both harbor infrastructure systems of crucial significance to a wide community. In addition, a significant proportion of private properties in Collingwood are at risk. On the other hand, Collingwood appears to have, on average, higher socio-economic status which is likely to yield better adaptive capacity, and less vulnerability of residents. Finally, Warrain has relatively high vulnerability on all 3 dimensions of exposure, sensitivity and adaptive capacity.
2. Shoalhaven Heads, Callala and Culburra are the three beaches whose residents have least adaptive capacity. Shoalhaven Heads has no private properties at risk; therefore, even with a comparatively lower adaptive capacity its overall vulnerability is quite low. On the other hand, Callala and Culburra have a significant number of at-risk private properties (but a relatively small number of at-risk public infrastructure components).
3. Under the preference scenarios considered:
   a) Mollymook and Collingwood generally maintain their high vulnerability ranking
   b) Preference between well-being of beach residents and that of users of public infrastructure has the strongest impact on rankings;
   c) If ranking is based on well-being of beach residents, and the golf club of Mollymook is not considered as a separate commercial criterion, Mollymook's vulnerability ranking is reduced.
   d) If sewerage systems are given priority, Callala beach is ranked lower and Culburra beach higher, relative to the base case.

How can these rankings inform adaptation action (whether based on the present analysis with its relatively narrow consultation process or based on some subsequent ranking exercise informed by wider consultation of stakeholders)? Two alternative approaches are suggested here, although more can of course be developed. First, a specific preference scenario can be adopted based on consensus and beaches ranked high are examined for possible adaptation action. The difficulty here is that consensus may not be obtained and opportunities for multiple-objective actions may be overlooked.

A second approach would consist of analyzing the results of all scenarios together and single out beaches that were regarded as more vulnerable by majority of the analyses. As an example, out of 24 analyses shown in Table 8-31, Mollymook, Collingwood and Shoalhaven Heads came up as most vulnerable on 16, 6 and 2 occasions, respectively. The remaining 5 beaches were never ranked most vulnerable. On the other hand, Collers was ranked as the least vulnerable, 18 out of 24 times. This suggests that the majority of the analyses are pointing towards Mollymook and Collers as the most and least vulnerable of the beaches. Actions targeting Mollymook, Collingwood and Shoalhaven Heads, together, would clearly be beneficial. A further refinement of such an approach is possible by analyzing the rankings of a specific dimension, rather than all 24 set of rankings together.

In any case, the results presented in this chapter already suggest some areas of focus for adaptation action:

a. Sewerage infrastructures (e.g., pumping stations M1, M2) of Mollymook beach are the main contributors to its vulnerability across all three dimensions. SD models developed for this beach showed that failure of these two pumping stations is critical and have the potential to affect areas beyond Mollymook (e.g., neighboring suburbs).

b. Disruption of traffic in some parts of the Mitchell parade (M28), which is a major collector road connecting the northern and southern part of the Council, is yet another main contributor to Mollymook's high vulnerability. Specially, the at-risk bridge on Mitchell parade (M24) has a high traffic volume, AADT of 9,765 at present. Disruption to these two infrastructure components would not only deprive 22 households of direct access to their residence, but would put additional pressure on the other roads of Shoalhaven as well.

c. The rising main at Collingwood beach (Col 3) that carries the treated waste of the whole catchment to an ocean outfall is at risk, and is mainly responsible for its higher vulnerability rankings across all three dimensions.

d. Apart from some vital at-risk public infrastructure, a large number of households are at risk in Collingwood.

e. The surf club and nearby car park, located on both Warrain and Shoalhaven Heads, are major contributors of the high vulnerability of these two beaches. These facilities are used both by tourists and locals and considered as one of the major public amenities of these two beaches.

f. Residents of Shoalhaven Heads, Callala and Culburra have comparatively lower adaptive capacity. With a large number of private properties at risk, low adaptive capacity of both Callala and Culburra's residents is one of the major contributors of vulnerability.

8.8 Usefulness of this exercise to decision makers of the council

A workshop was conducted with council stakeholders and decision makers that are involved in this study (listed in previous chapter) in order to present the results and discuss the usefulness of this exercise. In the previous chapter, the validity of the whole exercise was discussed (section 7.6.2) and it was stated that the validity of the exercise depends on its usefulness to policy makers. In the workshop, the following key points came out from the council stakeholders that can be seen as qualitative evidence of usefulness of the exercise.

1. Change of perception about local vulnerability: After presenting the results (vulnerability ranking of beaches), one stakeholder suggested that he perceived Shoalhaven Heads to be more vulnerable than Mollymook or Collingwood. The main reason for such a perception can be the past flooding history at Shoalhaven Heads. However, in this study beach vulnerability is not determined by exposure alone, rather by the possible effects on infrastructure and households that the beach harbours, as well. Shoalhaven Heads is highly exposed indeed, but does not have many infrastructure components or households inside the hazard line of the beach, which made the beach overall less vulnerable than Mollymook and Collingwood-two beaches that have a number of infrastructure and properties inside the hazard lines. Such conceptualization of vulnerability helped the stakeholders to change their perception about local vulnerability.

2. Inclusion of socio economic and institutional implications: Stakeholders suggested in the workshop that this exercise worked as a means for the policy makers of the council to ensure that the socioeconomic concerns of residents (as opposed to considering only possible economic damage to public properties) are being taken into account.

3. Infrastructure inter-dependency: Stakeholders suggested that modeling infrastructure-interdependency helped them to see the bigger picture concerning disruption to an infrastructure node. Especially useful was the identification of propagation and degree of severity of disruption to the sewerage treatment plant of Mollymook.

8.9 Conclusion

This chapter presented the results of the study which was conducted in collaboration with the Shoalhaven city Council in order to rank 8 beaches in terms of their relative vulnerability. Insights gained through the stakeholder consultation process were used to build a set of community preference scenarios and analyze their effects on the vulnerability rankings. Finally robustness of the results was tested with two types of robustness analyses (e.g., change in votes and thresholds, rank reversal). In both tests, the rankings were found to be robust. Analyzing the rankings generated under different scenarios, it was possible to identify areas of focus for adaptation action.

Chapter 9

Conclusions and future research

9.1 Summary of developments and findings

This thesis covered a broad range of issues related to indicator-based climate change vulnerability assessment (IBVA). It started with chapter 1 discussing the importance of climate change adaptation research in cities and the relevance of using IBVA in this context. It went on discussing the overall goal and objectives of this thesis and placed this research in the broader context of climate change research. As population density in cities, especially the coastal ones are very high and projected to be higher in future, environmental hazards associated with climate change are likely to affect a large number of population living in cities. Identifying potential vulnerability of the said population from potential implications of climate change involves identification of physical risks as well as their socio-economic and institutional implications. This exercise needs a combination of knowledge from multiple domains. Chapter 2 identified the methodological challenges of this exercise and conducted a meta-analysis in order to identify how present IBVA literature is dealing with that. It found that IBVA studies typically use aggregation methods that are based on the Multiple Attribute Utility Theory (MAUT) despite the fact that IBVA rarely satisfies the theoretical requirements of this approach. Only a small percentage of studies critically scrutinize prevalent assessment methodologies or attempt to develop new ones, despite the fact that well-founded questions have been raised in key theoretical papers about the methodological aspects of vulnerability assessment. Less than a third of papers sampled in this study give some consideration to uncertainty and an even smaller proportion to non-linearity.

Drawing on these conclusions, Chapter 3 presented a new general mathematical framework for CCVA. Key features of this framework are a) it starts with the IPCC well-known vulnerability conceptualization and mathematically expands it to cover any multi-dimensional conceptualization of vulnerability; b) it mathematically formalizes the inclusion of adaptation events in the context of CCVA. The developed framework was used to identify different sources of compensation problems, nonlinearities and uncertainties that are relevant in the context of an IBVA problem. In order to deal with the identified challenges, the following two chapters (chapter 4 and 5) developed outranking based frameworks for an IBVA ranking problem. Chapter 4 have argued that outranking procedures, previously only applied to decision-making problems, can be used for vulnerability assessment and may provide a better approach for teasing out policy-relevant information from uncertain vulnerability data.

Outranking procedures implicitly recognize the quantitative and qualitative dimensions of the assessment and work with descriptive categories that are matched with the level of quantitative sophistication of available data. An outranking approach forces the analyst to spell out and characterize the degree of uncertainty in the relationship between indicator and vulnerability, while allowing for a mix of cardinal and ordinal variables to be included. The process of building the indicator-based model can in fact be structured around the four questions defining difference thresholds and votes because they provide a systematic way of canvassing the proposed indicators and bringing to the fore assumptions underlying the model. Therefore, this chapter showed that the problem features of IBVA and MCDA are similar and that outranking methods developed in MCDA can be used in IBVA to deal with the challenges associated with aggregation of different types of indicators. It tailored the features and algorithms of an outranking method ELECTRE-III in vulnerability terminology and named it SEVA-I. Finally SEVA-I outranking formulation was applied to rank 15 coastal councils of Sydney as per their relative vulnerability during a heat wave. Rankings were tested for sensitivity to change in votes as well as rank reversal and found to be robust in both on both occasions.

Chapter 5 extended SEVA-I and developed a new outranking formulation for IBVA, SEVA-II, which incorporates different forms of non-linearity and degrees of compensation that obtain in vulnerability assessments. This was done by introducing harm criteria that can replace indicator or mediate the relationship between indicator and vulnerability. Harm can be conceived of as a more concrete, less abstract form of vulnerability that is more amenable to quantification. The mathematical formulation of SEVA-II developed in this chapter is flexible enough to accommodate a wide range of data types and, as stated earlier, generated rankings are found to be robust.

Chapter 6 used SEVA-II mathematical formulation to develop a coastal infrastructure vulnerability assessment framework that can be used at a local scale. The framework combined an outranking approach with a system dynamics model that incorporates the non-linearity of the service dependencies of infrastructure components and systems. A general equation was developed for capturing the dependencies and interdependencies of infrastructure systems at a local scale and a system dynamic model was developed for measuring the system performance under stress. The output of this exercise then could be used as a sensitivity harm criterion of a sea level rise IBVA model.

Chapters 7 and 8 applied the methodological developments discussed earlier to a real-life IBVA problem, an assessment of the vulnerability to a rise in sea levels of eight beaches in the Shoalhaven. Chapter 7 described the study area and its potential climatic hazards that are associated with SLR and presented the assessment methodology. Starting from the IPCC definition of vulnerability, two IBVA models, specific to the Shoalhaven context, were developed through consultation with the stakeholders and experts of council. One focused on the vulnerability of the infrastructure systems of Shoalhaven beaches considering their dependencies and interdependencies, while the other considered the well being of the residents living at the beach. This chapter also discussed the stakeholder consultation process that took place throughout this study.

Chapter 8 presented the results of the Shoalhaven study. Insights gained through stakeholder consultation were used to build a set of community preference scenarios and analyzed their effects on vulnerability rankings. Final rankings were found to be sensitive to changes in community preference scenarios. Finally two types of robustness analyses were conducted, namely, change in votes and thresholds and rank reversal. In both tests, the rankings were found to be robust.

In summary, the major contributions of this research are as follows.

1. Development of a general mathematical framework for CCVA problems, including IBVA.
2. Development of an analogy between IBVA and MCDA problems and an outranking formulation for IBVA.
3. Extension of the outranking formulation to incorporate different combinations of non-linearity and compensation that are often present in the context of IBVA
4. Development of a general method for identifying infrastructure dependencies and interdependencies at a local scale and a system dynamics model to measure the non-linear service performance under a given climatic stress, and integrating this model within an IBVA outranking framework.
5. Testing of the applicability of the developed outranking methods, frameworks and SD models in a real life multi stakeholder environment by applying them to rank 8 beaches of the Shoalhaven Council. This process also developed two IBVA models that are specific to Shoalhaven but can be tailored for use in other Councils.

9.2 Possible future developments

One of the major challenges of climate change vulnerability assessment is dealing with multiple sources of uncertainty, most importantly epistemic uncertainty. The quality and usefulness of IBVA, no matter how sophisticated the methodologies it uses, ultimately depends on the extent to which we know, understand and are able to quantify all significant processes generating vulnerability. This is made all the more complex by the non-linear, dynamic, multi-stress and multi-dimensional nature of these processes. With this qualification in mind, it is possible to consider a number of refinements to the works conducted in this thesis.

Outranking Framework and Analyses

i. As mentioned earlier, the use of outranking methods in the context of IBVA does not *measure* vulnerability, rather provides comparative vulnerability rankings of the SESs in hand. In contrast to that, MAUT-based simple additive or multiplicative approach can be used to develop indices of vulnerability. The development of indices is useful as they a) allow some measurement of the effect of an adaptation event to be made, b) provide a global platform for comparing SESs in different settings (albeit using similar criteria). Hence, developing ways of converting results of outranking methods into indices can be useful. One possible approach here is to introduce reference low-, medium- and high-vulnerability (fictional) SESs and using the ranking of a real SES relative to these references as a basis for building a vulnerability index.
ii. The ELECTRE-III outranking algorithm has been used as a starting point in this research for developing mathematical formulations and frameworks for IBVA. Another possible future work can be testing other outranking methods such as PROMETHEE, ELECTRE-IV and assessing their relative strengths and weaknesses in the context of IBVA. For example, ELECTRE-IV method is of particular interest because it does not require any criteria votes as input to the analysis.
iii. Given the spatial nature of most IBVA exercises, incorporating the outranking framework within the GIS system can be beneficial. This would facilitate visualization of IBVA rankings and, through the introduction of thresholds of difference into GIS, would provide more sophisticated forms of aggregation than simple layering.

SEVA Models

iv. To what extent are the SEVA methodology and/or models (for infrastructure users and beach residents) applicable to the assessment of vulnerability to SLR in other settings in Shoalhaven and elsewhere? To conduct such an extension it may be necessary to introduce other infrastructure components in the models such as power supply, telecommunication and emergency services, and improve the system dynamics simulation. The general equation developed in chapter 6 for measuring the system performance (SEVA-SD) can only take the stresses that come from one direction into account. Future work can expand this model so that it can accommodate stresses from upstream and downstream.

v. Another improvement of the SD model is possible by inserting it in probabilistic framework. For example, at present all of infrastructure nodes that fall inside the hazard lines are assumed to lose their functionality. A more sophisticated approach would attempt to quantify the probability of occurrence of such an event (e.g., possibility of disruption of a given infrastructure node based on its current safety precautions).

vi. Finally, the integration of an outranking IBVA with adaptation policies and adaptation options can be investigated. Starting points for such an exploration can be a) giving the outranking framework to provide a measure of the effect of adaptation events (point i above) and b) better understanding how decision-makers (such as the Shoalhaven Council referred to in this thesis) use the outcomes of vulnerability assessments.

APPENDIX

A1: Raw data of heat stress study

Vulnerability matrix and difference thresholds of indicators of vulnerability to heat of 15 local government areas, under the three dimensions of exposure, sensitivity and adaptive capacity (base case)

Notes:

1. Only the base case is shown here;
2. In the following 3 tables, indicators marked with stars are those for which we found no measure of uncertainty;
3. All indicators have $v_i=\infty$ and $w_i=1$ in the base case (∞ is represented by a large number); q_i and p_i were based on error estimates;
4. Direction of relationship indicates whether vulnerability rises (+) or declines (-) with increasing value of the indicator in question;
5. Date sources: Bureau of Meteorology (BOM), Australian Bureau of Statistics (ABS), Division of Local Government NSW (DLGNSW), Land and Property Management Authority (LPMA);
6. All data is for the year 2006 unless otherwise indicated.

Table A 1: Values and thresholds of exposure indicators for the 15 local government areas

	Average January maximum temperature (2005-2010)	**Average January minimum temperature (2005-2010)**	**Average # of days > 30°C per year (2005-2010)**	**Land cover (% of covered land)**	**Population density**	**Road density**
Unit	***^{o}C***	***^{o}C***	***Days***	***%***	***person/km^2***	***km/km^2***
Direction of relationship	+	+	+	+	+	+
Data Source	**BOM**	**BOM**	**BOM**	**ABS***	**ABS**	**LPMA**
q_i	***0.105***	***0.095***	***1.07***	***0.2^+***	***0.042^+***	***0***
p_i	***0.21***	***0.19***	***2.14***	***0.4^+***	***0.084^+***	***17.9***
Botany Bay	27.6	19.8	29.1	80.6	1660	9.0
Hornsby	28.0	18.5	35.3	12.6	327	2.0
Leichhardt	27.4	19.5	25.2	84.6	4625	17.8
Manly	26.0	19.9	18.3	65.4	2585	10.6
Mosman	25.5	20.3	13.7	74.6	3034	13.7
North Sydney	26.7	19.9	19.7	85.7	5550	19.2
Pittwater	27.0	18.6	25.2	32.6	600	4.0
Randwick	27.3	19.7	26.3	68.3	3300	11.2
Rockdale	27.9	19.5	32.1	82.4	3265	12.4
Sutherland	28.7	18.5	41.2	23.7	616	3.2
Sydney	27.1	19.9	22.4	84.4	5862	19.9
Warringah	26.8	18.7	23.8	41.1	896	5.0
Waverley	26.4	20.0	19.4	83.3	6571	16.2
Willoughby	27.1	19.4	24.2	78.7	2827	11.2
Woollahra	26.0	20.2	16.6	79.0	4087	13.8

* indicator corrected for vegetation with data sourced from the US geological survey LANDSAT

+Using relative difference (see comment below equation 4.3)

Table A 2: Values and thresholds of sensitivity indicators for the 15 local government areas

	% Population ≤ 65 years of Age	% Population ≤ 65 years of Age and living alone	% of population ≤4 years of age	% of people living in multi-unit dwellings
Unit	*%*	*%*	*%*	*%*
Direction of relationship	+	+	+	+
Data Source	**ABS**	**ABS**	**ABS**	**ABS**
q_i	***0.05****	***0.05****	***0.05****	***0.042****
p_i	***0.1****	***0.1****	***0.1****	***0.084****
Botany Bay	14.2%	1.2%	6.5%	34.9%
Hornsby	12.8%	0.7%	6.0%	11.1%
Leichhardt	9.2%	0.9%	7.0%	18.6%
Manly	13.5%	1.0%	6.6%	32.5%
Mosman	14.3%	1.0%	6.0%	32.3%
North Sydney	11.3%	1.1%	4.5%	54.8%
Pittwater	13.9%	0.9%	6.6%	8.2%
Randwick	12.8%	1.1%	5.4%	36.9%
Rockdale	15.1%	1.0%	6.4%	27.3%
Sutherland	12.7%	0.8%	6.4%	12.9%
Sydney	7.8%	1.1%	3.3%	48.5%
Warringah	14.5%	0.9%	6.8%	20.8%
Waverley	12.5%	1.0%	5.9%	40.4%
Willoughby	11.7%	0.8%	6.9%	29.6%
Woollahra	15.1%	1.1%	5.1%	36.5%

* Using relative difference (see comment below equation 4.3)

Table A 3: Values and thresholds of adaptive capacity indicators for the 15 local government areas (A$: Australian dollar); * Using relative difference (see comment below equation 4.3)

	% Population completing year 12	% Population that speaks language other than English	Median Home loan re-payment	%Home owners	Median House-hold income	% house-hold with internet access	Current Ratios	Per capita business rates	Per capita residential rates	Per capita community service expenses	Per capita environmental and health expenses	% of population requiring financial assistance
Unit	*%*	*%*	*A$/ month*	*%*	*A$/week*	*%*	*Asset/ Liability*	*A$/ business*	*A$/ residence*	*A$/person*	*A$/person*	*%*
Direction of relationship	-	+	-	-	-	-	-	-	-	-	-	+
Data Source	ABS	ABS	ABS	ABS	ABS	ABS	DLGNSW	DLGNSW	DLGNSW	DLGNSW	DLGNSW	ABS
q_i	***0.042****	***0.057****	***0.08****	***0.042****	***0.09****	***0***	***0***	***0***	***0***	***0***	***0***	***0.05****
p_i	***0.084****	***0.114****	***0.16****	***0.084****	***0.18****	***0.213***	***5***	***6478***	***639***	***119***	***46***	***0.1****
Botany Bay	38.2%	31.6%	1950	56.5%	995	56.9%	1.59	7640	530	63	29	18.8%
Hornsby	48.5%	18.8%	2000	75.5%	1514	77.6%	2.2	2325	768	41	29	10.4%
Leichhardt	55.5%	9.4%	2400	56.4%	1733	73.5%	2.89	5319	932	76	27	13.0%
Manly	52.3%	8.0%	2500	61.3%	1705	73.1%	1.15	3406	945	101	51	9.4%
Mosman	58.7%	8.0%	2600	61.8%	1916	76.4%	1.5	2082	929	66	44	6.2%
North Sydney	64.3%	13.5%	2364	46.2%	1772	75.9%	2.15	2359	411	36	43	7.3%
Pittwater	43.3%	4.7%	2167	77.6%	1486	76.0%	2.4	1754	1050	40	22	10.1%
Randwick	50.8%	21.5%	2150	51.4%	1185	67.2%	2.42	4817	788	30	28	15.0%
Rockdale	40.1%	33.0%	1820	63.8%	1035	60.0%	2.61	2224	671	12	10	18.8%
Sutherland	37.4%	6.5%	1950	76.0%	1374	69.9%	2.53	2015	904	47	6	13.0%
Sydney	53.5%	20.3%	2150	35.3%	1204	69.6%	6.15	8232	489	83	35	14.6%
Warringah	43.5%	10.5%	2150	70.2%	1387	71.4%	4.11	3362	892	44	29	11.9%
Waverley	52.3%	13.4%	2341	51.4%	1446	70.1%	3.36	3878	618	131	38	11.0%
Willoughby	56.8%	25.2%	2383	62.8%	1667	78.2%	4.61	4343	608	84	25	8.7%
Woollahra	58.9%	9.3%	2800	58.9%	1917	75.0%	3.94	2489	854	72	18	7.2%

Table A 4: Test of rank reversal SCF: (Spearman Correlation Factor)

		SES removed (Replaced by MOSMAN, the least vulnerable SES of base case)														
	Base case	Botany Bay	Randwick	Sydney	Waverley	North Sydney	Sutherland	Warringah	Leichhardt	Woollahra	Manly	Willoughby	Hornsby	Pittwater	Count of same relative rank in compared to base case (out of 12)	% of change in relative position of rank in compared to base case
SCF		**0.92**	**0.95**	**0.92**	**0.96**	**0.96**	**0.96**	**0.93**	**0.94**	**0.90**	**0.94**	**0.92**	**0.92**	**0.91**		
Rockdale	1	1	1	1	1	1	1	1	1	1	1	1	1	1	12	0%
Botany Bay	2	14	2	2	2	2	1	2	2	2	2	2	2	2	11	8%
Randwick	3	2	14	3	3	3	3	3	3	3	3	3	3	3	12	0%
Sydney	4	5	3	14	5	6	4	6	6	6	6	6	6	6	2	83%
Waverley	5	3	3	3	13	4	4	3	3	4	4	3	4	4	0	100%
North Sydney	5	7	5	6	7	14	6	8	8	9	8	8	8	8	0	100%
Sutherland	5	3	5	5	4	4	14	5	5	4	4	5	4	4	0	100%
Warringah	8	7	8	8	9	8	8	14	8	6	8	8	8	10	9	25%
Leichhardt	9	10	10	10	10	10	10	10	14	10	10	11	11	11	0	100%
Woollahra	9	5	5	6	5	6	6	6	6	13	6	6	6	6	0	100%
Manly	11	7	8	8	7	8	8	8	8	6	13	8	8	8	0	100%
Willoughby	11	11	11	11	11	11	11	11	11	11	11	14	12	12	0	100%
Hornsby	13	12	12	12	12	12	11	11	12	12	12	12	13	13	11	8%
Pittwater	14	13	13	13	13	13	13	13	13	13	13	13	13	14	12	0%
Mosman	15	14	14	14	13	14	14	14	14	13	13	14	14	14	12	0%

A2: Error estimation for heat stress study

Error estimation of data used for determining thresholds of difference for assessing heat stress vulnerability of 15 Councils of Sydney)

The following information is extracted from the Australian Bureau of Statistics (ABS) where the possible sources of error in the 2006 census data are discussed (Linkov et al. 2011).

"In 2006, the question on Age included the option to report either Date of Birth (DOB) or Age last birthday. The check box for selecting '100 years or more' that appeared in 2001 was removed, allowing people to record actual ages in this age range. The majority of respondents provided DOB information only (52.9%), while 36.6% reported both DOB and Age last birthday and 5.7% reported Age last birthday only. The remainder (4.8%) did not state either. Where both sets of information were provided, DOB information was used to derive an age in years (AGEP). Where age could not be derived or was not stated (or set to not stated during processing as discussed below) then it was imputed, using other information on the form, and using an age distribution of the population. **The imputation rate in 2006 for Age (AGEP) was 5.0%** compared with 3.6% for 2001. **Nearly all of this imputation is attributable to the 4.2% of persons in dwellings which were occupied on Census Night but did not return a completed form.** Persons are imputed into these dwellings together with some demographic characteristics including AGEP. In 2001, 2.2% of persons were imputed into dwellings for which no form was received. There were a small number of cases where age was set to 'not stated' because of inconsistencies between age and relationship data. This occurred most often because the Census concept of a parent and child relationship requires a 15 year age gap where such a relationship exists (and a 30 year age gap where a grandparent/grandchild relationship exists).Where this condition is not met, the age of the parent or grandparent is set to not stated and then imputed. These types of adjustments occurred for 0.2% of all persons. There are two main sources for error in age data: respondent error, and processing error.

Respondent error

Users of the data need to bear in mind that almost all census data are as originally reported by the respondents. Respondents occasionally provided the date that they filled out the form, or the date of their last birthday, as their date of birth. Such records that could be positively identified, using other information on the form, had their ages set to not stated and then imputed. Other respondent actions, such as crossing out of incorrect digits, transposing numbers (particularly by eCensus users), and 'sticky key' repetition errors (for eCensus users), are more difficult to determine, and such errors are likely to remain in final output.

Processing error

Age data was mostly captured from hand written numeric responses: therefore there is some risk of character recognition error. During processing, the vast majority of individual characters handwritten on paper forms met preset recognition confidence levels and were accepted without further examination. However, there are low-level patterns of regular numeric substitution in the final data that suggest that the automated preset recognition confidence tests may not have been sufficiently rigorous for some poor handwriting, affecting a small proportion of AGEP data. Characters that failed recognition confidence levels, were sent to a team of coders for further determination. Coders selected the most likely digit the respondent was trying to convey, based on visual inspection of an image of the response. If there was no way that a determination could be made regarding individual digits within Age last birthday, then the entire content of the field was deleted, so that misleading information was not passed on to later systems. For DOB, where the Year of Birth was unrecognizable and could not be ascertained from an associated Age last birthday response, that field was deleted. Age for these records was imputed at a later stage of processing. Sample checks were made throughout the data capture processing schedule, to ensure an acceptable level of processing quality was maintained.

Data confrontation

One way of measuring the accuracy of age data is to compare reported age, and derived age (calculated from DOB data) for the 36.6% of respondents who supplied both sets of information. Where both DOB and Age last birthday were provided, the two values for age were consistent in 91.7% of cases, giving high confidence that the age (AGEP) for these records were correct. For 6.2% of persons there was only one year difference between the data items. For the remaining 2.1%, however, where the difference was two or more years, respondent error (for either variable, or both), or character recognition problems during processing were the most likely causes. In all cases, the assumption was made that DOB was correct. It is equally probable (but unverifiable) that a similar degree of error exists in AGEP for those records where just Date of Birth, or just Age last birthday, was supplied by the respondent."

Table A 5: Main Source of uncertainty (Lines within quotation mark are adopted from data description of Australian Bureau of Statistics (Linkov et al. 2011)

SL No	**Indicators**	**Unit**	**Main source of uncertainty**	**Indifference Threshold q**	**Preference Threshold p=2q OR maximum difference between the SESs**
1	Present Average January maximum temperature	^oC	Temperature of each LGA has been derived from the interpolation of specific station data around that LGA. q is the estimated error in interpolation using IDW method in Arch-GIS.	**0.105**	**0.21**
2	Present Average January minimum temperature	^oC	Temperature of each LGA has been derived from the interpolation of specific station data around that LGA. q is the estimated error in interpolation using IDW method in Arch-GIS.	**0.095**	**0.19**
3	Present # Days > 30^0C	No	Temperature of each LGA has been derived from the interpolation of specific station data around that LGA. q is the estimated error in interpolation using IDW method in Arch-GIS.	**1.07**	**2.14**
4	Land Cover (% of covered Land)	%	Land cover vector data has been corrected for vegetation using 240mX240m resolution of ETM satellite image. Such correction includes land use classification of satellite data. These type of land classification incur some uncertainty in the data. Some of the literature suggests that these are around 20%	**20%**	**40%**
6	Road density	Km/Km^2	No error is assumed and p is the maximum difference between the SESs	**0**	**17.9**
5	Population density (2005)	$Person/km^2$	General imputation rate of 4.2% is adopted as the error	**4.2%**	**8.4%**
7	% Population ≤ 65 years of Age	%	Imputation rate for indicators related to age was 5%. Therefore this was adopted as the error of the indicators that are associated with age	**5%**	**10%**
8	% Population ≤ 65 years of Age and living alone	%		**5%**	**10%**
9	% of population ≤4 years of age	%		**5%**	**10%**
10	%of people living in multi unit dwellings	%	General imputation rate of 4.2% is adopted as the error	**4.2%**	**8.4%**
11	% Population completing year 12	%	General imputation rate of 4.2% is adopted as the error	**4.2%**	**8.4%**

SL No	**Indicators**	**Unit**	**Main Source of uncertainty**	**Indifference Threshold q**	**Preference Threshold p=2q OR maximum difference between the SESs**
12	% population that speaks language other than English	%	"There are many aspects which can affect the quality of Census data; the following information should be considered when viewing data on Language Spoken at Home (LANP). The primary purpose of this question is to obtain data on languages spoken at home, other than English. Therefore the category "English" should not be used as a measure of spoken English, but rather where English only is spoken at home. Most of the data (91.8%) is captured automatically from check box responses, so the risk of processing error is minimal. The remainder, consisting mainly of written responses, was coded by an automatic reading and coding process (7.3%), and clerically (0.9%). A very small number were difficult to clerically code (0.2%) and more relaxed rules were used by coders. All coding is subject to sample checks to ensure an acceptable level of quality. **The non-response rate for 2006 was 5.7%** compared with 4.8% for 2001. Part of this non-response is attributable to the 4.1% of persons in dwellings which were occupied on Census Night but did not return a completed form. Persons are imputed into these dwellings together with some demographic characteristics, however the values for Language Spoken at Home (LANP) remain not stated. In 2001, 2.1% of persons were imputed into dwellings for which no form was received. Inadequately described responses (written responses unable to be coded) comprised 0.05% of the data, down from 0.13% in 2001. In a small proportion of cases (testing has shown that this is around 1%), respondents provided an incorrect number of responses (for LANP respondents are asked to only mark one response only). In these cases responses are accepted in the order they appear on the form and the extra responses are rejected.	**5.7%**	**11.4%**

SL No	**Indicators**	**Unit**	**Main Source of uncertainty**	**Indifference Threshold q**	**Preference Threshold p=2q OR maximum difference between the SESs**
13	Median Home loan repayment	AUD/month	"There are many aspects which can affect the quality of Census data; the following information should be considered when viewing data on Housing Loan Repayments (monthly) Ranges (HLRD01). This data item is applicable to occupied private dwellings being purchased; this represents 32.2% of all occupied private dwellings. **The non-response rate for 2006 was 8.0%** compared with 5.6% for 2001. Unlike some other variables the non-response rate is not affected by the occurrence of non-responding dwellings, as these dwellings are not applicable for Housing Loan Repayments (monthly) Ranges (HLRD01). A contributing factor to non-responses are the 2.2% of dwellings being purchased where the "Nil payments" box was marked. For these dwellings Housing Loan Repayments (monthly) Dollar Values (HLRD) is treated as not stated. Household payments data is automatically captured from written numeric responses. This process is subject to some recognition error, particularly when decimal points are used. While the data is subject to normal sample checks to ensure an acceptable level of quality, numeric responses are accepted as reported. The data may then include a small proportion of dwellings with unusually large housing payment amounts, in the higher range categories."	**8.00%**	**16.00%**
14	%Home ownership	%	General imputation rate of 4.2% is adopted as the error	**4.20%**	**8.40%**
15	Median Household income	AUD/Week	"Income of individual is collected in ranges rather than specifically. For example, census question asks "Which is the appropriate range of your income? (A. 10,000 to 15,00 B. 15,000 to 25,000 etc). Then use the median of that range to find the median household income. BITRE (the authority responsible for this estimation) has access to wealth-specific auxiliary data for the major components of wealth, which together contribute 91 per cent of net worth. **Which refers that 9% of wealth might have been omitted from this data.** Moreover, not all of the population state about their income in the census. For example, ABS reports that 40% of Sydney LGA population did not state their income"	**9%**	**18%**
16	% household with internet access	%	"The categories of access are: 'broadband', 'dial-up' and 'other'. Broadband access includes ADSL, cable, wireless and satellite connections. Dial-up includes analog modem and ISDN connections. Other includes access through mobile phones, set-top boxes, games machines, or connections other than dial-up and broadband. " No error is assumed and p is the maximum difference between the SESs	**0**	**21.3**

SL No	**Indicators**	**Unit**	**Main Source of uncertainty**	**Indifference Threshold q**	**Preference Threshold p=2q OR maximum difference between the SESs**
17	Current Ratios	Asset/Liability (unit less)	"The current ratio is a measure of a council's ability to meet its financial obligations such as paymentfor goods and services supplied to council. A ratio greater than 1:1 indicates that unrestricted current assets exceedcurrent liabilities. It is an indication of a council's solvency. If the ratio is less than 1:1 the council should be takingsteps to improve its liquidity. A ratio of 1:1 or greater indicates a council has sufficient liquid assets on hand to meetits short term liabilities. A ratio of 1:1 or better is generally viewed by the Industry as satisfactory.Unrestricted current assets are those in which no form of restriction is imposed by regulations or some other externally imposed requirement. Restricted current assets have restrictions on the use of those assets (eg developer contributions, RTA contributions, water and sewerage rates, charges and grants, domestic waste management charges etc)." No error is assumed and p is the maximum difference between the SESs	**0**	**5**
18	Per capita business rates	AUD/Business	No error is assumed and p is the maximum difference between the SESs	**0**	**6478.0**
19	Per capita residential rates	AUD/Residence	No error is assumed and p is the maximum difference between the SESs	**0**	**639.0**
20	Per capita community service expenses	AUD/Person	No error is assumed and p is the maximum difference between the SESs	**0**	**119.1**
21	Per capita environmental and health expenses	AUD/Person	No error is assumed and p is the maximum difference between the SESs	**0**	**45.6**
22	% of population requiring financial assistance	%	"If the number of people receiving a certain financial assistance (e.g, Disability Support Pension, Parenting Payment etc) is very small (a value of less than 20, including zero) have been confidentiallised for privacy reasons. Therefore those areas have missing data. Moreover, these data has been collected from different government organization such as center link, Department of Veterans' Affairs (DVA), Department of Families, Housing, Community Services and Indigenous Affairs (FaHCSIA) etc. Therefore any error or uncertainty in such organization might have radiated in this data." The general error which is 5% imputation of data is adopted for this indicator.	**5%**	**10%**

A3: Definition of thresholds of difference in terms of harm

Table A 6: Definitions of thresholds of difference and relative importance factors for SEVA-II

Indifference threshold	q_i	All other harm criteria being equal, what is the difference in values of harm criterion H_i for two SESs below which the vulnerabilities of the two systems are the same?
Relative vulnerability threshold	p_i	All other harm criteria being equal, what is the difference in values of harm criterion H_i for two SESs above which one system is strictly more vulnerable than the other?
Dominance threshold	v_i	What is the difference in values of harm criterion H_i for two SESs a and b (H_{ib}-H_{ia}) above which a cannot be more vulnerable than b, regardless of the performances of a and b on other harm criteria (no compensation)?*
Relative importance factor	w_i	In determining whether a 'majority' of harm criteria supports the statement that one SES is at least as vulnerable as another, what is the strength of a 'vote' by harm criterion H_i relative to a reference harm criterion?

*this definition assumes that vulnerability increases with increasing harm criterion and would need to be suitably adjusted if the reverse is true ("... above which b cannot be more vulnerable than a, regardless ...").

A4: Details of decision scenarios

Table A 7: Scenario definitions and characteristics

Name	**Scenario**	**Use of SEVA-INFRA-SD harm criteria**	**Use of SEVA-HOUSE harm criteria**	**Use of system dynamics models for quantification of sensitivity harm criteria**	**Thresholds generated by averaging *only experts* opinion**	**Votes generated by averaging *only experts* opinion**	**Thresholds generated by averaging *all* participants opinion**	**Votes generated by averaging *all* participants opinion**	**Dominance thresholds used for *all harm criteria***	**No dominance thresholds were used for harm criteria related to "other infrastructure" category (H7,H12,H19)**	**Dominance thresholds were used only for harm criteria that are associated with the sewerage system**	**Harm criteria that are associated with sewerage system are allocated double votes**	**H20 , H21 and H22, H23 are lumped together**
Base Case	Basic analysis	√		√	√	√			√				
Base Case-without SD	Dependencies of infrastructure components were not considered	√			√	√			√				
Scenario-1	Average stakeholder judgment is preferred over expert judgment	√		√			√	√	√				
Scenario-2	Importance of public property is reflected more by the service it provides to the community than its financial value	√		√	√	√				√			
Scenario-3	Sewerage systems must be given priority compared with water and roads	√		√	√	√					√	√	
Scenario-4	Well-being of private households is more important than public infrastructure		√				√	√	√				√
Scenario-5	Commercial properties are equal or less important than the residential properties		√				√	√	√				√

A5: SEVA-Codes

This is the main function of SEVA-Code

```
clc
clear all
close all
```

Reads data from a spread sheet

```
NumOfCrt=xlsread('Database_2006.xlsx','BasicData','B1');
NumOfAlt=xlsread('Database_2006.xlsx','BasicData','B2');
PerformMat1=xlsread('Database_2006.xlsx','DatabaseForMATLAB','C12:F15');
PerformMat=PerformMat1';
WeightMat=xlsread('Database_2006.xlsx','DatabaseForMATLAB','C5:F5');
ThresholdMat1=xlsread('Database_2006.xlsx','DatabaseForMATLAB','C6:F11');
ThresholdMat=ThresholdMat1';
```

Builds concordance matrix

```
[Conc]=calcConcMat(NumOfAlt,NumOfCrt,PerformMat,ThresholdMat,WeightMat);
```

Builds discordance matrix

```
[d]=calcDisMat(NumOfAlt,NumOfCrt,PerformMat,ThresholdMat);
```

Builds credibility matrix

```
[S]=calcCredibilityMat(NumOfAlt,NumOfCrt,Conc,d);
```

Distillate alternatives and generates final rank

```
[aFindex,dFindex,FResult]=Distillation(NumOfAlt,S);
```

This function calculate indifference and preference thresholds

```
function [p q]=calcPrefThreshold(k,i,PerformMat,ThresholdMat)
p = abs(ThresholdMat(k,4) + ThresholdMat(k,3) * PerformMat(k, i));
q = abs(ThresholdMat(k,2) + ThresholdMat(k,1) * PerformMat(k, i));
```

This function calculate dominance thresholds

```
function [v]=calcVetoThreshold(k,i,PerformMat,ThresholdMat)
v = abs(ThresholdMat(k,6) + ThresholdMat(k,5) * PerformMat(k, i));
```

Concordance function

```
function[Conc]=calcConcMat(NumOfAlt,NumOfCrt,PerformMat,ThresholdMat,WeightMat)
Conc(1:NumOfAlt,1:NumOfAlt)=0;
TotalWt=0;
CWt(1:NumOfCrt)=0;
indcat=xlsread('Database_2006.xlsx','BasicData','B6:B9');
BaseParam=xlsread('Database_2006.xlsx','BasicData','C6:L9');
  for k = 1:NumOfCrt
     CWt(k) = WeightMat(1,k);
  end
  for i = 1:NumOfAlt
     for j = 1:NumOfAlt
        for k = 1:NumOfCrt
```

1. This part is for intuitively linear-deductively linear and full compensating (Type-01)

```
        if( indcat(k,1)==1)
         q1(1:NumOfAlt,1:NumOfAlt)=0;
         for m=1:NumOfAlt
            for n=1:NumOfAlt
            q1(m,n)=PerformMat(k,m)-PerformMat(k,n);
            end
         end
         p2=max(max(q1));
         q2=min(min(q1(q1>0)));
        p=p2;
        q=0;
         if ((PerformMat(k, j) -PerformMat(k, i)) <= q )
                Conc(i, j) = (Conc(i, j) + (1 * CWt(k)));
            elseif ((PerformMat(k, j) -PerformMat(k, i)) > p )
                Conc(i, j) = Conc(i, j) + 0;
            else
                Conc(i, j) = (Conc(i, j) + (p * CWt(k) + (PerformMat(k, i) * CWt(k)) -
(PerformMat(k, j) * CWt(k))) / (p - q));
         End
```

2. This part is for intuitively non-linear-deductively linear and full compensating (Type-02)

```
        elseif( indcat(k,1)==2)
```

```
         q1(1:NumOfAlt,1:NumOfAlt)=0;
          for m=1:NumOfAlt
             for n=1:NumOfAlt
             q1(m,n)=PerformMat(k,m)-PerformMat(k,n);
             end
          end
          [~, q]=calcPrefThreshold(k,i,PerformMat,ThresholdMat);
          p=max(max(q1));
          if ((PerformMat(k, j) -PerformMat(k, i)) <= q )
                  Conc(i, j) = (Conc(i, j) + (1 * CWt(k)));
              elseif ((PerformMat(k, j) -PerformMat(k, i)) > p )
                  Conc(i, j) = Conc(i, j) + 0;
              else
                  Conc(i, j) = (Conc(i, j) + (p * CWt(k) + (PerformMat(k, i) * CWt(k)) -
(PerformMat(k, j) * CWt(k))) / (p - q));
          end
```

3. This part is for intuitively non-linear-deductively linear and full or partial compensating (Type-03)

```
         elseif( indcat(k,1)==3)
          [p, q]=calcPrefThreshold(k,i,PerformMat,ThresholdMat);
          q1(1:NumOfAlt,1:NumOfAlt)=0;
          for m=1:NumOfAlt
             for n=1:NumOfAlt
             q1(m,n)=PerformMat(k,m)-PerformMat(k,n);
             end
          end
          if ((PerformMat(k, j) -PerformMat(k, i)) > p )
                  Conc(i, j) = Conc(i, j) + 0;
              elseif ((PerformMat(k, j) -PerformMat(k, i)) <= q )
                  Conc(i, j) = (Conc(i, j) + (1 * CWt(k)));
              else
                  Conc(i, j) = (Conc(i, j) + (p * CWt(k) + (PerformMat(k, i) * CWt(k)) -
(PerformMat(k, j) * CWt(k))) / (p - q));
          end
```

4. This part is for intutively non-linear-deductively linear and full, partial or no compensating (Type-04)

```
         elseif indcat(k,1)==4;
          [p q]=calcPrefThreshold(k,i,PerformMat,ThresholdMat);
              if ((PerformMat(k, j) -PerformMat(k, i)) <= q )
                  Conc(i, j) = (Conc(i, j) + (1 * CWt(k)));
              elseif ((PerformMat(k, j) -PerformMat(k, i)) > p )
                  Conc(i, j) = Conc(i, j) + 0;
              else
                  Conc(i, j) = (Conc(i, j) + (p * CWt(k) + (PerformMat(k, i) * CWt(k)) -
(PerformMat(k, j) * CWt(k))) / (p - q));
              end
```

5. This part is for intuitively linear-deductively non linear and full compensating (Type-05)

```
        elseif (indcat(k,1)==5)
        a1=BaseParam(k,5);
        a2=BaseParam(k,6);
```

```
        a3=BaseParam(k,7);
        H(1:NumOfCrt,1:NumOfAlt)=0;
        for ii=1:NumOfCrt
           for jj=1:NumOfAlt
              if ii==k
                  H(ii,jj)=(a1*PerformMat(k, jj)*PerformMat(k, jj))+(a2*PerformMat(k, jj))+a3;
              else
                 H(ii,jj)=0;
              end
           end
        end
        q2(1:NumOfAlt,1:NumOfAlt)=0;
          for m=1:NumOfAlt
             for n=1:NumOfAlt
             q2(m,n)=H(k,m)-H(k,n);
             end
          end
         pH1=max(max(q2));
         qH1=min(min(q2(q2>0)));
         pH=pH1+1;
         qH=qH1-1;
        if ((H(k, j) -H(k, i)) <= qH )
                  Conc(i, j) = (Conc(i, j) + (1 * CWt(k)));
             elseif ((H(k, j) -H(k, i)) > pH )
                  Conc(i, j) = Conc(i, j) + 0;
             else
                  Conc(i, j) = (Conc(i, j) + (pH * CWt(k) + (H(k, i) * CWt(k)) - (H(k, j) *
CWt(k))) / (pH - qH));
        end
```

6. This part is for intuitively non-linear-deductively non linear and full compensating (Type-06)

```
        elseif (indcat(k,1)==6)
        a1=BaseParam(k,5);
        a2=BaseParam(k,6);
        a3=BaseParam(k,7);
        H(1:NumOfCrt,1:NumOfAlt)=0;
        for ii=1:NumOfCrt
           for jj=1:NumOfAlt
              if ii==k
                  H(ii,jj)=(a1*PerformMat(k, jj)*PerformMat(k, jj))+(a2*PerformMat(k, jj))+a3;
              else
                 H(ii,jj)=0;
              end
           end
        end
        q2(1:NumOfAlt,1:NumOfAlt)=0;
          for m=1:NumOfAlt
             for n=1:NumOfAlt
             q2(m,n)=H(k,m)-H(k,n);
             end
          end
         pH=max(max(q2));
         qH=min(min(q2(q2>0)));
```

```
        if ((H(k, j) -H(k, i)) <= qH )
                Conc(i, j) = (Conc(i, j) + (1  * CWt(k)));
            elseif ((H(k, j) -H(k, i)) > pH )
                Conc(i, j) = Conc(i, j) + 0;
            else
                Conc(i, j) = (Conc(i, j) + (pH * CWt(k) + (H(k, i) * CWt(k)) - (H(k, j) *
CWt(k))) / (pH - qH));
        end
```

7. This part is for intuitively non linear- deductively non linear- full or partially compensating (Type-07)

```
        elseif (indcat(k,1)==7)
        a1=BaseParam(k,5);
        a2=BaseParam(k,6);
        a3=BaseParam(k,7);
        H(1:NumOfCrt,1:NumOfAlt)=0;
        for ii=1:NumOfCrt
           for jj=1:NumOfAlt
              if ii==k
                 H(ii,jj)=(a1*PerformMat(k, jj)*PerformMat(k, jj))+(a2*PerformMat(k, jj))+a3;
              else
                 H(ii,jj)=0;
              end
           end
        end
        q2(1:NumOfAlt,1:NumOfAlt)=0;
          for m=1:NumOfAlt
             for n=1:NumOfAlt
             q2(m,n)=H(k,m)-H(k,n);
             end
          end
          pH1=max(max(q2));
          pH=pH1-1;
          qH=BaseParam(k,8);
        if ((H(k, j) -H(k, i)) <= qH )
                Conc(i, j) = (Conc(i, j) + (1  * CWt(k)));
            elseif ((H(k, j) -H(k, i)) > pH )
                Conc(i, j) = Conc(i, j) + 0;
            else
                Conc(i, j) = (Conc(i, j) + (pH * CWt(k) + (H(k, i) * CWt(k)) - (H(k, j) *
CWt(k))) / (pH - qH));
        end
```

8. This part is for intuitively non linear- deductively non linear-full, partial or no compensation (Type-08)

```
          elseif (indcat(k,1)==8)
        a1=BaseParam(k,5);
        a2=BaseParam(k,6);
        a3=BaseParam(k,7);
        H(1:NumOfCrt,1:NumOfAlt)=0;
        for ii=1:NumOfCrt
           for jj=1:NumOfAlt
              if ii==k
                 H(ii,jj)=(a1*PerformMat(k, jj)*PerformMat(k, jj))+(a2*PerformMat(k, jj))+a3;
```

```
                else
                    H(ii,jj)=0;
                end
            end
        end
      pH=BaseParam(k,9);
      qH=BaseParam(k,8);
        if ((H(k, j) -H(k, i)) <= qH )
                    Conc(i, j) = (Conc(i, j) + (1 * CWt(k)));
              elseif ((H(k, j) -H(k, i)) > pH )
                    Conc(i, j) = Conc(i, j) + 0;
              else
                    Conc(i, j) = (Conc(i, j) + (pH * CWt(k) + (H(k, i) * CWt(k)) - (H(k, j) *
CWt(k))) / (pH - qH));
        end
            end
         end
      end
  end
for k = 1: NumOfCrt
  TotalWt = TotalWt + CWt(k);
end

 for i= 1: NumOfAlt

     for j= 1: NumOfAlt
         if (i ~= j)
            Conc(i, j)=Conc(i, j)/TotalWt;
         else
            Conc(i, j) = 1;
         end
     end
end
for i= 1: NumOfAlt
     for j= 1: NumOfAlt
        Conc(i,j)=round2(Conc(i,j),0.01);
     end
 end
   end
```

Discordance function

```
function [d]=calcDisMat(NumOfAlt,NumOfCrt,PerformMat,ThresholdMat)
d(1:NumOfAlt,1:NumOfAlt,1:NumOfCrt)=0;
indcat=xlsread('Database_2006.xlsx','BasicData','B6:B9');
BaseParam=xlsread('Database_2006.xlsx','BasicData','C6:L9');
  for i = 1:NumOfAlt
      for j = 1:NumOfAlt
         for k = 1:NumOfCrt
```

1. This part is for intuitively linear-deductively linear and full compensating (Type-01)

```
         if( indcat(k,1)==1)
          d(i, j, k) = 0;
```

2. This part is for intuitively non-linear-deductively linear and full compensating (Type-02)

```
elseif( indcat(k,1)==2)
 q1(1:NumOfAlt,1:NumOfAlt)=0;
 for m=1:NumOfAlt
    for n=1:NumOfAlt
    q1(m,n)=PerformMat(k,m)-PerformMat(k,n);
    end
 end
 p=max(max(q1));
 v=p;
 if ((PerformMat(k, j) - PerformMat(k, i)) <= p)
          d(i, j, k) = 0;
       elseif ((PerformMat(k, j) - PerformMat(k, i)) >= v)
          d(i, j, k) = 1;
       else
           d(i, j, k) = (PerformMat(k, j) - PerformMat(k, i)- p) / (v - p);
 end
```

3. This part is for intuitively non-linear-deductively linear and full or partial compensating (Type-03)

```
elseif( indcat(k,1)==3)
 q1(1:NumOfAlt,1:NumOfAlt)=0;
 for m=1:NumOfAlt
    for n=1:NumOfAlt
    q1(m,n)=PerformMat(k,m)-PerformMat(k,n);
    end
 end
 [p q]=calcPrefThreshold(k,i,PerformMat,ThresholdMat);
 p1=max(max(q1));
 v=p1+1;
 if ((PerformMat(k, j) - PerformMat(k, i)) <= p)
          d(i, j, k) = 0;
       elseif ((PerformMat(k, j) - PerformMat(k, i)) >= v)
          d(i, j, k) = 1;
       else
           d(i, j, k) = (PerformMat(k, j) - PerformMat(k, i)- p) / (v - p);
 end
```

4. This part is for intuitively non-linear-deductively linear and full, partial or no compensating (Type-04)

```
elseif indcat(k,1)==4;
 [p q]=calcPrefThreshold(k,i,PerformMat,ThresholdMat);
 q1(1:NumOfAlt,1:NumOfAlt)=0;
 for m=1:NumOfAlt
    for n=1:NumOfAlt
    q1(m,n)=PerformMat(k,m)-PerformMat(k,n);
    end
 end
   [v]=calcVetoThreshold(k,i,PerformMat,ThresholdMat);
       if ((PerformMat(k, j) - PerformMat(k, i)) <= p)
          d(i, j, k) = 0;
```

```
                elseif ((PerformMat(k, j) - PerformMat(k, i)) >= v)
                   d(i, j, k) = 1;
                else
                   d(i, j, k) = (PerformMat(k, j) - PerformMat(k, i)- p) / (v - p);
                end
```

5. This part is for intuitively linear-deductively non linear and full compensating (Type-05)

```
         elseif( indcat(k,1)==5)
          d(i, j, k) = 0;
```

6. This part is for intuitively non-linear-deductively non linear and full or compensating (Type-06)

```
         elseif indcat(k,1)==6;
        a1=BaseParam(k,5);
        a2=BaseParam(k,6);
        a3=BaseParam(k,7);
        H(1:NumOfCrt,1:NumOfAlt)=0;
        for ii=1:NumOfCrt
           for jj=1:NumOfAlt
              if ii==k
                 for x=1:NumOfAlt
                   H(x)=(a1*PerformMat(k, x)*PerformMat(k, x))+(a2*PerformMat(k, x))+a3;
                 end
              else
                  H(ii,jj)=0;
              end
           end
        end
        q2(1:NumOfAlt,1:NumOfAlt)=0;
          for m=1:NumOfAlt
             for n=1:NumOfAlt
             q2(m,n)=H(k,m)-H(k,n);
             end
          end
         pH=max(max(q2));
         vH=pH;
        if ((H(k, j) -H(k, i)) <= pH)
                   d(i, j, k) = 0;
             elseif ((H(k, j) -H(k, i)) >= vH)
                   d(i, j, k) = 1;
             else
                   d(i, j, k) = (PerformMat(k, j) - PerformMat(k, i)- pH) / (vH - pH);
        end
```

7. This part is for intuitively non linear- deductively non linear- full or partially compensating (Type-07)

```
         elseif (indcat(k,1)==7)
        a1=BaseParam(k,5);
        a2=BaseParam(k,6);
        a3=BaseParam(k,7);
                   H(1:NumOfCrt,1:NumOfAlt)=0;
        for ii=1:NumOfCrt
           for jj=1:NumOfAlt
              if ii==k
```

```
           for x=1:NumOfAlt
             H(x)=(a1*PerformMat(k, x)*PerformMat(k, x))+(a2*PerformMat(k, x))+a3;
           end
        else
           H(ii,jj)=0;
        end
    end
end
q2(1:NumOfAlt,1:NumOfAlt)=0;
  for m=1:NumOfAlt
      for n=1:NumOfAlt
      q2(m,n)=H(k,m)-H(k,n);
      end
  end
  pH1=max(max(q2));
  pH=pH1-1;
  vH=pH1+1;
if ((H(k, j) -H(k, i)) <= pH)
            d(i, j, k) = 0;
      elseif ((H(k, j) -H(k, i)) >= vH)
            d(i, j, k) = 1;
      else
            d(i, j, k) = (PerformMat(k, j) - PerformMat(k, i)- pH) / (vH - pH);
end
```

8. This part is for intuitively non linear- deductively non linear-full, partial or no compensation (Type-08)

```
 elseif (indcat(k,1)==8)
a1=BaseParam(k,5);
a2=BaseParam(k,6);
a3=BaseParam(k,7);
           H(1:NumOfCrt,1:NumOfAlt)=0;
for ii=1:NumOfCrt
    for jj=1:NumOfAlt
        if ii==k
           for x=1:NumOfAlt
             H(x)=(a1*PerformMat(k, x)*PerformMat(k, x))+(a2*PerformMat(k, x))+a3;
           end
        else
           H(ii,jj)=0;
        end
    end
end
q2(1:NumOfAlt,1:NumOfAlt)=0;
  for m=1:NumOfAlt
      for n=1:NumOfAlt
      q2(m,n)=H(k,m)-H(k,n);
      end
  end
 pH=BaseParam(k,9);
 vH=BaseParam(k,10);
if ((H(k, j) -H(k, i)) <= pH)
            d(i, j, k) = 0;
      elseif ((H(k, j) -H(k, i)) >= vH)
            d(i, j, k) = 1;
```

```
               else
                    d(i, j, k) = (PerformMat(k, j) - PerformMat(k, i)- pH) / (vH - pH);
         end
          end
          end
       end
   end
for i= 1: NumOfAlt
      for j= 1: NumOfAlt
         for k=1:NumOfCrt
         d(i,j,k)=round2(d(i,j,k),0.01);
         end
      end
 end
  end
```

This function calculates Lambda

```
function [Lambda]=calcLambda(i,j,S)
Lambda=0;
for i = 1:NumOfAlt
       for j = 1:NumOfAlt
         if (Lambda <= S(i, j) && (i ~= j))
             Lambda = S(i, j);
         end
       end
end
```

This function calculates credibility matrix

```
function [S]=calcCredibilityMat(NumOfAlt,NumOfCrt,Conc,d)
S(1:NumOfAlt,1:NumOfAlt)=0;
for i = 1: NumOfAlt
       for j = 1: NumOfAlt
           x=1;
          for k = 1: NumOfCrt
             if (d(i, j, k) <= Conc(i, j))
                y=1;
             else
                y= ((1 - d(i, j, k)) / (1 - Conc(i, j)));
             end
              x=x*y;
          end
           S(i,j)= Conc(i, j) * x;
       end
end
  for i= 1: NumOfAlt
      for j= 1: NumOfAlt
         S(i,j)=round2(S(i,j),0.01);
      end
  end
```

This function conducts the distillation process

```
function [aFindex,dFindex,FResult]=Distillation(NumOfAlt,S)
```

```
AlphaLambda=xlsread('Database_2006.xlsx','BasicData','B3');
BetaLambda=xlsread('Database_2006.xlsx','BasicData','B4');
```

This part distillate the alternatives in a descending order

```
 Dist(1:NumOfAlt)=0;
DescMat(1:NumOfAlt,1:NumOfAlt)=0;
AscMat(1:NumOfAlt,1:NumOfAlt)=0;
maxV = -NumOfAlt;
Results(1:NumOfAlt,1:2)=0;
Results(:,2)=1;
Stemp=S;
dFindex(1:NumOfAlt,1:3)=0;
dFindex(:,3)=1;
Check(1:NumOfAlt,1:1)=1;
  m=0;
  kk=0;
  jj=0;
  ff=0;
   for i = 1: NumOfAlt
      l=0;
       k=1;
      [NetSum]=calcNetSum(Stemp,NumOfAlt,AlphaLambda,BetaLambda,i);
       DescSortNetsum= sort(NetSum,'descend');
   if (NetSum==0)
      ff=ff+1;
      for iiii=1:NumOfAlt
          for jjjj=1:NumOfAlt
          if (Stemp (iiii,jjjj)==1)
             jj=jj+1;
             dFindex(jj,1)=iiii;
             dFindex(jj,2)=ff;
             dFindex(jj,3)=0;
             Check(jj,1)=0;
          end
          end
      end
      break
   end
       for j= 1: NumOfAlt
       if (NetSum(j)== DescSortNetsum (k))
         l=l+1;
         m=m+1;
         dFindex (m,1)=j;
         dFindex (m,2)=i;
       end
       end
    kk=kk+l;
if (l==1);
      jj=jj+1;
      dFindex (jj,3)=0;
      Check(jj,1)=0;
      ff=ff+1;
      dFindex (jj,2)=ff;
```

```
  for ss=1:kk
     if (dFindex(ss,3)== 0) && (dFindex(ss,1)~=0);
        c=dFindex(ss,1);
     for ii =1: NumOfAlt
        Stemp(c,ii)=0;
        Stemp(ii,c)=0;
     end
     end
  end
   else
```

This part starts the else command to sort the alternatives that came as equal rank initially.

```
   subStemp(1:NumOfAlt,1:NumOfAlt)=0;
   subFindex(1:l,1:3)=0;
   subFindex(:,3)=1;
   subCheck(1:l,1:1)=1;
   [subStemp]=calcsubStemp(kk,dFindex,NumOfAlt,Stemp);
   subkk=0;
   subm=0;
for subi=1:l
      subl=0;
      subk=1;
      t=0;
     [subNetSum]=calcsubNetSum(subStemp,NumOfAlt,AlphaLambda,BetaLambda,i);
     subDescSortNetsum= sort(subNetSum,'descend');
  if (subNetSum==0)
     ff=ff+1;
     for iiii=1:NumOfAlt
        for jjjj=1:NumOfAlt
        if (subStemp (iiii,jjjj)==1)
           jj=jj+1;
           dFindex(jj,1)=iiii;
           dFindex(jj,2)=ff;
           dFindex(jj,3)=0;
           Check(jj,1)=0;
        end
        end
     end
     for z5=1:kk
        if (dFindex(z5,3)== 0) && (dFindex(z5,1)~=0);
           a=dFindex(z5,1);
        for iii=1:NumOfAlt
           Stemp(a,iii)=0;
           Stemp(iii,a)=0;
        end
        end
     end
     break
  end
    for subj=1: NumOfAlt
       if (subNetSum(subj)== subDescSortNetsum (subk))
          subm=subm+1;
          subl=subl+1;
```

```
             subFindex(subm,1)=subj;
             subFindex(subm,2)=subi;
         end
     end
     subkk=subkk+subl;
  if (subl==1);
        ff=ff+1;
        jj=jj+1;
        dFindex(jj,1)= subFindex(subm,1);
        dFindex(jj,2)=ff;
        dFindex(jj,3)=0;
        subFindex(subi,3)=0;
        subCheck(subl,1)=0;
        Check(jj,1)=0;
        for z5=1:kk
           if (dFindex(z5,3)== 0) && (dFindex(z5,1)~=0);
               a=dFindex(z5,1);
           for iii=1:NumOfAlt
               Stemp(a,iii)=0;
               Stemp(iii,a)=0;
           end
           end
        end
   for zz=1:subm
       a=subFindex(zz,1);
       for ii =1: NumOfAlt
           subStemp(a,ii)=0;
           subStemp(ii,a)=0;
       end
   end
  else
   subkk2=0;
   for s=1:subl
[subStemp2]=calcsubStemp2(subkk,subFindex,NumOfAlt,subStemp);
[subNetSum2]=calcsubNetSum2(subStemp2,NumOfAlt,AlphaLambda,BetaLambda,i);
subDescSortNetsum2= sort(subNetSum2,'descend');
   if (subNetSum2==0)
       ff=ff+1;
       for iiii=1:NumOfAlt
           for jjjj=1:NumOfAlt
           if (subStemp2 (iiii,jjjj)==1)
               jj=jj+1;
               dFindex(jj,1)=iiii;
               dFindex(jj,2)=ff;
               dFindex(jj,3)=0;
               Check(jj,1)=0;
           end
           end
       end
       for z5=1:kk
           if (dFindex(z5,3)== 0) && (dFindex(z5,1)~=0);
               a=dFindex(z5,1);
           for iii=1:NumOfAlt
               Stemp(a,iii)=0;
```

```
            Stemp(iii,a)=0;
         end
         end
      end
      for zz=1:subm
      a=subFindex(zz,1);
      for ii =1: NumOfAlt
         subStemp(a,ii)=0;
         subStemp(ii,a)=0;
      end
      end
   break
   end
   for subj=1: NumOfAlt
        if (subNetSum2(subj)== subDescSortNetsum2 (1))
           subm2=subm2+1;
           subl2=subl2+1;
           subFindex2(subm2,1)=subj;
           subFindex2(subm2,2)=subi;
        end
   end
   subkk2=subkk2+subl2;
       if subl2==1
       ff=ff+1;
       jj=jj+1;
       dFindex(jj,1)= subFindex2(subm2,1);
       dFindex(jj,2)=ff;
       dFindex(jj,3)=0;
       subFindex(subi,3)=0;
       subCheck(subl2,1)=0;
       Check(jj,1)=0;
   for zz=1:subm2
      a=subFindex(zz,1);
      for ii =1: NumOfAlt
         subStemp(a,ii)=0;
         subStemp(ii,a)=0;
      end
   end
        for z5=1:kk
         if (dFindex(z5,3)== 0) && (dFindex(z5,1)~=0);
            a=dFindex(z5,1);
         for iii=1:NumOfAlt
            Stemp(a,iii)=0;
            Stemp(iii,a)=0;
         end
         end
        end
       else
subkk2=0;
   for s2=1:subl2
   [subStemp3]=calcsubStemp3(subkk2,subFindex2,NumOfAlt,subStemp);
   [subNetSum3]=calcsubNetSum3(subStemp3,NumOfAlt,AlphaLambda,BetaLambda,i);
   subDescSortNetsum3= sort(subNetSum3,'descend');
   if (subNetSum3==0)
```

```
   ff=ff+1;
   for iiii=1:NumOfAlt
      for jjjj=1:NumOfAlt
      if (subStemp3 (iiii,jjjj)==1)
         jj=jj+1;
         dFindex(jj,1)=iiii;
         dFindex(jj,2)=ff;
         dFindex(jj,3)=0;
         Check(jj,1)=0;
      end
      end
   end
   for z5=1:kk
      if (dFindex(z5,3)== 0) && (dFindex(z5,1)~=0);
         a=dFindex(z5,1);
      for iii=1:NumOfAlt
         Stemp(a,iii)=0;
         Stemp(iii,a)=0;
      end
      end
   end
   for zz=1:subm
   a=subFindex(zz,1);
   for ii =1: NumOfAlt
      subStemp(a,ii)=0;
      subStemp(ii,a)=0;
   end
   end
break
end
for subj=1: NumOfAlt
     if (subNetSum3(subj)== subDescSortNetsum3 (1))
        subm3=subm3+1;
        subl3=subl3+1;
        subFindex3(subm3,1)=subj;
        subFindex3(subm3,2)=subi;
     end
end
subkk3=subkk3+subl3;
    if subl3==1
    ff=ff+1;
    jj=jj+1;
    dFindex(jj,1)= subFindex2(subm2,1);
    dFindex(jj,2)=ff;
    dFindex(jj,3)=0;
    subFindex(subi,3)=0;
    subCheck(subl3,1)=0;
    Check(jj,1)=0;
for zz=1:subm3
   a=subFindex(zz,1);
   for ii =1: NumOfAlt
      subStemp(a,ii)=0;
      subStemp(ii,a)=0;
   end
```

```
  end
         for z5=1:kk
          if (dFindex(z5,3)== 0) && (dFindex(z5,1)~=0);
              a=dFindex(z5,1);
          for iii=1:NumOfAlt
              Stemp(a,iii)=0;
              Stemp(iii,a)=0;
          end
          end
         end
       end
  end
       end
  end
  end
end
if (subStemp==0);
      for gggg=1:subm
          bbb=subFindex(gggg,1);
          for iii=1:NumOfAlt
              Stemp(bbb,iii)=0;
              Stemp(iii,bbb)=0;
          end
      end
      break
end
  if (Check==0)
      break
  end
end
   end
```

This part distillate the alternatives in a ascending order

```
Dist(1:NumOfAlt)=0;
DescMat(1:NumOfAlt,1:NumOfAlt)=0;
AscMat(1:NumOfAlt,1:NumOfAlt)=0;
maxV = -NumOfAlt;
Stemp=S;
aFindex2(1:NumOfAlt,1:3)=0;
aFindex2(:,3)=1;
aCheck(1:NumOfAlt,1:1)=1;
  m=0;
  kk=0;
  jj=0;
  ff=0;
  subm2=0;
  subl2=0;
for i = 1: NumOfAlt
      l=0;
       k=1;
      [NetSum]=calcNetSum(Stemp,NumOfAlt,AlphaLambda,BetaLambda,i);
       AscSortNetsum= sort(NetSum,'ascend');
   if (NetSum==0)
      ff=ff+1;
```

```
      for iiii=1:NumOfAlt
          for jjjj=1:NumOfAlt
          if (Stemp (iiii,jjjj)==1)
              jj=jj+1;
              aFindex2(jj,1)=iiii;
              aFindex2(jj,2)=ff;
              aFindex2(jj,3)=0;
              aCheck(jj,1)=0;
          end
          end
      end
      break
  end
       for j= 1: NumOfAlt
       if (NetSum(j)== AscSortNetsum (k))
        l=l+1;
        m=m+1;
        aFindex2 (m,1)=j;
        aFindex2 (m,2)=i;
       end
       end
   kk=kk+l;
if (l==1);
      jj=jj+1;
      aFindex2 (jj,3)=0;
      aCheck(jj,1)=0;
      ff=ff+1;
      aFindex2 (jj,2)=ff;
  for ss=1:kk
      if (aFindex2(ss,3)== 0) && (aFindex2(ss,1)~=0);
          c=aFindex2(ss,1);
      for ii =1: NumOfAlt
          Stemp(c,ii)=0;
          Stemp(ii,c)=0;
      end
      end
  end
```

This part starts the else command to sort the alternatives that came as equal rank initially.

```
   else
   subStemp(1:NumOfAlt,1:NumOfAlt)=0;
   subaFindex(1:l,1:3)=0;
   subaFindex(:,3)=1;
   subaCheck(1:l,1:1)=1;
   [subStemp]=calcsubStemp(kk,aFindex2,NumOfAlt,Stemp);
   subkk=0;
   subm=0;
for subi=1:l
       subl=0;
       subk=1;
       t=0;
      [subNetSum]=calcsubNetSum(subStemp,NumOfAlt,AlphaLambda,BetaLambda,i);
      subAscSortNetsum= sort(subNetSum,'ascend');
```

```
 if (subNetSum==0)
     ff=ff+1;
     for iiii=1:NumOfAlt
         for jjjj=1:NumOfAlt
         if (subStemp (iiii,jjjj)==1)
             jj=jj+1;
             aFindex2(jj,1)=iiii;
             aFindex2(jj,2)=ff;
             aFindex2(jj,3)=0;
             aCheck(jj,1)=0;
         end
         end
     end
     for z5=1:kk
         if (aFindex2(z5,3)== 0) && (aFindex2(z5,1)~=0);
             a=aFindex2(z5,1);
         for iii=1:NumOfAlt
             Stemp(a,iii)=0;
             Stemp(iii,a)=0;
         end
         end
     end
     break
 end
   for subj=1: NumOfAlt
       if (subNetSum(subj)== subAscSortNetsum (subk))
           subm=subm+1;
           subl=subl+1;
           subaFindex(subm,1)=subj;
           subaFindex(subm,2)=subi;
       end
   end
   subkk=subkk+subl;
if (subl==1);
      ff=ff+1;
      jj=jj+1;
      aFindex2(jj,1)= subaFindex(subm,1);
      aFindex2(jj,2)=ff;
      aFindex2(jj,3)=0;
      subaFindex(subi,3)=0;
      subaCheck(subl,1)=0;
      aCheck(jj,1)=0;
      for z5=1:kk
         if (aFindex2(z5,3)== 0) && (aFindex2(z5,1)~=0);
             a=aFindex2(z5,1);
         for iii=1:NumOfAlt
             Stemp(a,iii)=0;
             Stemp(iii,a)=0;
         end
         end
      end
 for zz=1:subm
     a=subaFindex(zz,1);
     for ii =1: NumOfAlt
```

```
         subStemp(a,ii)=0;
         subStemp(ii,a)=0;
      end
   end
  else
   subkk2=0;
   for s=1:subl
   [subStemp2]=calcsubStemp2(subkk,subaFindex,NumOfAlt,subStemp);
   [subNetSum2]=calcsubNetSum2(subStemp2,NumOfAlt,AlphaLambda,BetaLambda,i);
   subAscSortNetsum2= sort(subNetSum2,'ascend');
   if (subNetSum2==0)
      ff=ff+1;
      for iiii=1:NumOfAlt
         for jjjj=1:NumOfAlt
         if (subStemp2 (iiii,jjjj)==1)
            jj=jj+1;
            aFindex2(jj,1)=iiii;
            aFindex2(jj,2)=ff;
            aFindex2(jj,3)=0;
            aCheck(jj,1)=0;
         end
         end
      end
      for z5=1:kk
         if (aFindex2(z5,3)== 0) && (aFindex2(z5,1)~=0);
            a=aFindex2(z5,1);
         for iii=1:NumOfAlt
            Stemp(a,iii)=0;
            Stemp(iii,a)=0;
         end
         end
      end
      for zz=1:subm
      a=subaFindex(zz,1);
      for ii =1: NumOfAlt
         subStemp(a,ii)=0;
         subStemp(ii,a)=0;
      end
      end
   break
   end
   for subj=1: NumOfAlt
        if (subNetSum2(subj)== subAscSortNetsum2 (1))
           subm2=subm2+1;
           subl2=subl2+1;
           subaFindex2(subm2,1)=subj;
           subaFindex2(subm2,2)=subi;
        end
   end
   subkk2=subkk2+subl2;
       if subl2==1
       ff=ff+1;
       jj=jj+1;
       aFindex2(jj,1)= subaFindex2(subm2,1);
```

```
        aFindex2(jj,2)=ff;
        aFindex2(jj,3)=0;
        subaFindex(subi,3)=0;
        subaCheck(subl2,1)=0;
        aCheck(jj,1)=0;
   for zz=1:subm2
       a=subaFindex(zz,1);
       for ii =1: NumOfAlt
           subStemp(a,ii)=0;
           subStemp(ii,a)=0;
       end
   end
          for z5=1:kk
           if (aFindex2(z5,3)== 0) && (aFindex2(z5,1)~=0);
               a=aFindex2(z5,1);
           for iii=1:NumOfAlt
               Stemp(a,iii)=0;
               Stemp(iii,a)=0;
           end
           end
          end
        else
subkk2=0;
   for s2=1:subl2
   [subStemp3]=calcsubStemp3(subkk2,subaFindex2,NumOfAlt,subStemp);
   [subNetSum3]=calcsubNetSum3(subStemp3,NumOfAlt,AlphaLambda,BetaLambda,i);
   subAscSortNetsum3= sort(subNetSum3,'ascend');
   if (subNetSum3==0)
       ff=ff+1;
       for iiii=1:NumOfAlt
           for jjjj=1:NumOfAlt
           if (subStemp3 (iiii,jjjj)==1)
               jj=jj+1;
               aFindex2(jj,1)=iiii;
               aFindex2(jj,2)=ff;
               aFindex2(jj,3)=0;
               aCheck(jj,1)=0;
           end
           end
       end
       for z5=1:kk
           if (aFindex2(z5,3)== 0) && (aFindex2(z5,1)~=0);
               a=aFindex2(z5,1);
           for iii=1:NumOfAlt
               Stemp(a,iii)=0;
               Stemp(iii,a)=0;
           end
           end
       end
       for zz=1:subm
       a=subaFindex(zz,1);
       for ii =1: NumOfAlt
           subStemp(a,ii)=0;
           subStemp(ii,a)=0;
```

```
       end
       end
   break
   end
   for subj=1: NumOfAlt
         if (subNetSum3(subj)== subAscSortNetsum3 (1))
             subm3=subm3+1;
             subl3=subl3+1;
             subaFindex3(subm3,1)=subj;
             subaFindex3(subm3,2)=subi;
         end
   end
   subkk3=subkk3+subl3;
        if subl3==1
        ff=ff+1;
        jj=jj+1;
        aFindex2(jj,1)= subaFindex2(subm2,1);
        aFindex2(jj,2)=ff;
        aFindex2(jj,3)=0;
        subaFindex(subi,3)=0;
        subaCheck(subl3,1)=0;
        aCheck(jj,1)=0;
   for zz=1:subm3
       a=subaFindex(zz,1);
       for ii =1: NumOfAlt
           subStemp(a,ii)=0;
           subStemp(ii,a)=0;
       end
   end
          for z5=1:kk
           if (aFindex2(z5,3)== 0) && (aFindex2(z5,1)~=0);
               a=aFindex2(z5,1);
           for iii=1:NumOfAlt
               Stemp(a,iii)=0;
               Stemp(iii,a)=0;
           end
           end
          end
        end
   end
        end
   end
   end
end
if (subStemp==0);
       for gggg=1:subm
           bbb=subaFindex(gggg,1);
           for iii=1:NumOfAlt
               Stemp(bbb,iii)=0;
               Stemp(iii,bbb)=0;
           end
       end
       break
end
```

```
  if (aCheck==0)
      break
   end
end
end
aFindex1(1:NumOfAlt,1:2)=0;
FMax=0;
   for i = 1:NumOfAlt
      if (FMax<= aFindex2(i, 2))
         FMax = aFindex2(i, 2);
      end
   end
   aFindex1(1,2)=FMax;
   aFindex1(1,1)=aFindex2(1,1);
   for i=2:NumOfAlt
      aFindex1(i,1)=aFindex2(i,1);
   if (aFindex2(i,2)==1);
      aFindex1(i,2)=FMax;
   elseif (aFindex2(i,2)==aFindex2(i-1,2));
      aFindex1(i,2)=aFindex1(i-1,2);
   else (aFindex2(i,2) ~= aFindex2(i-1,2));
       aFindex1(i,2)=aFindex1(i-1,2)-1;
   end
   end
aFindex=sortrows(aFindex1,2);
```

This part finds the intersection of descending and ascending distillation

```
FResult(1:NumOfAlt,1:4)=0;
FResult(:,4)=1;
bCheck(1:NumOfAlt,1)=1;
m=0;
n=0;
h=0;
a1=0;
a2=0;
a3=0;
for i=1:NumOfAlt
    l=0;
    for j=1:NumOfAlt
        if (dFindex(j,2)==i)
            l=l+1;
        end
    end
        if(l==1);
            subFResult=0;
            Ascomp(1:l,1:2)=0;
            m=m+1;
            subFResult(1,1)=dFindex(m,1);
            for ii=1:NumOfAlt
                if (aFindex(ii,1)==subFResult);
                    Ascomp(1,1)=aFindex(ii,1);
                    Ascomp(1,2)=aFindex(ii,2);
                end
```

```
  end
  c=0;
  subAscomp(1:NumOfAlt,1)=0;
  FResult(m,1)=dFindex(m,1);
 for i2=1:NumOfAlt
   if (Ascomp (1,2)==FResult(i2,2))
    c=c+1;
    subAscomp(c,1)=FResult(i2,2);
   end
 end
   if c>0
    a1=subAscomp(c,1);
  a2=0;
  for i3=1:m;
    if FResult(i3,2)==a1
      a2=FResult(i3,3);
    end
  end
  FResult(m,2)=Ascomp(1,2);
  FResult(m,3)=a2+1;
  FResult(m,4)=0;
  bCheck(m,1)=0;
   else
     a1=Ascomp(1,2);
     a2=0;
   for i3=1:m;
    if (FResult(i3,4)==0 && FResult(i3,1)~=0)
     a2=FResult(i3,3);
    end
   end
     h=h+1;
     FResult(m,2)=Ascomp(1,2);
     FResult(m,3)=a2+1;
     FResult(m,4)=0;
     bCheck(m,1)=0;
   end
if (bCheck==0)
  break
end
else
subFResult(1:l,1:2)=0;
Ascomp(1:l,1:2)=0;
for i3=1:l
 subFResult(i3,1)=dFindex(m+i3,1);
end
for ii=1:l
  for ii2=1:NumOfAlt
    if (aFindex(ii2,1)==subFResult(ii,1));
      Ascomp(ii,1)=aFindex(ii2,1);
      Ascomp(ii,2)=aFindex(ii2,2);
    end
  end
end
sortAscomp=sortrows(Ascomp,2);
```

```
        subAscomp(1:NumOfAlt,1)=0;
for i1=1:l
         c=0;
         subAscomp(1:NumOfAlt,1)=0;
       for i2=1:NumOfAlt
          if (sortAscomp (i1,2)==FResult(i2,2))
           c=c+1;
           subAscomp(c,1)=FResult(i2,2);
          end
       end
if c>0
           a1=subAscomp(c,1);
           zz=0;
if i1==1
            a2=0;
        for i3=1:m;
           if FResult(i3,2)==a1
              a2=FResult(i3,3);
           end
        end
        h=h+1;
        m=m+1;
        FResult(m,1)=sortAscomp(i1,1);
        FResult(m,2)=sortAscomp(i1,2);
        FResult(m,3)=a2+1;
        FResult(m,4)=0;
        bCheck(m,1)=0;
else
           if sortAscomp(i1,2)-sortAscomp(i1-1,2)==0
              for yy1=1:m
                 if FResult(yy1,2)==sortAscomp(i1,2)
                    a2=FResult(yy1,3);
                 end
              end
                 m=m+1;
                 h=h+1;
                 FResult(m,1)=sortAscomp(i1,1);
                 FResult(m,2)=sortAscomp(i1,2);
                 FResult(m,3)=a2;
                 FResult(m,4)=0;
                 bCheck(m,1)=0;
           else
        a2=0;
        for i3=1:m;
           if FResult(i3,2)==a1
              a2=FResult(i3,3);
           end
        end
        h=h+1;
        m=m+1;
        FResult(m,1)=sortAscomp(i1,1);
        FResult(m,2)=sortAscomp(i1,2);
        FResult(m,3)=a2+1;
        FResult(m,4)=0;
```

```
        bCheck(m,1)=0;
          end
end
else
           a1=sortAscomp(i1,2);
           a2=0;
           m=m+1;
           FResult(m,1)=sortAscomp(i1,1);
           FResult(m,2)=sortAscomp(i1,2);
           bCheck(m,1)=0;
         for i3=1:m;
          if (FResult(i3,4)==0 && FResult(i3,1)~=0)
           a2=FResult(i3,3);
          end
         end
           h=h+1;
            FResult(m,4)=0;
           FResult(m,3)=a2+1;
end
     if (bCheck==0)
        break
     end
end
     end
     clear Ascomp
      if (bCheck==0)
        break
     end
end
```

'Netsum' function used in distillation

```
function [NetSum]=calcNetSum(Stemp,NumOfAlt,AlphaLambda,BetaLambda,i)
TMat(1:NumOfAlt,1:NumOfAlt)=0;
sMax=0;
  for i2 = 1:NumOfAlt
     for j = 1:NumOfAlt
        if (sMax <= Stemp(i2, j) && (i2 ~= j))
          sMax = Stemp(i2, j);
        end
     end
  end
if i==1
  sLambda=0.15;
else
   sLambda=(AlphaLambda*sMax)+BetaLambda;
end
Lambda = sMax-sLambda;
for i2 = 1: NumOfAlt
  for j = 1: NumOfAlt
        if (Stemp(i2, j) > Lambda)&& ((Stemp(i2, j)-Stemp(j, i2))>sLambda)
          TMat(i2, j) = 1;
        else
```

```
            TMat(i2, j) = 0;
          end
    end
end
NetSum(1:NumOfAlt)=0;
for i2 = 1: NumOfAlt
   RowSum=0;
      ColSum=0;
    for j=1: NumOfAlt
       RowSum= RowSum+ TMat(i2, j);
       ColSum = ColSum + TMat(j, i2);
    end
     NetSum(i2) = RowSum - ColSum;
end
```

‘Stemp’ function used in distillation

```
function [Stemp]=calcStemp(TMat)
NetSum(1:NumOfAlt)=0;
for i = 1: NumOfAlt
   RowSum=0;
      ColSum=0;
    for j=1: NumOfAlt
       RowSum= RowSum+ TMat(i, j);
       ColSum = ColSum + TMat(j, i);
    end
     NetSum(i) = RowSum - ColSum;
end
```

‘subNetSum’ function used in distillation

```
function [subNetSum]=calcsubNetSum(subStemp,NumOfAlt,AlphaLambda,BetaLambda,i)
TMat(1:NumOfAlt,1:NumOfAlt)=0;
sMax=0;
   for i2 = 1:NumOfAlt
      for j = 1:NumOfAlt
          if (sMax <= subStemp(i2, j) && (i2 ~= j))
             sMax = subStemp(i2, j);
          end
      end
   end
if i==1
   sLambda=0.15;
else
     sLambda=(AlphaLambda*sMax)+BetaLambda;
end
Lambda = sMax-sLambda;
for i2 = 1: NumOfAlt
   for j = 1: NumOfAlt
          if (subStemp(i2, j) > Lambda)&& ((subStemp(i2, j)-subStemp(j, i2))>sLambda)
             TMat(i2, j) = 1;
          else
             TMat(i2, j) = 0;
          end
   end
```

```
end
subNetSum(1:NumOfAlt)=0;
for i2 = 1: NumOfAlt
   RowSum=0;
        ColSum=0;
    for j=1: NumOfAlt
        RowSum= RowSum+ TMat(i2, j);
        ColSum = ColSum + TMat(j, i2);
    end
     subNetSum(i2) = RowSum - ColSum;
end
```

‘subNetSum2’ function used in distillation

```
function[subNetSum2]=calcsubNetSum2(subStemp2,NumOfAlt,AlphaLambda,BetaLambda,i
)
TMat(1:NumOfAlt,1:NumOfAlt)=0;
sMax=0;
   for i2 = 1:NumOfAlt
       for j = 1:NumOfAlt
            if (sMax <= subStemp2(i2, j) && (i2 ~= j))
                sMax = subStemp2(i2, j);
            end
       end
   end
if i==1
    sLambda=0.15;
else
     sLambda=(AlphaLambda*sMax)+BetaLambda;
end
Lambda = sMax-sLambda;
for i2 = 1: NumOfAlt
    for j = 1: NumOfAlt
            if (subStemp2(i2, j) > Lambda)&& ((subStemp2(i2, j)-subStemp2(j, i2))>sLambda)
                TMat(i2, j) = 1;
            else
                TMat(i2, j) = 0;
            end
    end
end
subNetSum2(1:NumOfAlt)=0;
for i2 = 1: NumOfAlt
   RowSum=0;
        ColSum=0;
    for j=1: NumOfAlt
        RowSum= RowSum+ TMat(i2, j);
        ColSum = ColSum + TMat(j, i2);
    end
     subNetSum2(i2) = RowSum - ColSum;
end
```

‘subNetSum3’ function used in distillation

```
function[subNetSum3]=calcsubNetSum3(subStemp3,NumOfAlt,AlphaLambda,BetaLambda,i
)
```

```
TMat(1:NumOfAlt,1:NumOfAlt)=0;
sMax=0;
  for i2 = 1:NumOfAlt
      for j = 1:NumOfAlt
          if (sMax <= subStemp3(i2, j) && (i2 ~= j))
             sMax = subStemp3(i2, j);
          end
      end
  end
if i==1
   sLambda=0.15;
else
    sLambda=(AlphaLambda*sMax)+BetaLambda;
end
Lambda = sMax-sLambda;
for i2 = 1: NumOfAlt
   for j = 1: NumOfAlt
          if (subStemp3(i2, j) > Lambda)&& ((subStemp3(i2, j)-subStemp3(j, i2))>sLambda)
             TMat(i2, j) = 1;
          else
             TMat(i2, j) = 0;
          end
   end
end
subNetSum3(1:NumOfAlt)=0;
for i2 = 1: NumOfAlt
  RowSum=0;
      ColSum=0;
   for j=1: NumOfAlt
      RowSum= RowSum+ TMat(i2, j);
      ColSum = ColSum + TMat(j, i2);
   end
    subNetSum3(i2) = RowSum - ColSum;
end
```

‘subStemp’ function used in distillation

```
function [subStemp]=calcsubStemp(kk,dFindex,NumOfAlt,Stemp)
  t=0;
  A(1:NumOfAlt,1)=0;
   for z=1:kk
       if (dFindex(z,3)== 1) && (dFindex(z,1)~=0);
      a=dFindex(z,1);
      t=t+1;
      A(t,1)=a;
      for ii=1:NumOfAlt
         subStemp(a,ii)=Stemp(a,ii);
         subStemp(ii,a)=Stemp(ii,a);
      end
       end
   end
for z=1:t
   for iii=1:NumOfAlt
   if A(z,1)==iii
   else
```

```
        b=0;
        for z1=1:t
            if A(z1,1)==iii
                b=b+1;
            end
        end
            if b>0
            else
        for iiii=1:NumOfAlt
        subStemp(iii,iiii)=0;
        subStemp(iiii,iii)=0;
        end
            end
    end
    end
end
end
```

‘subStemp2’ function used in distillation

```
function [subStemp2]=calcsubStemp2(subkk,subFindex,NumOfAlt,subStemp)
   t=0;
   A(1:NumOfAlt,1)=0;
    for z=1:subkk
        if (subFindex(z,3)== 1) && (subFindex(z,1)~=0);
      a=subFindex(z,1);
      t=t+1;
      A(t,1)=a;
      for ii=1:NumOfAlt
          subStemp2(a,ii)=subStemp(a,ii);
          subStemp2(ii,a)=subStemp(ii,a);
      end
       end
    end
for z=1:t
    for iii=1:NumOfAlt
    if A(z,1)==iii
    else
        b=0;
        for z1=1:t
            if A(z1,1)==iii
                b=b+1;
            end
        end
            if b>0
            else
        for iiii=1:NumOfAlt
        subStemp2(iii,iiii)=0;
        subStemp2(iiii,iii)=0;
        end
            end
    end
    end
end
end
```

‘subStemp3’ function used in distillation

```
function [subStemp3]=calcsubStemp3(subkk2,subFindex2,NumOfAlt,subStemp)
  t=0;
  A(1:NumOfAlt,1)=0;
   for z=1:subkk2
      if (subFindex2(z,3)== 1) && (subFindex2(z,1)~=0);
     a=subFindex2(z,1);
     t=t+1;
     A(t,1)=a;
     for ii=1:NumOfAlt
        subStemp3(a,ii)=subStemp(a,ii);
        subStemp3(ii,a)=subStemp(ii,a);
     end
      end
   end
for z=1:t
   for iii=1:NumOfAlt
   if A(z,1)==iii
   else
      b=0;
      for z1=1:t
         if A(z1,1)==iii
            b=b+1;
         end
      end
         if b>0
         else
      for iiii=1:NumOfAlt
      subStemp3(iii,iiii)=0;
      subStemp3(iiii,iii)=0;
      end
         end
   end
   end
end
end
```

Function used for rounding the values up to two decimal points

```
function z = round2(x,y)
error(nargchk(2,2,nargin))
error(nargoutchk(0,1,nargout))
if numel(y)>1
  error('Y must be scalar')
end
z = round(x/y)*y;
```

A6: List of papers

	Name of the Paper	Author	Year of Publication	Journal
1	A time-series analysis of mortality and air temperature in Greater Beirut	A. El-Zein et al.	2004	Science of the Total Environment
2	On the association between high temperature and mortality in warm climates	A. El-Zein et al.	2005	Science of the Total Environment
3	Assessing coincidence between priority conservation areas for vertebrate groups in a Mediterranean hotspot	A. Estrada, R et al.	2011	Biological Conservation
4	Estimating least-developed countries' vulnerability to climate-related extreme events over the next 50 years	A. G. Patt et al.	2010	Proceedings of the National Academy of Sciences of the United States of America
5	The giant squid Architeuthis: An emblematic invertebrate that can represent concern for the conservation of marine biodiversity	A. Guerra et al.	2011	Biological Conservation
6	Climate change-related vulnerabilities and local environmental public health tracking through GEMSS: A web-based visualization tool	A. Houghton et al.	2012	Applied Geography
7	Responses of reef fish communities to coral declines on the Great Barrier Reef	A. J. Cheal et at.	2008	Marine Ecology-Progress Series

	Name of the Paper	Author	Year of Publication	Journal
8	What determines farmers' resilience towards ENSO-related drought? An Empirical assessment in Central Sulawesi, Indonesia	A. Keil et al.	2008	Climatic Change
9	The surface of vulnerability: An analytical framework for examining environmental change	A. L. Luers	2005	Global Environmental Change-Human and Policy Dimensions
10	Modeling vulnerability and resilience to climate change: A case study of India and Indian states	A. L.Brenkert et al.	2005	Mitigation and Adaptation Strategies for Global Change
11	Application of fuzzy models to assess susceptibility to droughts from a socio-economic perspective	A. Michlik et al.	2008	Regional Environmental Change
12	Detection and Assessment of Ecosystem Regime Shifts from Fisher Information	A. T. Karunanithi et al.	2008	Ecology and Society
13	An indicator framework for the climatic adaptive capacity of natural ecosystems	B. Czúcz et al.	2011	Journal of Vegetation Science
14	Vulnerability of South African animal taxa to climate change	B. F. N. Erasmus et al.	2002	Global Change Biology
15	Igniting change in local government: lessons learned from a bushfire vulnerability assessment	B. L. Preston et al.	2009	Mitigation and Adaptation Strategies for Global Change
16	How does fishing alter marine populations and ecosystems sensitivity to climate?	B. Planque et al.	2010	Journal of Marine Systems

	Name of the Paper	Author	Year of Publication	Journal
17	Climate change and social vulnerability: Toward a sociology and geography of food insecurity	Bohle, H. G., et al.	1994	Global Environmental Change
18	Community involvement in management for maintaining coral reef resilience and biodiversity in southern Caribbean marine protected areas	C. Camargo et al.	2009	Biodiversity and Conservation
19	Ecological and socio-economical thresholds of land and plant-community degradation in semi-arid Mediterranean areas of southeastern Spain	C. L. Alados et al	2011	Journal of Arid Environments
20	Sea urchins, macroalgae and coral reef decline: a functional evaluation of an intact reef system, Ningaloo, Western Australia	C. L. Johansson et al.	2010	Marine Ecology-Progress Series
21	The role of maps in neighborhood-level heat vulnerability assessment for the city of toronto	C. Rinner et al.	2010	Cartography and Geographic Information Science
22	Adapting to climate change in Andean ecosystems: Landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems	C. Valdivia et al.	2010	Annals of the Association of American Geographers
23	Targeting attention on local vulnerabilities using an integrated index approach: The example of the climate vulnerability index	C.A. Sullivan et al.	2005	

	Name of the Paper	Author	Year of Publication	Journal
24	Indexing variability: A case study with climate change impacts on ecosystems	D. Coulson et at	2006	Ecological Indicators
25	The socio-spatial dynamics of extreme urban heat events: The case of heat-related deaths in Philadelphia	D. P. Johnson et al.	2009	Applied Geography
26	Are the endemic water beetles of the Iberian Peninsula and the Balearic Islands effectively protected?	D. Sanchez-Fernandez et ak.	2008	Biological Conservation
27	Easier surveillance of climate-related health vulnerabilities through a Web-based spatial OLAP application	E. Bernier et al.	2009	International Journal of Health Geographics
28	Vulnerability of national economies to the impacts of climate change on fisheries	E. H. Allison et al.	2009	Fish and Fisheries
29	Towards the harmonization of water-related policies for managing drought risks across the EU	E. Kampragou et al.	2011	Environmental Science and Policy
30	Uncertainty in resilience to climate change in India and Indian states	E. L. Malone et al.	2008	Climatic Change
31	Evaluating regional vulnerability to climate change: Purposes and methods	E. L. Malone et al.	2011	Wiley Interdisciplinary Reviews: Climate Change
32	Climate change and water resources in Lebanon and the Middle East	E.Bou-Zeid et al.	2002	Journal of Water Resources Planning and Management-Asce

	Name of the Paper	Author	Year of Publication	Journal
33	Typologies of crop-drought vulnerability: an Empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961-2001)	E. Simelton et al.	2009	Environmental Science and Policy
34	Developing Credible Vulnerability Indicators for Climate Adaptation Policy Assessment	Eriksen, S. et al.	2007	MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE
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44	Application of Sea Level Rise Vulnerability Assessment Model to Selected Coastal Areas of Turkey	G. Ozyurt et al.	2009	Journal of Coastal Research
45	Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity	G. Yohe et al.	2002	Global Environmental Change-Human and Policy Dimensions
46	Insights into the composition of household vulnerability from multicriteria decision analysis	H. Eakin et al.	2008	Global Environmental Change-Human and Policy Dimensions
47	How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment	H. M. Füssel	2010	Global Environmental Change
48	Vulnerability: A generally applicable conceptual framework for climate change research	H. M. Füssel	2007	Global Environmental Change
49	Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking	H. M. Füssel and R. Klein	2006	Climatic Change

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65	Redesigning biodiversity conservation projects for climate change: examples from the field	K. A. Poiani et al.	2011	Biodiversity and Conservation
66	Why worry? Community water system managers' perceptions of climate vulnerability	K. Dow et al	2007	Global Environmental Change

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86	The vulnerability of ecosystem services to land use change	M. J. Metzger et al.	2006	Agriculture Ecosystems & Environment
87	Rapid biodiversity assessment of arthropods for monitoring average local species richness and related ecosystem services	M. K. Obrist	2010	Biodiversity and Conservation
88	Last millennium palaeoenvironmental changes from a Baltic bog (Poland) inferred from stable isotopes, pollen, plant macrofossils and testate amoebae	M. Lamentowicz et al.	2008	Palaeogeography, Palaeoclimatology, Palaeoecology
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101	Hurricane preparedness as anticipatory adaptation: A case study of community businesses	P. D. Howe	2011	Global Environmental Change-Human and Policy Dimensions
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104	Interannual hypoxia variability in a coastal upwelling system: Ocean-shelf exchange, climate and ecosystem-state implications	P. M. S. Monteiro et al.	2008	Deep-Sea Research Part I: Oceanographic Research Papers
105	Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity	P. Reidsma et al.	2007	Climatic Change

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108	Adaptation investments: a resource allocation framework	R. Barr et al.	2010	Mitigation and Adaptation Strategies for Global Change
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125	Sustaining Ecological Integrity with Respect to Climate Change: A Fuzzy Adaptive Management Approach	T. Prato	2010	Environmental Management
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127	Climate change impacts on water resources in the upper Blue Nile River Basin, Ethiopia	U. Kim	2009	Journal of the American Water Resources Association
128	Sea-level rise - a review of recent past and near-future trends	V. Gornitz	1995	Earth Surface Processes and Landforms
129	A framework to assess adaptive capacity of the water resources system in Nepalese river basins	V. P. Pandey et al.	2011	Ecological Indicators
130	Changing skewness: An early warning signal of regime shifts in ecosystems	V.; Jayaprakash Guttal, C.	2008	Ecology Letters
131	Glacial-interglacial changes in moisture balance and the impact on vegetation in the southern hemisphere tropical Andes (Bolivia/Peru)	W. D. Gosling et al.	2008	Palaeogeography, Palaeoclimatolog y, Palaeoecology
132	Approaches to vulnerability to climate change	W. N. Adger	1996	Working Paper - Centre for Social and Economic Research on the Global Environment
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