Systems Approach to Regional Climate Change Adaptation Strategies in Metropolises




Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group

Sydney Coastal Councils

National Research FLAGSHIPS Climate Adaptation

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Executive Summary

As part of the Australian Government Department of Climate Change (DCC) National Climate Change Adaptation Program (NCCAP), the Sydney Coastal Councils Group (SCCG) has partnered with the CSIRO working in collaboration with University of the Sunshine Coast to undertake a two-year research project on regional approaches to managing climate vulnerability in the Sydney region.

The future climate of the SCCG region is projected to be both warmer and drier. Meanwhile, sea-level rise is projected to increase the risk of inundation and erosion of the SCCG coastline. These climatic changes will have important implications for the SCCG region. Given the diversity of the topographic, demographic and socio-economic characteristics of the SCCG landscape, different areas within the region are likely to be affected in different ways. As a result, local governments are likely to experience unique management challenges that arise from the local context.

The goal of the DCC project is to explore this issue of climate change risk management, specifically adaptation, in the SCCG region. Rather than the commonly utilised approach of generating scenarios of climate change and discussing their potential impacts, this project focuses on examining the capacity of the 15 SCCG member Councils to adapt to climate change. This incorporates not only challenges associated with access to financial capital, technology and information to facilitate adaptation, but perhaps more importantly, the institutional processes and barriers that influence the implementation of adaptive measures.

This report represents the first stage in this project, the assessment and mapping of climate change *vulnerability* throughout the SCCG region, which the Intergovernmental Panel on Climate Change (IPCC) defines as follows:

> *"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."*

Five areas of potential climate impacts were selected for vulnerability assessment:

- Extreme heat and human health effects
- Sea-level rise and coastal hazards
- Extreme rainfall and urban stormwater management
- Bushfire
- Natural ecosystems and assets

In conducting these vulnerability assessments, simple conceptual models identifying the key processes and assumptions were developed for each of the above impact areas. These models were subsequently utilised to select a broad range of indicators reflecting the three components of vulnerability: exposure, sensitivity and adaptive capacity. These indicators were integrated within a geographic information system to facilitate mapping of relative vulnerability and to draw generalisations at the Council level. Results were also compared with the subjective perceptions of vulnerability among SCCG member Council staff.

The resulting regional vulnerability maps provide an indication of the relative vulnerability of different areas within the SCCG to different climate change impacts. However, while vulnerability scores represent the potential for an adverse impact to occur, they do not necessarily indicate the magnitude of the impact or its probability, and any attempt to combine or compare vulnerability scores across impacts should be done cautiously. Therefore, while the assessment provides an indication of potential areas that should be considered further, ultimately more focused work is required to develop a comprehensive understanding of risk that may guide future management decisions.

Vulnerability mapping identified a number of hotspots within the SCCG region that were considered relatively more at-risk to the effects of climate change. These included northwest and southern Hornsby Shire Council, eastern Pittwater Council, the SCCG Councils between Sydney Harbour and Botany Bay (particularly Rockdale and Botany Bay City Councils), as well as northern Sutherland Shire Council (Figure A; Table A). Overall, this pattern of vulnerability was consistent with the spatial patterns of human development in the region. For example, Hornsby, Warringah and Sutherland Shire Councils generally had the largest proportion of low vulnerability areas, although localised hotspots were readily identifiable in all Councils. When deconstructed, the sources of vulnerability varied significantly from location to location – some areas had high levels of climate exposure, others high sensitivity, while others were hindered by low adaptive capacity. Such variability in the drivers of vulnerability is important for the development of interventions.

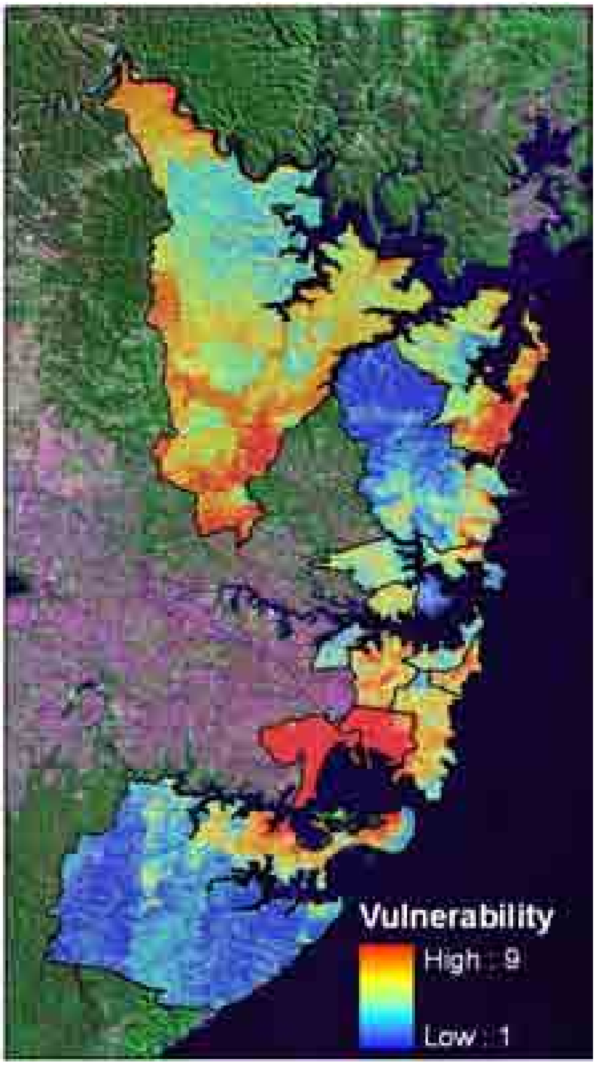


***Figure A**. Overall vulnerability of the SCCG region to climate change, based upon the vulnerability layers for the five impact areas. High values indicate a relatively high degree of vulnerability to future climate change while low values indicate low vulnerability.*

Results of the assessment were subsequently shared with stakeholders in SCCG member Councils. Compared with the subjective perceptions of vulnerability among Council staff, there was agreement among three of the impact areas: sea-level rise, extreme rainfall and, particularly, bushfire. However, there appeared to be some clear differences in how vulnerability was framed with respect to extreme heat and ecosystems. Furthermore, while stakeholders generally responded favourably to the visual accessibility of maps and the emphasis on the diversity of drivers that can contribute to vulnerability, there were challenges in the communication of assessment results.

In consideration of these results, some general conclusions regarding regional climate change vulnerability and its assessment emerged:

1) There is significant spatial variability throughout the SCCG region with respect to climate change vulnerability. Depending on the impact under consideration, vulnerability could be highly fragmented or concentrated in certain areas. This suggests the need to tailor management activities to accommodate not only the unique challenges posed by different impacts, but also the diversity of the landscape.

2) The socio-economic circumstances of the SCCG landscape emerge as key drivers affecting future vulnerability. Factors such as demographics, socio-economic conditions, and human agency that influence response capabilities are often equally if not more important than biophysical hazards in dictating the potential for harm.

3) While the results of a vulnerability assessment provide potentially valuable information, particularly with respect to prioritisation of impacts and areas for further investigation, significant insight and learning about drivers of vulnerability and adaptive capacity can be gained simply through the process of conducting the assessment. Knowledge capture throughout the assessment process is important for maximising the utility of the exercise and improving future research and applications.

Table A. Mean Vulnerability Scores for the 15 SCCG Councils.

Council	***Impact Area***					
	Extreme Heat	***Sea-Level Rise***	***Extreme Rain***	***Bushfire***	***Ecosystems***	***Net***
Botany Bay	7	9	8	2	9	9
Hornsby	6	1	4	7	4	5
Leichhardt	7	8	7	2	8	7
Manly	6	7	8	2	7	6
Mosman	4	3	7	1	7	4
North Sydney	7	2	9	1	8	7
Pittwater	6	5	7	4	5	6
Randwick	6	6	8	2	8	7
Rockdale	9	9	9	3	9	9
Sutherland	3	4	4	5	4	3
Sydney	5	8	8	1	8	7
Warringah	3	2	6	3	4	3
Waverley	4	4	7	1	7	5
Willoughby	7	1	7	2	7	6
Woollahra	4	6	8	1	7	5
Average	***6***	***5***	***7***	***3***	***7***	***6***

High values indicate a relatively high degree of vulnerability to future climate change while low values indicate low vulnerability. Colours reflect relative degrees of vulnerability, with blue (low vulnerability) associated with scores of 1 to 3, green (moderate vulnerability) with scores of 4-6, and red (high vulnerability) with scores of 7 to 9.

The assessments of climate change vulnerability did not represent ends in and of themselves, but rather a starting point for further exploration of vulnerability and adaptive capacity within the SCCG region. Vulnerability maps represented just one of a number of tools that were utilised in the project to elicit information about adaptive capacity. In addition, stakeholders had the opportunity to respond to the vulnerability maps to identify potential strengths or weaknesses, creating the opportunity for revision of the vulnerability maps in light of new insight, information and/or data.

1. Background

Chapter Summary

- ***The Sydney Coastal Councils Group (SCCG), in conjunction with CSIRO and the University of the Sunshine Coast, have undertaken a research project to explore the adaptive capacity of the SCCG member Councils with respect to climate change.***
- ***Significant climate change is projected to occur in the Sydney Metropolitan region in the decades ahead, which, in conjunction with inherent climate variability, will expose the region to a diverse array of climate hazards and consequences that must be managed.***
- ***This report presents the results of a preliminary climate change vulnerability assessment and mapping exercise for the SCCG region. These results should not necessarily be taken as an end in and of themselves, but rather as a starting point for subsequent communication efforts with local government stakeholders regarding vulnerability and adaptive capacity.***

As part of the Australian Government Department of Climate Change (DCC) National Climate Change Adaptation Program (NCCAP), the Sydney Coastal Councils Group (SCCG) has partnered with the CSIRO in collaboration with the University of the Sunshine Coast to undertake research on regional approaches to managing climate vulnerability in the Sydney region (Figure 1). The SCCG is a Regional Organisation of Councils (ROC) established in 1989, and currently has a membership of 15 councils adjacent to Sydney marine and estuarine environments, and represents over 1.3 million Sydneysiders. The aims of the SCCG are to promote cooperation and co-ordination among Member Councils in consultation with the boarder community on issues of regional significance concerning the sustainable management of the urban coastal environment.

Over the course of almost two years, the Sydney integrated assessment project will help the region's coastal Councils assess the potential biophysical effects of climate change, with subsequent emphasis on examining local capacities to adapt to potential climate change impacts. These activities will be carried out in a series of stages, namely: (i) vulnerability mapping; (ii) stakeholder engagement; (iii) assessment of adaptive capacity; and (iv) project assessment.

Figure 1. *SCCG member Councils*

This report presents the methodology and results from the first phase of this project, vulnerability mapping. An introduction to climate change in the Sydney region as well as the concept of vulnerability is provided. This is followed by presentation of the methods by which vulnerability mapping was conducted and results for the region as a whole, as well as aggregate results at the Council level. Some discussion is also provided regarding how stakeholders responded to the presentation of the assessments results.

Given the scope of the project, this report should not be taken as an end in and of itself. Rather, the vulnerability mapping was conducted with the intention of initiating a dialogue among researchers and stakeholders within local government regarding the potential vulnerability of SCCG Councils to climate change. This dialogue was extended through subsequent work to develop a more comprehensive and participatory perspective on climate change and the opportunities and barriers to adapting to that change within the SCCG (Hulme et al., 2007).

1.1 Guidance for Using this Report

This report was developed to provide technical information regarding the vulnerability assessment undertaken as part of the *Systems Approach to Regional Climate Change Adaptation Strategies in Metropolises* project conducted on behalf of the SCCG. It represents the second and final edition of the report, which has been revised over the course of the project to reflect comments and criticisms from SCCG local government stakeholders and capture some of the lessons and insight gained along the way.

The report seeks to accomplish a variety of goals:

1) Provide an introduction to the concept of vulnerability in the context of climate change;
2) Identify some of the key climate change vulnerabilities of the SCCG region and some of the prior work that has been undertaken in their assessment;
3) Identify some of the key determinants of vulnerability;
4) Present spatial representations of relative vulnerability to some key impacts throughout the SCCG;
5) Summarise some of the issues that occurred with communicating with local government stakeholders about climate change impacts and vulnerability; and
6) Provide some key conclusions and lessons gleaned from the assessment that may be useful in future research efforts.

While the maps of vulnerability presented herein represent an assessment of the relative vulnerability of different areas of the SCCG region to climate change impacts, this assessment is not, nor was it intended to be, the final word on the region's vulnerability and risk. There are a variety of assessment methods that yield different types of outputs, and as with any such assessment there is a variety of potentially relevant information that has not been incorporated. As such, this assessment should be viewed as a complement to existing local knowledge about natural hazards, vulnerability and risk in the region, but certainly not a replacement for that knowledge.

More specifically, the assessment provides an indication of where a suite of risk factors for a particular type of climate change impact occur with greater frequency relative to other areas. It does not, however, provide an indication of the actual magnitude or absolute probability of an adverse event. In addition, due to the lack of a common quantitative metric (i.e., estimates of impacts in dollars), direct comparisons between vulnerability scores for different types of impacts is challenging and should be done cautiously. In other words, just because an area is identified as having a higher vulnerability score for sea-level rise than for bushfire events, this does not necessarily mean that sea-level rise is a larger management challenge or that larger damages will arise in this sphere of government responsibilities in the future. Making such determinations requires additional information regarding the magnitude of the impact in terms of socio-economic and ecological damages.

It is hoped that this report serves as a useful reference document for initiating thinking within local governments in the SCCG region regarding vulnerability and the factors that may contribute to vulnerability in the future. Furthermore, the documentation of the assessment process may prove useful to ongoing efforts to better understand the implications of climate change in Australia and the pursuance of adaptation.

2. Climate Change Basics

2.1 The Changing Global Climate

Over the past few centuries, the rate at which human beings have altered the Earth system and the various ecosystems of which it is comprised has grown exponentially. Species extinctions, deforestation, urbanisation and other changes to the landscape, along with the release of toxic substances to sea, land, and air have all been associated with rapid increases in the global population and economic activity (Steffen et al., 2004). Within the past several decades, it has become clear that the progressive growth of the human influence on the planet is now affecting the climate system itself (IPCC, 2001a; 2007). In 2007, the Intergovernmental Panel on Climate Change (IPCC), the world's leading scientific assessment body on climate change, published its *Fourth Assessment Report* that concluded (IPCC, 2007),

> *"Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. . . .Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns."*

The IPCC also concluded that the warming trends observed in Australia over the past century are linked to this global pattern of anthropogenic warming. As the climate is a major factor determining not only the spatial distribution of the world's plants and animals, but also the productivity of human enterprises such as agriculture and forestry, such climate change is likely to have significant consequences at the global, national and regional scale.

The source of this climatic change lies in the historical dependence of human beings upon fossil fuels as the primary source of the energy driving global mobility and commerce. To date, human consumption of fossil fuels has grown in step with the global population and economy, and the unintentional side-effect of their combustion has been a significant change in the composition of the Earth's atmosphere. The atmosphere has multiple components, several of which are naturally-occurring gases referred to as 'greenhouse gases,' due to their ability to trap heat. The primary greenhouse gas is water vapour, but others such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are also important. Energy from the sun passes through the atmosphere and warms the surface of the planet (Figure 2; State of Victoria, 2004). While most of this heat is simply radiated back into space, some is trapped by greenhouse gases. This has a warming effect on the atmosphere and ultimately keeps the planet at an average annual temperature of approximately 15°C. Without this process, the global average surface temperature would be closer to -18°C.

Centuries of human combustion of fossil fuels, along with land-clearing, have increased the flow of greenhouse gases to the atmosphere, increasing their concentration and subsequently magnifying the natural greenhouse effect. Carbon dioxide levels have increased by approximately 36% relative to their concentrations prior to the industrial revolution. At the end of 2007, the average atmospheric CO_2 concentration was 383 parts per million (ppm; NOAA, 2007) – higher than at any point over at least the past 650,000 years (Siegenthaler et al., 2005). Meanwhile, other greenhouse gases such as N_2O and CH_4 have increased by 17% and 151%, respectively (Spahni, 2005).

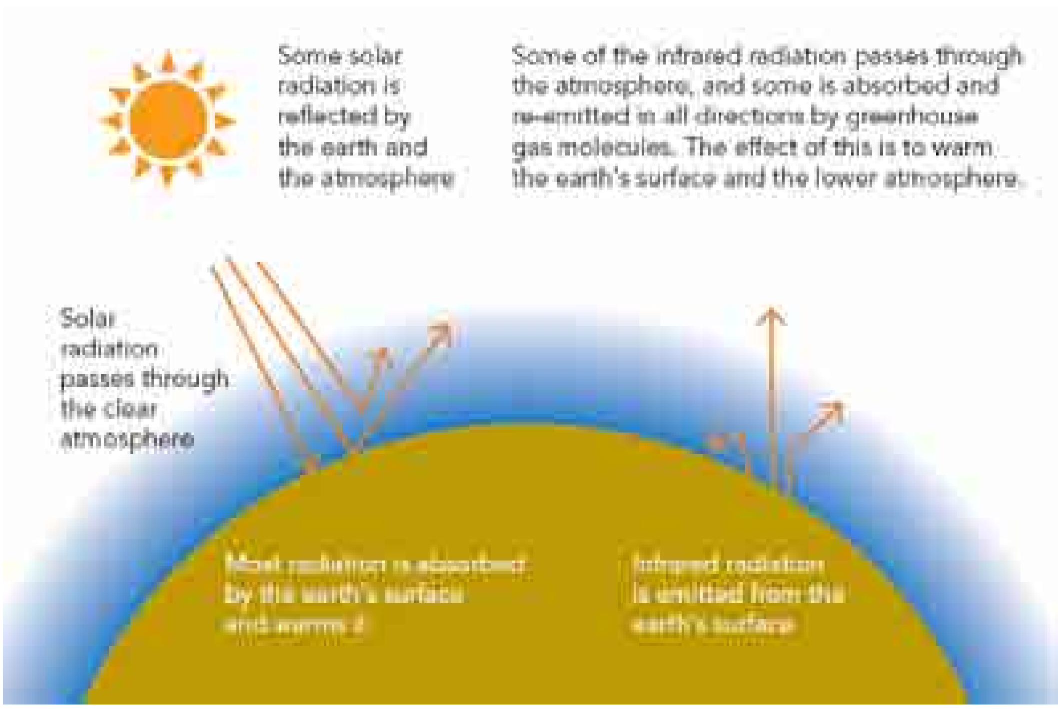


Figure 2*. The greenhouse effect (State of Victoria, 2004)*

The net effect of these changes to the atmosphere has been a warming of the planet. Since the mid-19th century, the average temperature at the Earth's surface has increased by approximately 0.8°C (IPCC, 2007). Such warming has also contributed to an acceleration in the rate of global sea-level rise (IPCC, 2007). Additional warming is projected over the 21^{st} century and beyond in response to continued emissions of greenhouse gases. The IPCC projected future increases in global mean temperature of 1.1–6.4°C by the year 2100, along with an increase in sea level of 18–59 cm not including an additional contribution of ~20 cm from destabilisation of large ice sheets (IPCC, 2007). The IPCC cautioned that due to uncertainties about the rate of climate change and its effects on ice sheets, higher levels of sea-level rise cannot be excluded. The actual magnitude of climate change that is ultimately realised will depend in large part upon future human emissions of greenhouse gases. Nevertheless, it is clear that humans, and the environment in which they live, are currently surrounded by a changing climate, and how we respond to this change over the next few decades will be central to achieving global economic and environmental sustainability.

2.2 Climate Change in the SCCG Region

Prior assessments of climate variability and change have identified a significant warming trend in New South Wales (NSW) over the past several decades (Hennessy et al., 2004a,b). Since 1950, the State has warmed by approximately 0.9°C, with more hot days/nights and fewer cold days/nights. Annual total rainfall has declined, particularly along the coast, due in-part to El Niño events, although an influence of anthropogenic climate change has not been excluded as a contributing factor. Projections of future climate change indicate that the State as a whole will continue to warm (Figure 3), although the coastal regions will warm less quickly. Projections of rainfall are more variable, although most climate models currently used to simulate future climate conditions indicate a reduction in annual rainfall in the decades ahead (CSIRO and BOM, 2007).

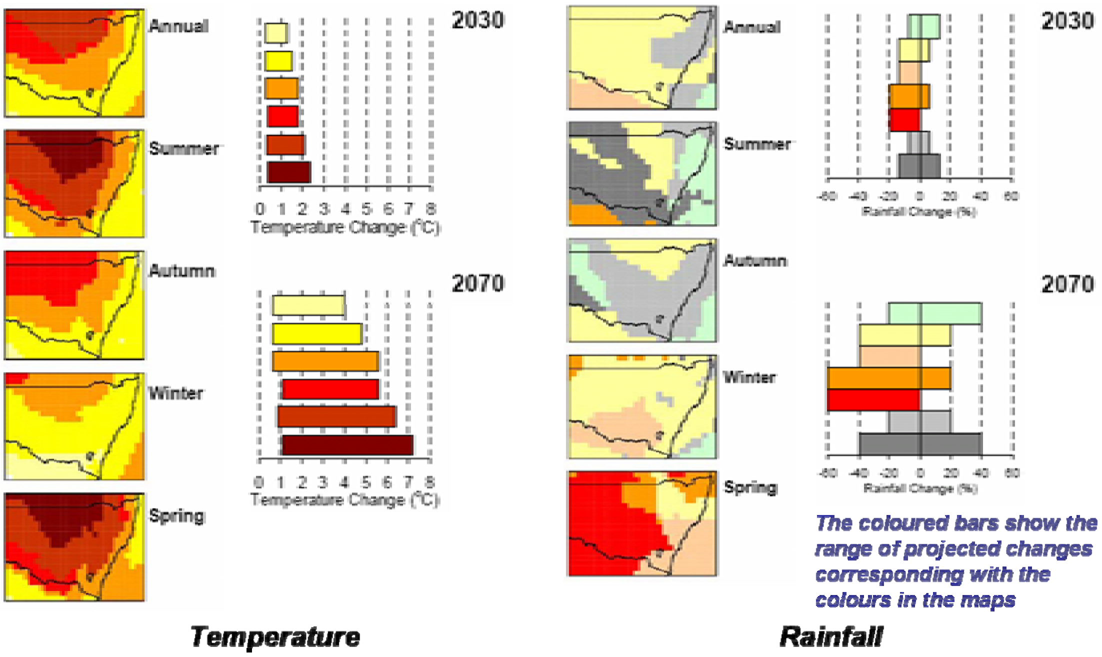


***Figure 3**. Regional climate change projections for NSW (Hennessy et al., 2004a; Preston, 2007). Note that temperature increases tend to be lower along the coastal margins relative to inland areas. Meanwhile, climate models indicate the potential for both increases and decreases in annual rainfall.*

Such regional changes in climate will manifest in the SCCG region as well, with both warmer and drier conditions expected (Preston, 2007; Table 1). Currently, summers in the Sydney Metro region are relatively warm, with average maximum January temperatures of approximately 26–29°C (Table 2). However, temperature variability is significant, as evidenced by the number of days annually where temperatures exceed 35ºC. While these are relatively rare events (~3–5 days per year) along the coastal margins, areas further inland experience significantly more (~10–14 days per year), particularly at lower altitudes. Winters are cool, with average minimum July temperatures of 3–8°C, and the warmer temperatures tend to be found along the coast. Projections of future climate conditions indicate temperatures in the SCCG region may warm by 0.6 to 1.3°C by 2030 and 1.1 to 4.3°C by 2070 (CSIRO and BOM, 2007; Table 1).

Meanwhile, the SCCG region receives approximately 1,100 to 1,200 mm of rainfall each year, but rainfall totals vary spatially, with the greatest precipitation occurring closer to the coastline. Peak precipitation occurs between November and May, and the variability in rainfall from one year to the next is high. Hail storms are common, the worst being the April 1999 event which cost $2.3 billion (IDRO, 2006). Fires are also common, often occurring in bushland ringing the region's urban areas, which contain low-density residential development. Climate change is projected to affect rainfall patterns in the SCCG region, with changes of -3 to +9% by 2030 and -25 to +10% by 2070 (CSIRO and BOM, 2007). Despite the broad range of projected outcomes, the majority of climate models indicate total rainfall is likely to decline in the region (CSIRO and BOM, 2007).

Table 1. Projected Climate Change in the SCCG Region

	Projected Change	
	2030	***2070***
Temperature[1]		
Annual Average	+0.6– +1.3°C	+1.1 – +4.3°C
Annual # Days below 0°C	+0	+0
Annual # Days above 35°C	+1 – +2	+0 – +8
Rainfall		
Annual Average[1]	-3 – +9%	-25 – +10%
Annual Extreme Rainfall[2]	1 day: +7% 3 day: +10%	1 day: +5% 3 day: +3%
Sea-Level Rise[3]	+3 – +16 cm	+7 – +50 cm
Potential Evaporation[1]	+2 – +5%	+3 – +15%
# Droughts per decade[4]	-1 – +2	-2 – +6
Wind Speed[1]	-5 – +4%	-15 – +12%
Relative Humidity (%)[1]	-1 – +1%	-4 – +1%
Solar Radiation (%)[1]	-1 – +2%	-3 – +6%
# Fire Days[5]	+0 – +2	+1 – +6

[1] Range represents the 10th and 90th percentiles based upon a temperature distribution generated from a range of climate models and emissions scenarios (see CSIRO and BOM, 2007).
[2] Defined as range of change in 1 in 40 year rainfall totals. Values represent results from a limited set of climate model projections for central eastern NSW (see Hennessy et al., 2004b).
[3] Sea-level rise estimates are based upon results from the MAGICC simple climate model used in the IPCC (2001) Third Assessment Report. The sea-level projections from MAGICC are estimated to be within 10% of those produced by the updated methods of the Fourth Assessment Report (2007). See also Table 3 for more details on sea-level rise uncertainties and other sea level projections derived from other studies and methods.
[4] The values for drought represent average monthly drought frequencies, based upon the Bureau of Meteorology's criteria for serious rainfall deficiency (see also Burke et al., 2006).
[5] Number of days annually with a "very high" or "extreme" fire danger index. Changes are for 2020 and 2050, respectively, as in Hennessy et al. (2005).

Despite this trend toward drier conditions, the possibility of increases in extreme rainfall events remains (Abbs et al., 2006). Similarly, other climate extremes are likely to manifest more frequently or with greater intensity in the future including drought events, extreme winds, and fire weather. The coastal zone of the SCCG region will also be increasingly affected by sea-level rise and its interactions with natural tidal and storm-surge variability. Further details about these changes are described in the table above (Table 1), which compares projected changes in 2030 and 2070 for a number of climate variables. These projections account for a broad range of assumptions about future global greenhouse gas emissions, as well as differences in how various climate models represent the climate system.

These climatic changes will have important implications for the SCCG region. However, given the wide diversity of land uses, environmental condition, and population and development densities found throughout the region, different areas are likely to be affected by different hazards in different ways. As a result, local governments are likely to experience unique management challenges that arise from the local context. One tool for exploring such variable climate risk is through the analysis of climate change vulnerability across the SCCG region and each of the 15 member Councils.

3. Defining Vulnerability

Chapter Summary

- ✓ ***Vulnerability assessment provides a useful vehicle for assessing the potential for different systems, sectors, populations and locales to be harmed by climate change.***
- ✓ ***While not providing explicit predictions of climate change outcomes or impacts, measures of vulnerability provide a qualitative view of climate risk that is consistent with the risk management paradigm.***
- ✓ ***Prior attempts to map climate change vulnerability provide methodological models that informed this study, but specific approaches are often tailored to the needs of specific projects.***
- ✓ ***A common theme in vulnerability mapping is the integration of data regarding future climate changes and impacts with demographic and socio-economic indicators of adaptive capacity.***

A formal definition of the concept of vulnerability can be taken from the literature on sustainability science:

> *"Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation of stress/stressor (White, 1974)."*

Less formally, this suggests vulnerability is a reflection of the potential for a system to experience harm in response to some external influence, pressure or hazard. The relevant system or process may be an individual or population; a business enterprise or an entire regional economy; a single species or an entire ecosystem. The concept of vulnerability is broadly used across a range of disciplines, including finance, security, public health, economic development, natural hazards and, of course, climate change. The IPCC has developed a definition of vulnerability that is specific to climate change:

> *"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 (IPCC, 2001b)."*

This definition, though similar in many ways to the previous, highlights some additional considerations regarding vulnerability, specifically that of coping capacity. Increasingly, there is recognition that the potential for adverse effects from a hazard such as climate change is not simply a function of the hazard itself, but also the strategies and options that are available to a system to respond to and ameliorate that hazard. For example, human beings manage many systems (e.g., agriculture and water resources) to cope with what is an inherently variable climate through a broad array of decision support tools (e.g., seasonal forecasts), system operations (e.g., planting times), infrastructure (e.g., flood defences), or policy (e.g., water restrictions or development guidelines). This issue of human agency and capacity is therefore fundamental to considerations of vulnerability to climate change.

Furthermore, vulnerability reflects the degree of potential harm or susceptibility – not explicitly a prediction of future outcomes, such as is commonly generated through impact models and assessments. Rather, it is an analysis of determinants or risk factors that contribute to such susceptibility. While this may in fact be informed through the use of various modelling tools that indicate the relative susceptibility of different regions, communities or sectors to climate change, a broad array of other tools may also be employed. These may include stakeholder self-reported perceptions of vulnerability or the identification of relevant indicators that are commonly associated with susceptibility to harm or adverse outcomes.

It should be noted that the concept of vulnerability is used in at least two different contexts with respect to climate change (O'Brien et al., 2004). It is perhaps more often used as an *end point* of an assessment process which reflects the net implications after the consideration of future climatic changes, the response of the system of interest, and the capacity of the system to cope or adapt to minimise adverse consequences. Alternatively, vulnerability is a *starting point* or an inherent state of a system or landscape upon which climate change will act, which is often informed through inspection of social and ecological challenges or coping capacity in the present day.

Although O'Brien et al. (2004) argue that these different interpretations of vulnerability create challenges for managing climate risk, the two do not necessarily exist in opposition. Any attempt to assess or understand vulnerability should be iterative and even cyclical in nature, whereby conclusions or perceptions in one phase are used as the point of initiation for subsequent phases. Hence, there is no reason why a vulnerability assessment that focuses on quantifying vulnerability as the net sum of various drivers cannot be used as a starting point for further investigation of the implications of that vulnerability, who or what systems are vulnerable and why, and through what mechanisms such vulnerabilities can be addressed. It is this dual approach that is pursued in the SCCG project – a top-down vulnerability assessment (represented by this report) formed a foundation for a participatory dialogue about the implications of that vulnerability for climate risk and how it may be managed.

3.1 Exposure, Sensitivity & Adaptive Capacity

Objective assessments commonly decompose climate change vulnerability into three constituent components: exposure, sensitivity and adaptive capacity (Figure 4; Allen Consulting, 2005; Metzger et al., 2005; Smit and Wandel, 2006).

Exposure refers to the exposure of a system of interest to stimuli that act on that system. This can be readily conceptualised as climate variability and/or the various changes in the climate system that are often of concern to stakeholders: temperature increases, rainfall variability and change (including extremes), or changes in the frequency or intensity of tropical cyclones. However, communities or systems are often exposed to hazards through natural climate variability, independent of future changes in the climate system.

Sensitivity refers to the responsiveness of a system to climate hazards. This is often represented conceptually as a dose-response model – the more sensitive a system, the larger the rate or magnitude of an adverse response to a given hazard. Sensitivity may vary considerably from one system, sector or population to another.

Adaptive capacity refers to the ability of a system to change in a way that makes it better equipped to manage its exposure and/or sensitivity to climatic influences. Although a broad range of factors have been identified which are argued to reflect adaptive capacity, it remains a difficult concept to define explicitly within vulnerability assessments (Adger and Vincent, 2005). Capacity is often measured in terms of resource availability (e.g., human, technological, and financial capital). Yet the institutional and governance networks that exist to deploy those resources are also essential, and any number of socio-political barriers may exist that impede successful adaptation (Hulme et al., 2007). As a consequence, *"the contextual nature of vulnerability, the difficulties of validating indicators, and considerations of timescale, provide challenges to the development of robust indicators"* (Adger and Vincent, 2005).

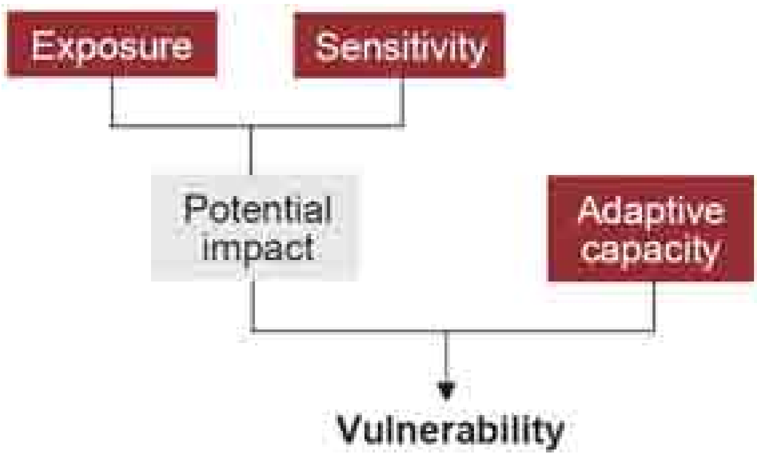


Figure 4. *Components of Vulnerability (Allen Consulting, 2005).*

The first two components, exposure and sensitivity, dictate the gross vulnerability of a system or process and thereby provide an indication of potential susceptibility to adverse impacts. Meanwhile, the third, adaptive capacity, reflects the ability of the system to manage, and thereby reduce, gross vulnerability. For this project, adaptive capacity is conceptualised broadly, with emphasis placed on the fact that successful adaptation is a function not only of capacity in the form of the availability of resources to address vulnerability, but also the institutional barriers or constraints on the application of that capacity (Hulme et al., 2007). When integrated with exposure and sensitivity, the result is net vulnerability, which accounts for the ability of a system to manage risk to prevent potential impacts from being realised. Systems and processes may therefore have high gross vulnerability but relatively moderate net vulnerability due to high adaptive capacity (Bogardi et al., 2006). On the other hand, low gross vulnerability may be compromised by a limited degree of adaptive capacity that elevates net vulnerability when hazards eventually arise.

Uncertainties in climate change as well as the sensitivity of different processes and systems to that change create challenges for rigorously assessing vulnerability. An exhaustive quantitative description of a system of interest with its many and varied influences and interactions is often prohibitive. The estimation of the potential for adaptive responses, in particular, has been recognised as one of the key challenges to the rigorous assessment of vulnerability (Patt et al., 2005). This arises in part from the complex role of human agency in determining responses, but also the inherent unpredictability of future social and economic changes, particularly over long time-scales.

Given such complexity, attempts to assess vulnerability have often relied upon suites of relevant indicators that are assumed or demonstrated to be significantly correlated with different components of vulnerability (e.g., Adger et al., 2004; O'Brien et al., 2004; Brooks et al., 2005; Metzger et al., 2005; Lindley et al., 2006). For example, a suite of indicators may be developed that represent the exposure of a system to a given natural hazard, while another set of indicators may be developed that represents the capacity of the system to cope or adapt to such hazards. Although this approach prevents one from predicting outcomes (e.g., the number of lives lost or estimates of damages in dollars), it enables an assessment to draw from multiple sources of information to develop 'weight-of-evidence' estimates of vulnerability. Nevertheless, such estimates must still be cautiously interpreted and, where possible, they should be evaluated to ensure they are consistent with understanding of the system of interest.

3.2 Vulnerability and Risk

Minimising the likelihood of adverse consequences from climate change at least-cost is essentially a risk management exercise that must occur across a range of geopolitical scales from local to global, from public to private. Risk can be defined as the product of consequence and likelihood (ISO, 2002), while risk management is defined as the culture, processes and structures directed towards realising potential opportunities whilst managing adverse effects (Figure 5; Australian Standards, 2004).

The concept of vulnerability has close connections with that of risk, to the extent that the two terms are often casually used interchangeably. For example, both terms obviously concern themselves with measures of adverse consequences, and to a certain extent, both embody the issue of likelihood (see the prior definitions for vulnerability and risk). Perhaps the most straightforward means of distinguishing the two is to identify *vulnerability* as a measure of the susceptibility of a system to harm, whereas *risk* is the likelihood of a specified harm occurring.

Alternatively, it can be useful to consider the risk management paradigm in its entirety and identify where the linkages to vulnerability and its various components lie. Risk management applies scientific and technical analyses, guided by the subjective interests and priorities of stakeholders, to estimate the likelihood of different outcomes. The process is often conceptualised as a series of steps, which identify the context, characterise the hazards and/or potential consequences, assess the likelihood of different outcomes, evaluate risk, and, ultimately, make a decision regarding the appropriate method(s) for reducing risk (Figure 5). Each of these steps provide relevant linkages to the concept of vulnerability:

***Figure 5**. The risk management paradigm (from AGO, 2006)*

1) ***Establish the context*** – As discussed above, some view vulnerability as a pre-existing condition upon which other stressors or hazards (such as climate change) may act. As such, vulnerability may prove highly relevant for establishing the context of a risk management exercise, as risk assessment and management is typically undertaken where there is a perceived vulnerability.

2) ***Identify the Risks*** – To the extent that prior assessments or knowledge of vulnerability are available, this may help in the identification of risks in risk management (see Allen Consulting, 2005). That may be facilitated through the insight vulnerability assessments offer regarding understanding of the mechanisms by which climate change may affect a particular system and/or the identification of particularly susceptible systems, sectors or communities.

3) ***Analyse the Risks*** – Estimating the likelihood of a given outcome is a function of the hazards to which a system is exposed and a broad array of associated characteristics that may influence outcomes (e.g., system sensitivity). As such, the more vulnerable a system, the more likely a given adverse outcome may be. Therefore, while vulnerability assessment cannot necessarily provide absolute estimates of probability, it can function as a qualitative analysis or relative risk.

4) ***Evaluate the Risks*** – Just as a risk analysis can be used to identify key risks that require treatment, so too can vulnerability assessment be used in the identification and prioritisation of key vulnerabilities (see Allen Consulting, 2005). Such an evaluation may highlight the challenges for a particular population or enterprise as well as indicate areas where more focused risk assessment should be conducted.

5) ***Treat the Risks*** – Once the likelihood of outcomes have been quantified, evaluated and prioritised, decisions must be made regarding how to treat those risks. Here again, vulnerability is relevant. For example to the extent that vulnerability is high due to limited adaptive capacity, this may dictate the availability, scope, and effectiveness of risk treatment options. In addition, options that reduce vulnerability will also reduce risk, even if that reduction in risk cannot be readily quantified

(Sarewitz et al., 2003). However, the lack of quantitative information for evaluating different risk treatment strategies may limit the utility of vulnerability assessments for decision support.

For the purpose of this report, what is important in comparing and contrasting vulnerability and risk is that vulnerability does not predict explicit outcomes or the likelihood of outcomes. Rather it reflects where the greatest potential for harm lies, and elucidates the various factors that may contribute to that harm and how they interact. This has various advantages and disadvantages. Perhaps the most relevant arguments for focusing on vulnerability are four-fold: a) adverse climatic events are unavoidable, independent of anthropogenic climate change, and thus there is benefit in reducing vulnerability regardless of future changes in risk; b) humans possesses significant, but heterogeneous, capacities to cope with and adapt to climate risk, which establish the context in which climate hazards occur; c) reductions in vulnerability contribute to a reduction in risk, but the inverse is not necessarily true (Sarewitz et al., 2003; Tol, 2006);[1] and d) attempts to assess risk (i.e., predict outcomes and their likelihood) often neglect the complex social context of risk while irreducible uncertainty makes any quantitative prediction questionable.

The Achilles Heel of vulnerability, however, is adaptive capacity, a concept that is challenging to quantify for the present, much less project into the future (Adger and Vincent, 2005; Patt et al., 2005). The assessment of vulnerability requires understanding the interconnections of complex environmental and socio-economic systems as well as how they may change in the future, including (but not limited to) how they will respond to climate change (Füssel and Klein, 2006). Researchers are poorly equipped to project relationships between drivers of environmental change and environmental responses into the future while simultaneously accounting for the changing context of the interaction due to shifts in socio-economic conditions, values and decision-making. Furthermore, while actions to manage current vulnerability may be argued to be robust, 'no regrets' measures, it is often difficult to provide a cost justification for the investment, as the analysis necessary to demonstrate a long-term positive return on the investment is absent (Sarewitz et al., 2003; Patt et al., 2005). This, in turn, inhibits attempts to integrate information regarding vulnerability into existing decision-making frameworks. For example, it may be self-evident that bolstering defenses around a flood-prone area will reduce vulnerability to future floods, but in the absence of information regarding the cost-effectiveness of the approach, it remains unclear whether such an investment is a good one. Judging such cost-effectiveness requires knowing something about future risk. This limitation is particularly relevant to issues of climate change and local governments charged with making risk management decisions.

3.3 Vulnerability Mapping

A broad array of attempts have been made to map climate change vulnerability across a wide-range of spatial scales and sectors. In so doing, a variety of approaches have been employed, reflecting the integrative nature of considering not only the biophysical changes in the climate

[1] *Sarewitz et al. (2003) offer an example to illustrate this point. Insurance is a common risk management strategy, which reduces the likelihood of an adverse outcome (i.e., unrecovered economic losses associated with a hazard or disaster). Yet while insurance reduces risk, it does nothing to reduce vulnerability – it protects the bearer against financial loss by spreading risk without addressing the event or circumstances that create the loss. In contrast, attempts to focus on vulnerability invariably reduce the likelihood of losses and thereby minimise the residual risk that must be spread through insurance.*

that may affect social and environmental systems, but also the factors that contribute to sensitivity and adaptive capacity. Commonly, mapping of vulnerability involves the acquisition of spatial information that falls into two broad categories, biophysical vulnerability and social/ecological vulnerability (Adger et al., 2004). Consistent with the vulnerability framework, information on these two types of vulnerability are often integrated. However, some assessments concentrate on one or the other, depending on the nature of the information that is sought (e.g., Port of Melbourne Authority, 1992; Thieler et al., 2000; Titus and Richman, 2001).

3.3.1 Biophysical Vulnerability

Biophysical vulnerability largely refers to the 'exposure' component of the vulnerability framework – the characteristics of the physical environment (including changes in that environment) that create the potential for harm to societal or environmental systems. Information regarding the spatial distribution of biophysical vulnerability is often obtained through either indicators of relevant biophysical conditions or trends or models of the behaviour of physical systems to current or future conditions, including climate change.

For example, in a vulnerability assessment of storm-surge, sea-level rise, and flooding in Hampton Roads, Virginia, USA, biophysical vulnerability was assessed through the use of a coastal storm surge model, perturbed with sea-level rise projections (Kleinosky et al., 2006). In a coastal vulnerability assessment of the Victoria Coastline (Port of Melbourne Authority, 1992), Brunn rule estimates of coastal erosion in response to sea-level scenarios were combined spatially with coastal typologies. In mapping the biophysical vulnerability of agriculture in India, a climate sensitivity index was developed that reflects landscape dryness and monsoon dependence, combined with climate model simulations of future climate changes (O'Brien et al., 2004). Similarly, Thorton et al. (2006) used climate model projections to estimate changes in climate and agricultural growing seasons in Africa. In examining vulnerability to heat-related mortality in the UK, Lindley et al. (2006) developed 'hazard layers' based upon a stochastic weather generator integrated with climate projections from a regional climate model. In contrast to these model-dependent examples, two different biophysical vulnerability assessments of the US coastline were based upon observed metrics of physical characteristics and trends, such as tidal ranges, wave heights, coastal slope and elevation, and observed erosion rates (Thieler et al., 2000; Titus and Richman, 2001). These multiple indicators were integrated qualitatively to inform biophysical vulnerability.

3.3.2 Social/ecological Vulnerability

Social vulnerability largely refers to the 'sensitivity' and 'adaptive capacity' components of the vulnerability framework – the socio-economic or ecological characteristics of systems that enhance or ameliorate the potential for harm in response to biophysical conditions or changes. These two components may be assessed individually or treated collectively. Again, understanding of the spatial distribution of social/ecological vulnerability can be gained through models. For example, The Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) project in Europe used an ecosystem model to examine the spatial distribution of ecosystem sensitivity to climate change (Metzger et al., 2005). Such approaches often incorporate similar approaches as traditional impact assessment, using models to generate estimates of potential quantitative impacts.

However, capturing adaptive capacity is often quite difficult within impact models, and thus vulnerability assessments often utilise a range of additional indicators in the assessment of social/ecological vulnerability. The ATEAM project combined its assessment of potential impact with an 'adaptive capacity index', based upon the spatial distribution of multiple socio-economic and demographic indicators such as GDP per capita, female activity rate and income inequality. Kleinosky et al. (2006) based their assessment of social vulnerability of the coastal zone on indicators of poverty, gender, race and ethnicity, age, and disabilities. Lindley et al. (2006) identified social groups vulnerable to heat-related mortality based upon indicators of age, future population projections and income disparities. O'Brien et al. (2004) utilised biophysical, socio-economic and technological indicators of adaptive capacity of Indian agriculture, which included such things as soil dryness, ground water availability, adult literacy rates, gender equity, availability of irrigation, and quality of infrastructure. Meanwhile, Thornton et al. (2006) looked at a suite of social vulnerability indicators in African hot-spots for future changes in growing seasons.

3.3.3 Common Themes

From the above examples, there are some commonalities among different attempts to map vulnerability to climate change. First, there is widespread use of climate models and/or climate scenarios to generate quantitative or qualitative estimates of future exposure to biophysical hazards. Second, regardless of whether information on exposure is used in impact modelling to estimate the spatial distribution of potential impact, there is a strong reliance upon additional indicators of demographic, social, and economic circumstances to capture social vulnerability and adaptive capacity in overall estimates of net vulnerability. A number of investigators have published studies of potentially useful indicators that included some degree of validation, in which indicators were significantly correlated with the outcomes they were intended to represent (Adger et al., 2004; Brooks et al., 2005; Table 2). While the indicators provided by Brooks et al. (2005) are applicable to distinguishing social vulnerability at the national scale, they reflect the general nature of such indicators. Specifically, they reflect themes of access to resources (social and financial capital), health status, political influence, and equity. Such characteristics are important in determining sensitivity and adaptive capacity across a range of spatial scales, from national to local.

Table 2. Key Indicators of Social Vulnerability at the National Level (Brooks et al., 2005)
Population with access to sanitation
Literacy rate, 15-24 year olds
Maternal mortality
Literacy rate, over 15 years old
Calorific intake
Voice and accountability
Civil liberties
Political rights
Government effectiveness
Literacy ratio (female to male)
Life expectancy at birth

Some of the core challenges that emerge in attempting to map vulnerability are the identification of appropriate information and indicators to define biophysical and social/ecological vulnerability and the manner in which information should be integrated. Addressing the former challenge is aided by the existing literature on vulnerability assessment and mapping which illustrates potentially useful indicators and methods for generating estimates of biophysical changes, sensitivity and adaptive capacity.

The latter challenge, however, tends to be more project-specific. Due to the strong socio-economic component of vulnerability, it is often necessary to integrate data from a variety of sources collected for different reasons. For example, while climate data may be available for specific points and/or for uniform grids over a given landscape, socio-economic and demographic data is often collected at geopolitical levels, such as national, state and local government jurisdictions or census collection areas. Hence, information may be collected at different scales and come in different forms (e.g., quantitative vs. qualitative). Furthermore, the nature of information that is available at the international to national scale may be quite different than that available at the local scale. In the absence of a complex integrated quantitative model that represents all the linkages and relationships between such data, combining them in a way that is meaningful and valid can be quite difficult. A broad array of approaches appear in the literature and there is little in the way of standardised methods. The approaches outlined later in this report bear similarities to those utilised elsewhere (e.g., Walker et al., 2006), but overall were developed to reflect the specific data sources available for the SCCG region and the overall intent of the project.

4. Scope of Vulnerability Assessment and Mapping

Chapter Summary

- ✓ ***The vulnerability assessment presented is this report was used as a starting point for subsequent discussions of vulnerability and adaptive capacity among local government stakeholders in the SCCG region.***
- ✓ ***A time horizon of approximately 25 years was used to assess and map vulnerability throughout the SCCG region for five impact areas: extreme heat and health effects; sea-level rise and coastal hazards; extreme rainfall and urban stormwater management; bushfire; and ecosystems and natural resources.***
- ✓ ***Simple conceptual models that describe the relationships among exposure, sensitivity and adaptive capacity for these five impact areas were constructed and used to guide subsequent stages of the assessment.***

The vulnerability assessment and mapping for the SCCG region were primarily used as a vehicle for initiating discussion of climate vulnerability, adaptation, and adaptive capacity among the SCCG member Councils. As such, the project embodied both concepts of vulnerability: end point and starting point (Section 3). The work presented in this report treats vulnerability as an end point of an assessment process, through a top-down joint assessment of exposure, sensitivity, and adaptive capacity. However, top-down assessments may neglect the subjective perceptions of stakeholders with respect to priority consequences and coping capacity. Furthermore, as indicators of adaptive capacity are often based upon metrics that represent access to resources and proxies for equality in society and governance, they tend to be somewhat generic, proxy indicators of more complex and contextual social, economic, and cultural processes associated with a particular system (Adger and Vincent, 2005). As the primary goal of the current project was to evaluate adaptive capacity among SCCG member Councils, such top-down assessments may be overly prescriptive in estimating vulnerability. For example, Smit and Wandel (2006) state that the goal of vulnerability assessment,

> *"is not to produce a score or rating of a particular community's current or future vulnerability. Rather, the aim is to attain information on the nature of vulnerability and its components and determinates."*

In recognition of this, the SCCG project utilised the output of this vulnerability assessment as a starting point for a more intensive, bottom-up assessment of vulnerability and adaptive capacity of local government through participatory workshops and interviews with stakeholders as well as evaluation of existing management plans. Stakeholders were provided the opportunity to review the vulnerability assessment and comment on the appropriateness and relevance of different indicators and their implications for vulnerability. Such feedback subsequently helped to further inform vulnerability. As this bottom-up assessment of adaptive capacity was conducted at the Council level, it lacks the spatial resolution that can be obtained through more objective indicators. On the other hand, it probably resulted in a more relevant and detailed description of adaptation potential and the barriers and opportunities associated with adaptation as determined by local stakeholders.

4.1 Sectors of Interest

The landscape of the SCCG region varies significantly, from highly urbanised and densely populated communities, to more regional areas that are less intensively utilised, as well as areas primarily valued for their role in nature conservation. As a result, the vulnerability of people, assets, and ecosystems within the SCCG region is likely to vary significantly from point to point, as well as among different types of climate changes and impacts. Furthermore, the management of the potential risks of climate change may vary significantly, with responsibility for risk being borne in some instances by an individual, and in others by local, state, or federal government. To capture this diversity in potential climate change consequences and adaptation challenges, five areas of potential climate damages were selected for vulnerability assessment and mapping:

- **Extreme heat and human health effects**
  - *Which land areas are associated with a greater vulnerability to adverse health effects associated with extreme heat events?*
- **Sea-level rise and coastal hazards**
  - *Which land areas are vulnerable to the effects of sea-level rise, storms, and storm surge impacts on property and infrastructure?*
- **Extreme rainfall and stormwater management**
  - *Which land areas are vulnerable to significant urban stormwater runoff that must be managed?*
- **Bushfire**
  - *Which land areas are vulnerable to significant bushfire events?*
- **Natural ecosystems and assets**
  - *Which land areas are associated with ecological systems and natural resources that are more or less resilient to the effects of climate change?*

All of these potential impacts have relevance to the Sydney region (see Preston, 2007). Among climate-related hazards, extreme heat events are the leading cause of mortality in the developed world. The sea-level rise that is projected to occur over the next century in response to anthropogenic climate change will have inherent consequences for the SCCG's coastlines, particularly in combination with natural tidal variability and storm events. Extreme rain events, runoff, and flooding are likely to increase the need for stormwater management and flood protection in vulnerable areas exposed to increases in such events. Bushfire is a well-documented threat to the less developed areas surrounding Sydney, where there is sufficient vegetation to fuel bushfires yet still a presence of human communities and enterprises in harm's way. Finally, despite encompassing some of the highest population density in the nation and profound disturbance of the natural landscape since settlement, the region also possesses wildlife, conservation areas, estuaries, and a diversity of natural amenities that may be vulnerable to the joint effects of changes in temperature, rainfall and sea-level rise. However, it should be noted that the vulnerability assessment identifies the relative vulnerability of different land areas to potential impacts, but does not specify the nature of the impact or the receptor. For example, knowing a land area is vulnerable to coastal hazards doesn't necessarily account for the vulnerability of different buildings or infrastructure, which will undoubtedly vary.

The following section presents some simple conceptual models and supporting documentation describing the potential pathways of climate change vulnerability for these five sectors. These conceptual models were subsequently used to guide the selection of vulnerability indicators that were used in the vulnerability assessment and mapping (see Section 5).

4.2 Temporal Outlook

The vulnerability of the SCCG region to the aforementioned climate change impacts is clearly a product of changing biophysical and socio-economic factors. Future increases in exposure to climate hazards, for example, will create or enhance vulnerability. Meanwhile, changing populations, wealth and development patterns will influence the spatial distribution of assets and resources that experience climate hazards. As such, where possible, the vulnerability assessment and mapping attempted to incorporate these processes that will affect future vulnerability. Generally, when looking at the future, the assessment utilises a time horizon of ~25 years (e.g., out to 2030). This time-scale is generally consistent with planning horizons for government and the private sector, and projections of climate and socio-economic trends over this time are relatively robust compared to longer time horizons.

Nevertheless, the current climatological and socio-economic conditions within the SCCG region form an important component of future vulnerability. For example, current variability in climate and weather across the region influences the nature of climatic hazards experienced at any given location. Current demographic and socio-economic conditions among SCCG households influence the sensitivity to climatic events and are indicative of future capacity to manage risk. Meanwhile, future climate impacts to the ecosystems and natural resources of the region must be considered in the context of existing pressures. As such, while attempting to produce an image of vulnerability that is relevant over the next few decades, the assessment also strongly reflects climate vulnerability and risk at present.

4.3 Conceptual Models of Vulnerable Sectors

4.3.1 Extreme Heat and Health Effects

Approximately 176 individuals aged 65 or older are estimated to die each year in Sydney due to heat-related causes, which is roughly 40 per 100,000 (Woodruff et al., 2005). These deaths predominantly occur during summer months when temperatures are at their peak, and despite the widespread finding that elderly individuals are more sensitive to heat events, analysis indicates that mortality does not simply occur in individuals where death was otherwise imminent, but in generally healthy individuals that would have been expected to continue living for years in the absence of the heat event (UK NHS, 2005).

Climate change is projected to enhance the risk of heat-related morbidity and mortality in the decades ahead due to rising temperatures that increase the frequency of days with maximum temperatures above a given threshold (Martens, 1998; Kalkstein et al., 1997; Patz et al., 2001; Woodruff et al., 2005), as well as the duration of persistent heat events that last for multiple days. Guest et al. (1999) found that Sydney was one of the more sensitive of Australia's cities to increases in heat-related mortality. For example, Woodruff et al. (2005) projected that annual maximum temperatures in Sydney would increase by 3.0 to 5.1°C by the year 2100. Meanwhile, an assessment of changes in extreme heat days estimated that the number of days where Sydney experiences temperatures above 35°C would increase from 3 at present to 4–6 by 2030 and 4–18 by 2070 (Hennessy et al., 2004b). In response to such climate changes, Woodruff et al. (2005) projected that the heat-related annual death rate among people 65 and older would increase to 70 to 239 per 100,000 individuals. This combined with a relatively rapid rate of population growth in Sydney suggests the potential for deaths of 432 to 1,042 by the end of the century (Woodruff et al., 2005). Though less-well documented in the context of climate change, epidemiological research also indicates that young children and infants are also sensitive to temperature extremes due to poor thermo-regulation (Guest et al., 1999; Scheers-Masters et al., 2004). It should also be noted that decreases in cold-related morbidity and mortality may partially or wholly offset increases in heat-related mortality in some instances (Guest et al., 1999; Dixon et al., 2005).

Changes in the climate system and, specifically, temperature increases therefore represent a key component of vulnerability within the conceptual model (Figure 6). Clearly, average or baseline temperatures experienced across the region currently influence the spatial distribution of extreme heat events and will continue to do so in the future. However, extreme heat events are a function not only of average temperatures but temperature variability. Thus, those regions that are more prone to anomalously high temperatures are likely to be more at risk of experiencing an extreme heat event. Naturally, increases in regional temperatures will be another major factor influencing the risk of extreme heat events and adverse consequences in the future.

Significant research has also demonstrated that the thermal environment in urban areas is highly complex and heterogeneous, due to the various types of land use, building materials, and infrastructure associated with the urban landscape (Bridgman et al., 1995). The urban heat island effect, for example, is a well-documented phenomenon where urban areas tend to have higher average temperatures than surrounding areas, particularly at night (Chen and Zhou, 2004; Chen et al., 2006). Although this suggests that urban heat islands should have little influence on health, as they occur during the coolest time of the day, research has indicated that they deprive exposed individuals of overnight cool temperatures that offer relief from high day-time maximum temperatures (Clarke, 1972). Analysis of thermal environments around different locations in Melbourne with different development densities revealed a tendency for higher temperatures (particularly night time temperatures) in the more densely developed areas (Coutis et al., 2007). As such, future development decisions and densities are likely to have an influence on the thermal environment of urban areas, including Sydney. More importantly, research has also found that mortality during extreme heat events is higher in urban areas due to the thermal effects of heat islands (Buechley et al., 1972; Clarke, 1972; Smoyer, 1998).

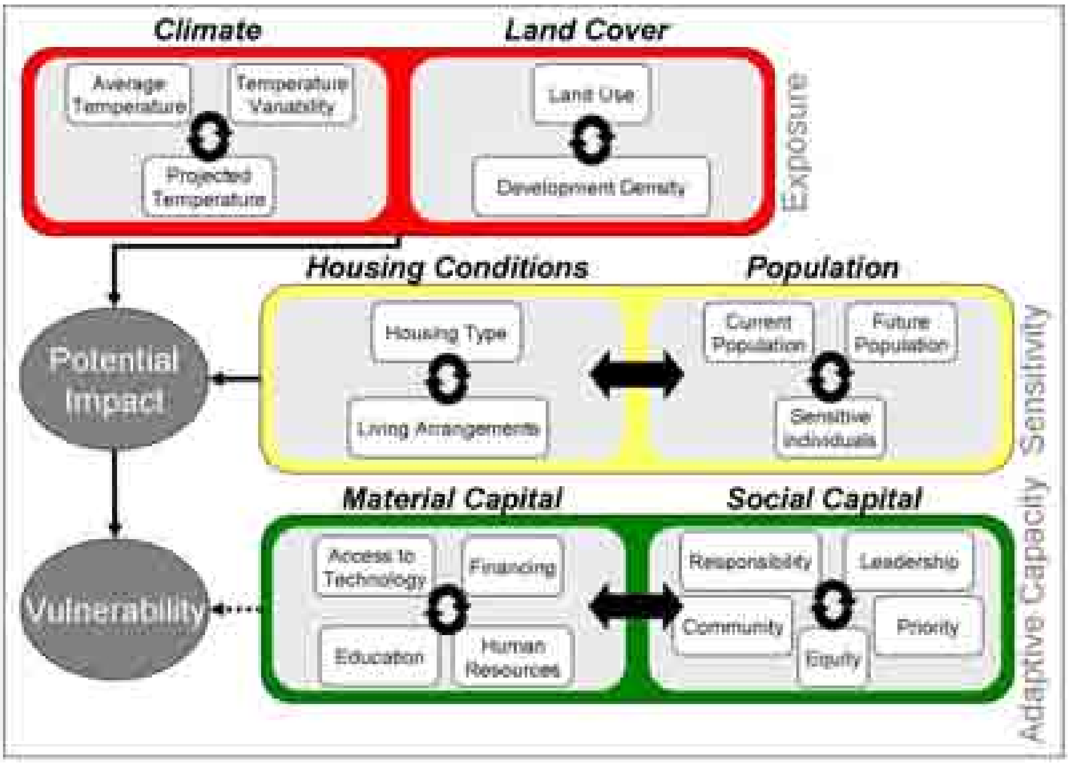


Figure 6. *Conceptual model of the vulnerability of human health to climate change.* ***Exposure*** *(red) is driven by interactions between the climate system and the landscape.* ***Sensitivity*** *(yellow) is a function of the characteristics of the exposed population and the conditions in which they live. The combination of exposure and sensitivity creates the potential for an adverse impact.* ***Adaptive capacity*** *(green) is a function of the material and social capital that can address potential impacts and ameliorate vulnerability. Critical interactions and processes are represented by arrows.*

The risk of adverse health effects in response to high temperature events is also heavily dependent upon socio-economic and demographic characteristics. First and foremost, the sensitivity of different areas across the SCCG region to extreme heat events is dependent upon the size of the exposed population. The greater than number of individuals exposed, the greater the likely number of deaths, as evidenced by observed heat-related mortality across Australian cities (Woodruff et al., 2005). With the population of the Sydney region and most of the SCCG member Councils rising, more individuals are likely to be exposed in a future warmer climate. Among those individuals, some sub-populations have been identified as more sensitive than others. The elderly (usually identified as those 65 years of age and older) as well as small children and infants are considered high-risk groups for heat-related morbidity and mortality, largely due to diminished thermo-regulatory capacity. Hence, one would expect cases of heat-related morbidity and mortality to be disproportionately attributed to these age groups.

In addition to simple demographics, some research has also identified housing conditions as risk factors for heat-related morbidity and mortality. For example, a UK study of housing health and safety estimated that heat-related mortality was largely restricted to housing in multiple-occupancy structures, with those living just under the roof particularly at risk (Office of the Prime Minister, 2003). This is supported by a range of earlier studies (Centers for Disease Control, 1981; Kilbourne *et al.*, 1982; Semenza *et al.*, 1996; Smoyer, 1998). As such, there is a reasonable possibility that areas of Sydney with a higher proportion of multi-occupation housing may be more at risk of adverse health effects during extreme heat events than single-occupation housing, particularly if such housing is older and/or associated with lower-income households. In addition, experience with the 2003 heat wave in Europe illustrated the fact that vulnerable sub-populations such as the elderly were more at risk if confined or with reduced mobility (Vandentorren et al., 2006), which may be exacerbated when individuals live alone (Semenza et al., 1999).

Finally, the conceptual model also accounts for the role of adaptive capacity in ameliorating the potential adverse impacts of extreme heat events. Here, as with the other impact areas, adaptive capacity was seen as an interaction between material capital and resources and social capital that collectively erect barriers to the implementation of risk management policies and measures. Alternatively, one may view this as a 'stocks-and-flows' problems, whereby resources represent stocks of capital, technology, and infrastructure which flow into or through the community to reduce risk, provided there are no barriers that limit that flow. Undoubtedly, such resources and barriers exist at a range of scales and their relationships are complex, but certainly they interact in important ways.

With respect to material capital, financial resources convey adaptive capacity by enabling individuals, households and communities to access technology and infrastructure to reduce vulnerability to extreme heat (e.g., air conditioning and the associated energy costs or newer more thermally efficient housing; Vandentorren et al., 2006). It also increases the number of communication channels through which individuals may gain information on extreme heat events (e.g., forecasts through television, radio, internet) that enable preventive measures to be taken. In addition, access to education could be argued to enhance individuals' ability to interpret information regarding heat risk and manage that risk accordingly. Clearly, however, all of these different resources are interconnected, as it is difficult to isolate material wealth from access to technology or educational attainment.

The effective use of such resources may be compromised by a broad range of social/cultural barriers. Such barriers may exist at the level of the individual household such as language barriers that limit access to communication channels or lack of responsibility or authority to modify housing to manage risk (e.g., renters). In addition, barriers can exist at the level of government, which is tasked with making planning decisions that affect the environment, coordinating emergency management responses, and educating and warning the public about heat waves and risk. Lack of institutional knowledge, authority or effectiveness can be a barrier to efficient government responses to manage risk. Lack of foresight regarding future climate risk, in particular, may pose a significant barrier to adaptation. Again, as with resources, these different factors interact in complex ways.

4.3.2 Sea-Level Rise and Coastal Management

The coastal zone is clearly a dominant feature of the SCCG region, and one which poses opportunities as well as risks. The NSW Department of Natural Resources estimates that the annualised costs of coastal flooding, erosion, and other hazards are estimated at approximately $200 million (DNR, 2006). As such, sustainable management of the SCCG coast can aid in not only avoiding significant damage costs, but also increasing access and amenity for the public and conserving coastal habitat and biodiversity. However, the dense coastal development in the SCCG region and growing population creates challenges for coastal management and hazard mitigation.

Table 3. Recent Estimates of Global Sea-Level Rise

Study	SLR	Notes
Modelling Approaches		
IPCC (2001a)	9–88 cm	Accounts for thermal expansion, glacier and ice sheet mass balance, and dynamical processes.
IPCC (2007)	18–59 cm	Accounts for thermal expansion only – no accounting for dynamical ice sheet behaviour.
IPCC (2007; with dynamical ice sheet discharge)	18–76 cm	Same as above but with 0–17cm added to account for dynamical ice sheet discharge (from IPCC, 2007).
Empirical/Observational Approaches		
Rahmstorf (2006)	50–140 cm	Assumes rates of sea-level rise are proportional to changes in global mean temperature. Extrapolates future SLR from IPCC scenarios for future temperature changes.
Church and White (2006)	28–34 cm	Extrapolated from recent trends in sea-level rise acceleration. Range is consistent with median estimates from IPCC (2001) and (2007).
Hybrid Approaches		
IPCC (2007); Meier et al. (2007)	23–140 cm	Combines IPCC (2007) estimates of thermal expansion for 2090–2099 with projections of glacier and ice sheet contributions by 2100 from Meier et al. (2007) that include acceleration from dynamical instability based upon observed trends.
Paleoclimatic Analogy		
Hansen et al. (2006)	Up to 60 cm per decade (600 cm per century) post-2100	Paleoclimatic evidence indicates that sea-levels were 25 metres higher when global temperatures were 2-3°C warmer. Further, dynamical ice sheet processes can lead to rapid disintegration of ice sheets and rapid rates of sea-level rise. The timing of these processes is speculative, but such rapid rates are probably not relevant over this century.

Climate change is anticipated to further exacerbate coastal management challenges in the decades ahead. This is largely a function of rising sea-levels that will increase rates of erosion along susceptible stretches of coastline, inundate low-lying areas, and interact with climate variability such as synoptic weather fronts, to enhance storm surges above current levels. Modelling of weather patterns along the NSW coast indicates the potential for increases in the frequency of weather events that contribute to extreme winds and, subsequently, storm surges (Hennessy et al., 2004b). Given a sea-level rise of 20 cm by 2050, coastal erosion of up to 22 metres is projected for Collaroy/Narrabeen beach, rising to 110 metres given a 1 in 50 year storm surge, with associated economic losses of $230 million (Hennecke et al., 2004). More recently, Cowell et al. (2006) estimated median erosion at Manly Beach from sea-level rise of 33.2 metres (±90 metres) by 2100. Estimates from Victoria also indicate the potential for significant coastal erosion in response to sea-level rise (Port of Melbourne Authority, 1992).

The conceptual model of coastal vulnerability to climate change is therefore a function of changes in sea-level combined with the inherent variability of dynamic coastlines caused by tidal ranges, and weather patterns. These dictate sea levels over the short-, medium-, and long-term as well as the wave action and energy to which coastlines are exposed. Research conducted for the NSW and Victorian coasts indicates that in examining changes in coastal hazards in the future, sea-level rise is the major driver (McInnes et al., 2005), although changes in sea-level pressure and wind strength and direction can also influence extreme sea level heights at the margins. Projections of future sea-level rise vary considerably (Table 3), depending upon the method utilised to generate estimates (e.g., GCM simulations, empirical assessment of observations and trends, or paleoclimatic analogy) and the various components of sea-level rise that are incorporated (e.g., thermal expansion, ice sheet mass balance, and ice sheet dynamics). Furthermore, regional sea-level rise may vary significantly from global averages. For example, recent sea level trends around the Australian continents have been significantly higher than the global average (BOM, 2006).

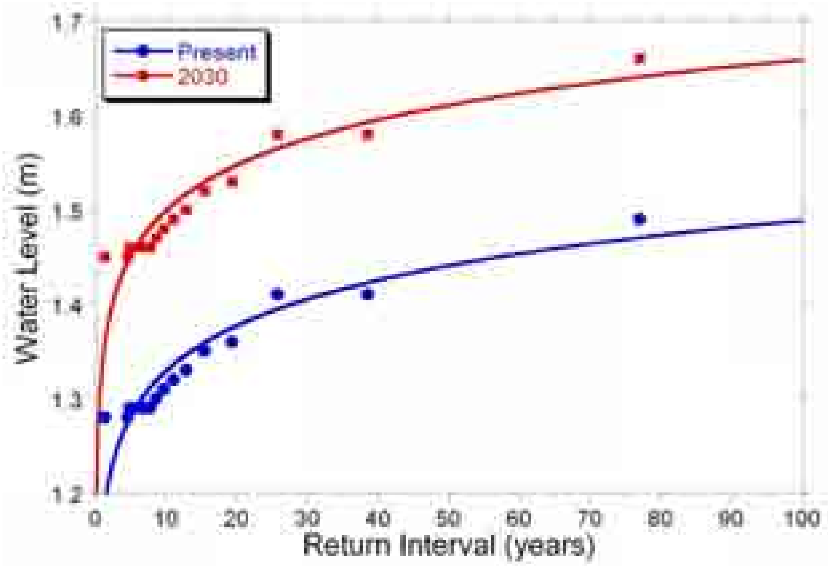


Figure 7. Return intervals for water levels in Sydney Harbour. Present data are based upon 20 rank events observed between 1914 and 1990 normalised to mean tidal level (MHL, 1991). values for 2030 were calculated simply by adding a worst-case estimate of sea-level rise by 2030 of 17 cm (McInnes et al., 2005).[2]

[2] *Present data were adjusted from indian spring tide level to mean tidal level by subtracting 91 cm (DNR 2007). Resulting 100 year return interval ~1.6 m is comparable to that calculated for the Pittwater Council shoreline of 1.5 m (Lawson and Treloar, 2004). Water levels do not account for waves.*

In addition to sea-level rise alone, the SCCG coastline is currently, and will continue to be, adversely affected by extreme sea levels associated with tides and storm surges as well as waves and other storm-related impacts (e.g., extreme winds). For example, historical extreme water levels in Sydney Harbour suggest a current 100-year annual return interval (ARI) of just under 1.5 metres (Figure 7). Extrapolation of this relationship to 2030 decreases the ARI for the same event to approximately 8 years. This dramatic shift is due largely to the fact that the magnitude of projected sea-level rise is large relative to the characteristic variability in storm surge heights in Sydney Harbour. As a consequence, existing planning frameworks for the SCCG coastline will have to be updated to account for this shift in the nature of coastal hazards.

Table 4. Vulnerability Matrix for Different Beach Typologies (Voice et al., 2006)

Type of Coast	Climate Change Effect	Potential Impact
Open Beach	Sea level rise and increased waves	Loss of beach width and beach amenity. Potential erosion of backing dunes or land if beach totally inundated - Loss of erosion buffer for storms - Intrusion of saline water into freshwater sandy aquifers
	Increased tropical cyclone intensity	More intense erosion events in generally low energy environments, wave effects elevated by storm surge
Beach Backed by Hard Protection	Sea level rise and increased waves	Loss of beach width and beach amenity. Potential undermining and collapse of hard protection
Sand Barrier	Sea level rise and increased waves	Potential erosion and inland migration of barrier or barrier breaching - Loss of erosion buffer for storms
Sand Dunes	Sea level rise and increased waves	Potential erosion of foredune leading to blowouts and inland migration of transgressive dunes - Loss of erosion buffer for storms
Coastal Lake Beaches	Sea-level Rise	Loss of beach width - Intrusion of saline water into freshwater sandy aquifers
Sand Islands	Sea level rise and increased waves	Reduction in size and change in shape of island - Intrusion of saline water into freshwater aquifer

The sensitivity of coastlines to sea-level rise and other coastal hazards is highly variable. The biophysical sensitivity is largely a function of the geography of the coastal landscape. Factors such as the elevation of coastal land above sea level as well as its slope influence the risk of inundation and erosion. In addition, different types of coastal frontage may be more or less susceptible to inundation and erosion than others. This is illustrated in Table 4, which addresses the range of potential impacts of sea-level rise associated with different beach types (see also Port of Melbourne Authority, 1992; Sharples, 2004). However, risk is not confined to low-lying sandy beaches, as erosion also can undercut and destabilise coastal cliffs.

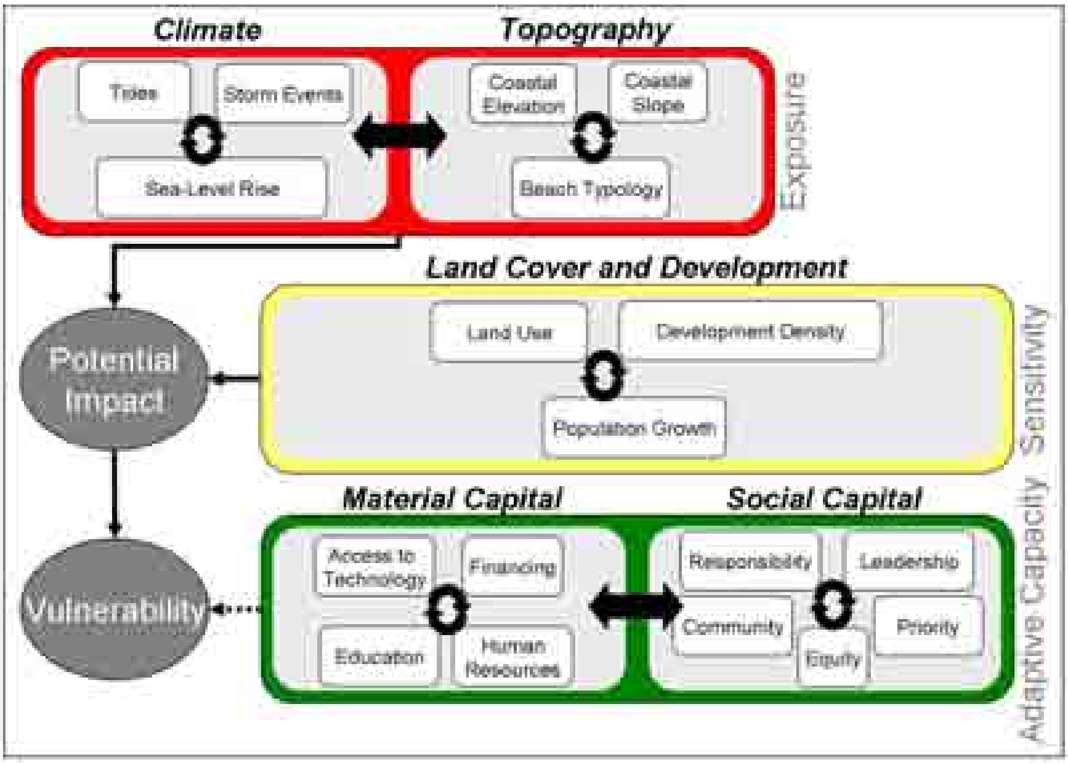


Figure 8. *Conceptual model of the vulnerability of coastlines to climate change.* ***Exposure*** *(red) is driven by interactions between the climate system and the landscape topography.* ***Sensitivity*** *(yellow) is a function of the assets and infrastructure on the landscape. The combination of exposure and sensitivity creates the potential for an adverse impact.* ***Adaptive capacity*** *(green) is a function of the material and social capital that can address potential impacts and ameliorate vulnerability. Critical interactions and processes are represented by arrows.*

The other aspect of coastal sensitivity to climate change is the assets that may be in harm's way, whether they are buildings such as houses or life saving clubs, infrastructure such as roads or water and sewer pipes, assets such as parks and reserves or ecosystems such as coastal wetlands. All of these also contribute directly or indirectly to public amenity and sense of place. For the current project, ecosystems and natural resources were excluded in the coastal vulnerability assessment, due to the inclusion of natural ecosystems as one of the five impact areas of interest. Hence, the conceptual model for coastal vulnerability was restricted to direct societal assets associated with human development of the coastline. The sensitivity of coastal systems is thus dependent upon the number and density of coastal developments, their proximity to hazards, and their value. Areas with greater accumulation of buildings, infrastructure and wealth in close proximity to the coastline are at greater risk of being affected by future sea-level rise, coastal inundation and erosion, and storm events. In contrast, more sparsely developed coastlines or those where development is set back from the coastline have fewer human assets in harm's way, and thus are less sensitive to the biophysical effects of climate change.

As with the health effects of extreme heat events, the conceptual model for coastal vulnerability also incorporated adaptive capacity as a means of ameliorating the impacts in the coastal zone (Figure 8). Again, adaptive capacity was seen as an interaction between material and social capital. Financial resources convey adaptive capacity by enabling individuals, households and communities to access technology and infrastructure to reduce coastal vulnerability. In particular, financial and technical resources may enable communities to assess risk and develop plans for managing hazards. This may include activities such as construction of sea walls, beach nourishment, conservation easements, or other shoreline modifications. Generally, the higher the value of the affected land area, the greater the likelihood that protective measures will be taken (Yohe et al., 1999). Furthermore, such resources also enable individuals to relocate, retreating from advancing coastlines or otherwise hazardous areas. Material resources also increase the opportunities for risk communication about long-term climate change and coastal hazards, as well more immediate coastal weather events, such as storms. Again, access to education enhances individuals' ability to interpret information regarding the implications of climate change on coastlines and act accordingly.

The barriers to effective use of resources in coastal risk management that arise from deficiencies of social capital may be many and varied. Responsibilities of different decision-making events are often divided among different levels of government, agencies and enterprises. Perhaps most importantly for coastal vulnerability is the issue of foresight in decision-making. While storm events and their associated challenges may fall within the scope of existing hazard management activities of local government, future climate change is likely to alter the nature of the hazard over the long-term. As such, for planning and design of hazard mitigation activities over the near-term to be robust, they must take the long-term implications of climate change under consideration. This may be difficult due to political considerations as well as constraints on budgets or simply lack of awareness among decision-makers as to the need to account for climate change.

4.3.3 Extreme Rainfall and Stormwater Management

Extreme rainfall events and the management of the subsequent runoff is a fundamental challenge for many urban and rural regions. High magnitudes of rainfall over short-time windows can contribute to high levels of runoff that increase flood risk in drainage areas (Fowler and Kilsby, 2003). The challenge is particularly acute for urban environments due to the large proportion of impervious land cover (e.g., buildings, roads, parking lots) that causes a much higher proportion of runoff to rainfall than in natural landscapes. Furthermore, urban development often disrupts the natural drainage of the landscape and development may occur in what otherwise would be wetland or floodplain areas (WMA, 2005).

Hence, urban communities make significant investments in stormwater management networks, designed to safely store, retard, or conduct storm water runoff to suitable discharge points. When the capacity of such drainage networks is exceeded and/or further development alters the flow of runoff, localised flooding can occur. For example, a study of flood hazard in Randwick City Council and City of Sydney recorded a history of five floods in a local area between 1949 and 2001, with flood heights of 0.2 to 1 metre (WMA, 2005). An extreme rain event in Wollongong in 1998 that exceeded the 100 year ARI, brought 445 mm of rain in 24 hours, resulting in a 50-year ARI flood and $125 million in damages (Yeo, 2002).

Climate change is projected to alter the frequency and/or intensity of extreme rainfall events in Australia, including central coastal NSW. A 2004 assessment of projected changes in extreme rainfall in NSW estimated 1-day extreme rain events would increase in central coastal NSW in spring, summer and autumn, but decreases in winter (Hennessy et al., 2004b). A more recent assessment of extreme rainfall events in southeast Australia also projected a long-term increase in 1-day extreme rain events, and a decrease in ARIs in much of central coastal NSW (Abbs et al., 2006; Figure 9). The signal of increasing rainfall was larger later in the century. Such increases in extreme rainfall events are anticipated to increase flood risk and damages, unless stormwater management infrastructure and flood mitigation measures are updated. In fact, Minnery and Smith (1994) argue that *"for urban areas the most significant climatic impacts are likely to result from an increased frequency of extreme events, including flooding."* A modelling study by Schreider et al. (2000) concluded that for a doubling of the preindustrial concentration of atmospheric carbon dioxide, the 1 in 100-year flood under current conditions would become a 1 in 44-year event for the Upper Parramatta River, a 1 in 35-year flood for the Hawkesbury–Nepean and a 1 in 10 for Queanbeyan and Canberra. A study by Minnery and Smith (1996) found that climate change may double flood-related damages in urban areas of NSW (see also Smith, 1998; Schreider et al., 2000).

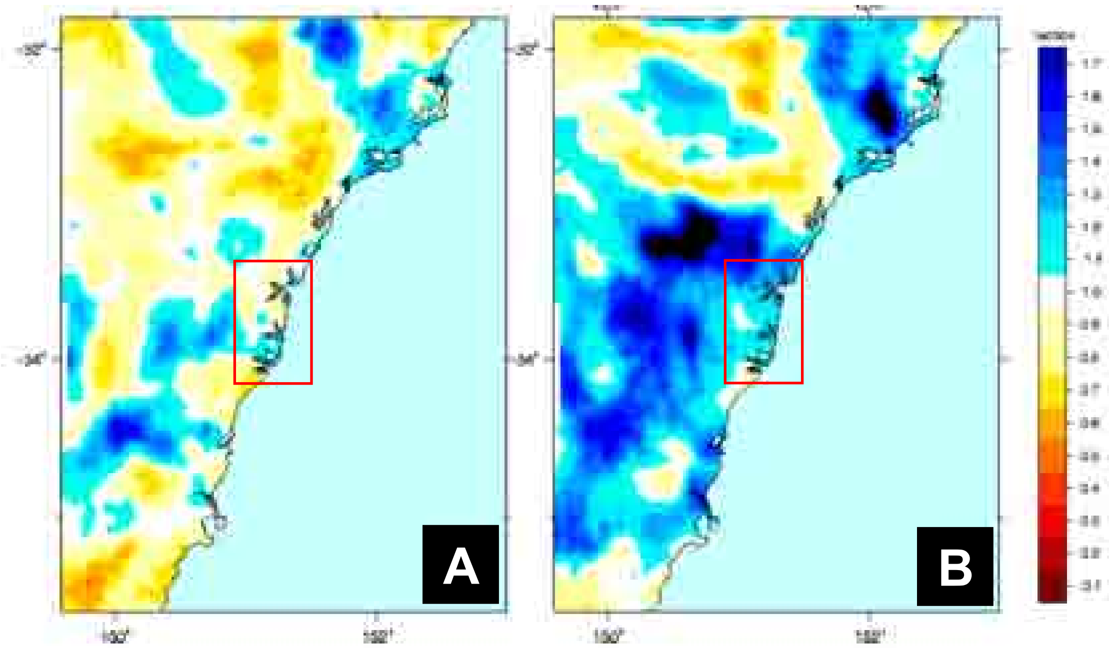


Figure 9. *Projected fractional change in extreme rainfall events in central coastal NSW in A) 2030 and B) 2070. Changes greater than 1.0 indicate an increase in extreme rainfall, while changes less than 1.0 indicate a decrease (Abbs et al., 2006). The red box indicates the approximate location of the SCCG region.*

In light of this research, the conceptual model for extreme rainfall vulnerability characterises exposure as an interaction among average baseline rainfall levels, rainfall variability that contributes to anomalously high rainfall events, and projected changes in future rainfall (and extreme rainfall in particular) (Figure 10). Areas within the SCCG region that currently experience higher average rainfall amounts as well as a greater frequency of anomalously high rainfall events will be more vulnerable than those receiving lower rainfall totals. Furthermore the spatial distribution of future changes in extreme rainfall will also influence vulnerability, as those areas at greater risk of experiencing increases in such events are likely to also be at greater risk of flooding and flood damages.

The sensitivity of different areas of the SCCG region to extreme rainfall events is a complex interaction among topography, land use and cover, and soil conditions. Topography influences the drainage pathway of runoff across the landscape which is influenced by relative elevation between points and the slope of the landscape (Ziu and Todini, 2002). The conceptual model assumes that higher elevation areas with steep slopes are less vulnerable to flooding, as rainfall is more likely to runoff to lower elevation plains and depressions, provided flow paths are available. Land cover dictates the extent to which rainfall can penetrate into the soil, attenuating runoff (Ziu and Todini, 2002). Areas that are densely developed are assumed to have a higher proportion of impervious surface, resulting in a high rate of runoff (Carlson and Arthur, 2000). More natural landscapes and particularly those with significant vegetation are assumed to retard runoff resulting in a lower fraction of immediate runoff, although catchments may continue to discharge into surface water networks over time. Finally, the ratio of rainfall to runoff is also influenced by the existing saturation state of the soils (i.e., the amount of water those soils can hold; Bronstert et al., 2002). This is a parameter that varies considerably over time depending upon the timing of rainfall, temperature and evaporation, and the structure of the soil. Nevertheless, across a landscape, some areas will tend to have higher capacities to hold water than others, which again may increase the potential for those soils to absorb rainfall and retard runoff.

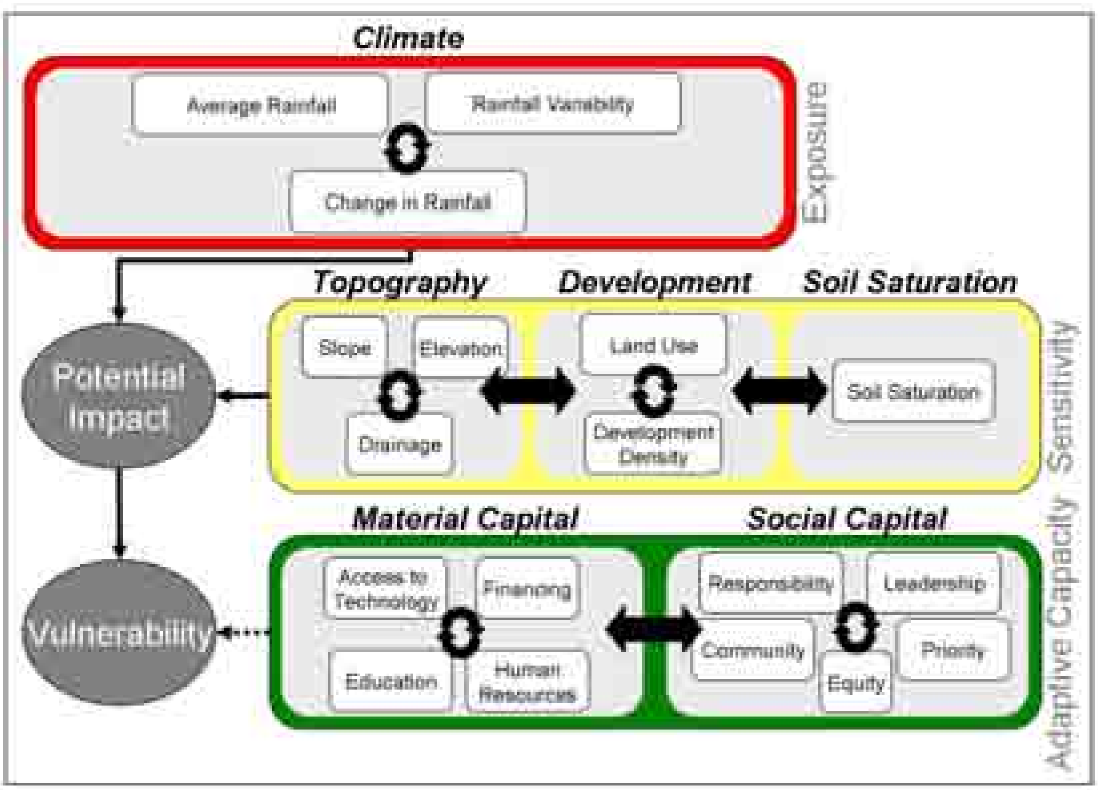


Figure 10. *Conceptual model of the vulnerability of landscapes to extreme rainfall events.* ***Exposure*** *(red) is driven by the climate system and the rainfall generated.* ***Sensitivity*** *(yellow) is a function of the interactions among topography, land use and development and soil conditions. The combination of exposure and sensitivity creates the potential for an adverse impact.* ***Adaptive capacity*** *(green) is a function of the material and social capital that can address potential impacts and ameliorate vulnerability. Critical interactions and processes are represented by arrows.*

In regard to adaptive capacity, the management of flood risk is largely the responsibility of local government (WMA, 2005). Granted, material resources may increase the likelihood that individuals obtain higher quality (and presumably more resilient) housing or flood insurance. However, financial resources are probably more critical for local government as they dictate the potential for investments in stormwater management plans and drainage infrastructure. Resources also increase the opportunities for risk communication about extreme rain events and flood risk, while education enhances individuals' ability to interpret risk information.

Deficiencies of social capital may impede planning decisions that affect flood risk and/or coordination of emergency management responses. Lack of institutional knowledge, authority or effectiveness can be a barrier to efficient government responses to manage risk, and equity issues may cause some areas to be more likely to receive hazard mitigation measures. Lack of foresight regarding future climate risk, and the need to review and revise existing management plans and infrastructure may pose a significant barrier to adaptation.

4.3.4 Bushfire

Bushfires are a major economic, social and environmental hazard in Australia. Between 1967 and 1999 bushfires cost the Australian economy around $2.5 billion (Allen Consulting, 2005). From 1960 to 2001, there were 224 fire-related deaths and 4,505 injuries in Australia (McMichael et al., 2003). The Sydney metropolitan region is particularly vulnerable to bushfires (Chapman, 2000; Gillen, 2005), as evidenced by recent severe bushfire seasons (e.g., 2001–2002) that have caused significant economic damages to property, disrupted essential services, and caused both injury and death.

While the relationship between weather, climate and bushfire risk is a complex one, it is clear that all other factors being equal, warmer and drier conditions increase the risk of bushfires and their severity (BTE, 2001). As such, global warming is likely to increase the frequency and severity of bushfires in Australia (Hennessy et al., 2005), consistent with projections from other nations (Stocks et al., 1998; Goldammer and Price, 1998; Wotton et al., 2003; Brown et al., 2004; Pearce et al., 2005). Climate and fire weather projections from the Sydney region indicate that the metropolitan area is also likely to experience increases in fire risk. Due to warmer and drier conditions in the region (Table 1), the number of days that Sydney experiences a fire danger index of 'very high' or 'extreme' is projected to increase from approximately 9 at present to 9 to 11 by 2020 and 10 to 15 by 2050 (Hennessy et al., 2005). As Sydney is located on the coast, these projected increases in fire risk are relatively moderate compared to some other regions of southeastern Australia (Hennessy et al., 2005). Yet given the damages associated with past events, any increase in risk is likely to pose a challenge to emergency management services.

In assessing the exposure of the SCCG member Councils to future bushfire risk, the conceptual model emphasises the climatic conditions, including future climatic changes that influence fire weather (Figure 11). Although patterns of temperature and rainfall (including both magnitude and variability) are a dominant feature of fire weather, humidity and wind speed (and direction) also influence fire risk.

The risk of ignition and spread of bushfire across a landscape, the rate of movement, and the intensity with which it burns are also influenced by topography and available fuel loads. These factors therefore influence the sensitivity of the SCCG landscape to bushfire risk. Research regarding fire dynamics indicates that bushfires spread more quickly and burn more intensely on upward slops than on flat landscapes (Bradstock et al., 1998; Brooks et al., 2004; Erten et al., 2004), and, conversely, spread more slowly on downward slopes. More specifically, the slope direction or aspect differentially exposes slopes to different sun and wind regimes that may enhance risk (Erten et al., 2004). Generally, elevation can also influence bushfire risk indirectly, as rainfall increases and temperatures decrease with elevation (BMBMC, 1997), although the elevation gradients over the SCCG region may not be sufficient for elevation to significantly influence fire risk.

Fuel loads are a critical component of bushfires (Brooks et al., 2004). Hence, the most hazardous bushfires in metropolitan Sydney tend to occur around the fringes of development, where significant human communities and infrastructure are present, but where there is also significant native and modified vegetation to fuel bushfires. For example, during the December 2002 bushfires, Sydney was effectively surrounded by multiple bushfires, yet none of these penetrated into the urban centre (although electricity, transport, and rail services were affected). Therefore, the conceptual model captures these interactions between land use and cover, development and vegetation. To the extent that development is limited and significant vegetation is present, sensitivity to bushfire is likely to be higher, whereas more developed areas are likely to be less sensitive. However, fire ignition has also been correlated with access of people to bushfire prone areas (Brooks and Esque, 2002), as humans are one of the core factors contributing to fire ignition. Therefore, some caution must be exercised in making such generalisations.

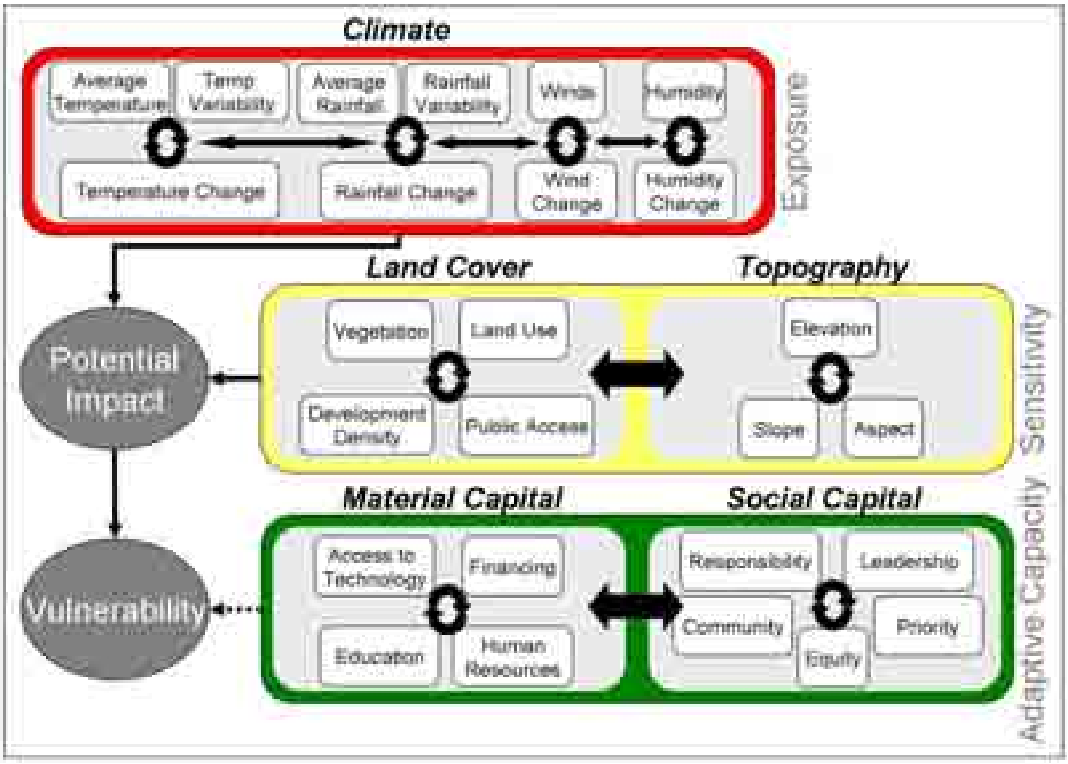


Figure 11. *Conceptual model of the vulnerability of landscapes to bushfire events.* ***Exposure*** *(red) is driven by interactions within the climate system the contribute to fire weather.* ***Sensitivity*** *(yellow) is a function of topography and factors that affect landscape fuel loads. The combination of exposure and sensitivity creates the potential for an adverse impact.* ***Adaptive capacity*** *(green) is a function of the material and social capital that can address potential impacts and ameliorate vulnerability. Critical interactions and processes are represented by arrows.*

Bushfires are one of the hazards that are routinely managed via multiple government agencies including NSW State Emergency Services and NSW Rural Fire Service in cooperation with a range of other local and state government institutions. In addition, one must recognise the important role that individual households and property owners play in protecting property, reducing damages, and communicating with government agencies. Therefore, the conceptual model for bushfire vulnerability recognises this important management role, through its treatment of adaptive capacity. With respect to material capital, financial resources convey adaptive capacity by enabling individuals, households and communities to access technology and infrastructure to reduce vulnerability to bushfire (e.g., personnel, equipment and vehicles for fire prevention and suppression). It also increases the number of communication channels through which individuals may gain information on bushfire risk and events (e.g., communication of total fire ban days through television, radio, internet or real-time monitoring of bushfire locations) that enable preventive measures to be taken. In addition, access to education could be argued to enhance individuals' ability to interpret information regarding bushfire risk and manage that risk accordingly.

The effective use of such resources may be compromised by a broad range of barriers associated with social capital. Such barriers may exist at the level of the individual household such as language barriers that limit access to communication channels or lack of responsibility, authority, or incentive to take preventive action. In addition, barriers can exist at the level of government, which is tasked with making planning decisions that affect the environment including execution of fuel burn offs, coordination of emergency management responses, and educating and warning the public about bushfire risk and prevention (Bradstock et al., 1998; Hennessy et al., 2005). Lack of institutional knowledge, authority or effectiveness can be a barrier to efficient government responses to manage risk. For example, Gillen (2005) has suggested that the segregation and limited coordination of relevant bushfire management responsibilities between developers and emergency managers contributes to Sydney's bushfire vulnerability. Lack of foresight regarding future climate change and how bushfire risk (and subsequently management strategies) may be affected may pose a significant barrier to adaptation.

4.3.5 Ecosystems and Natural Resources

The ecosystems, biodiversity and natural resources within the SCCG region are valued by the region's population and provide social as well as ecological benefits. However, Sydney is also the most densely populated city on the Australian continent, and thus much of the natural landscape has been significantly altered by humans, particularly in the wake of colonisation in the late 18th century. Across the SCCG member Councils, one sees a significant spatial gradient with respect to human development of the landscape, with dense development around Sydney Harbour and the CBD dominated by buildings and infrastructure. Meanwhile, the northern and southern Councils of Hornsby, Pittwater and Sutherland Shire have extensive estuarine and wetland areas as well as significant native vegetation, which collectively is managed for its substantial conservation value.

Broadly, climate change is projected to challenge natural ecosystems and biodiversity. While a detailed assessment of the potential risk to the region's natural ecosystems has not been conducted, assessments conducted elsewhere aid in identifying the key issues of concern (Howden et al., 1999; Pickering et al., 2004; Allen Consulting, 2005). The spatial distribution of plants and animals is heavily influenced by ambient climatic conditions, with individual species being adapted to a particular characteristic climate habitat, sometimes referred to as a 'climate envelope' (IPCC, 2002; Parmesan and Galbraith, 2004). Changes in temperature and/or rainfall alter the shape and distribution of that envelope, shifting it to a different area or altitude, or causing it to expand or shrink. If plant and animal species are unable to make commensurate adjustments to changing habitat (either by changing their location or adapting to new climate conditions) they are susceptible to being eliminated from a particular location. This may have secondary consequences when affected species have interactive relationships with other species based upon competition or predation.

The conceptual model of natural ecosystem vulnerability to climate change therefore highlights future changes in temperature and rainfall as the key factors driving exposure (Figure 12). Undoubtedly, changes in temperature and rainfall variability also influence the distribution of species. For example, minimum temperatures often influence the southern range of sub-tropical species, while some plants are more or less sensitive to periodic drought events.

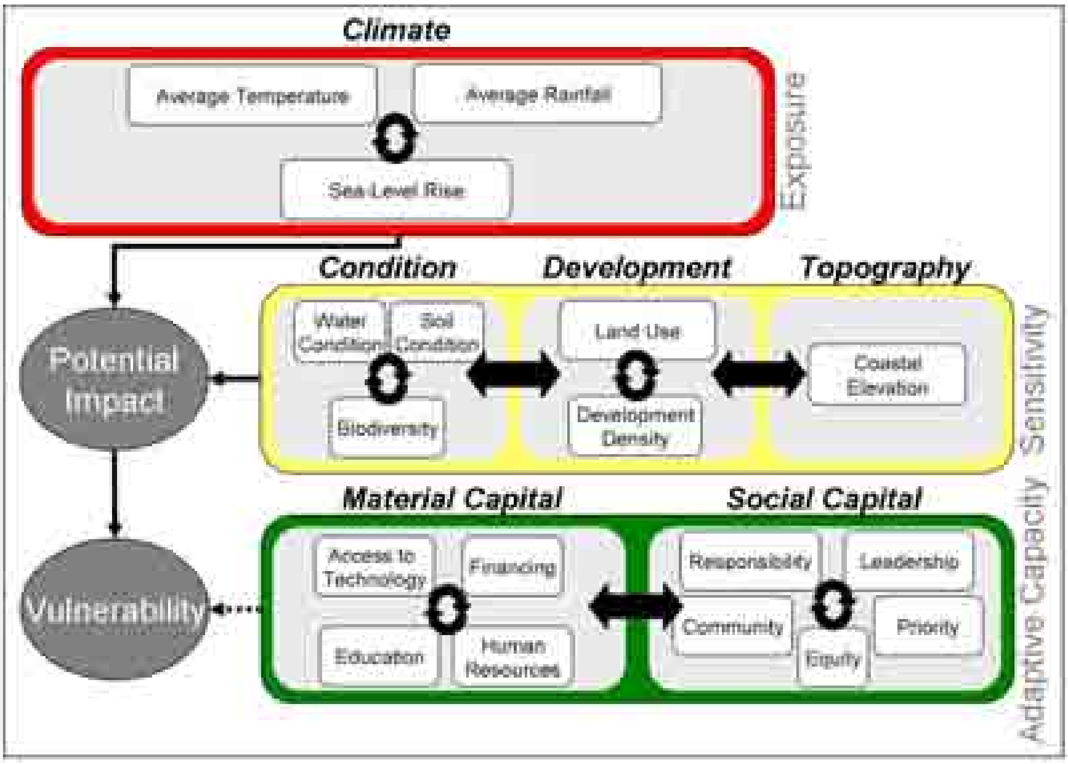


Figure 12. *Conceptual model of the vulnerability of ecosystems to climate change.* ***Exposure*** *(red) is driven by the climate system.* ***Sensitivity*** *(yellow) is a function of the landscape condition, human development and land use and topography. The combination of exposure and sensitivity creates the potential for an adverse impact.* ***Adaptive capacity*** *(green) is a function of the material and social capital that can address potential impacts and ameliorate vulnerability. Critical interactions and processes are represented by arrows.*

In the absence of such species-specific information on sensitivity to changes in climate variables, the conceptual model for natural ecosystem sensitivity viewed sensitivity in the context of resilience. Specifically, those areas under multiple pressures (land clearance and development) are likely to be less resilient to future changes in climate than those that are more characteristic of an undisturbed system. Such pressures were conceptualised as originating from three different sources. First, the condition of the existing landscape and waterways (i.e., soil and water quality) and the status of native vegetation represent the environmental context upon which future climate change will act. Areas currently experiencing degradation, impairment, or disturbance are assumed to be less resilient to future changes in climate. Second, human development such as buildings, industry, infrastructure, and other modifications of the landscape further degrade and homogenise the natural environment limiting the diversity and magnitude of wildlife that it can support. Such development also prevents the landscape from reverting to its original state over time. Third, in the coastal margins, topography influences the risk of coastal habitat and ecosystems being inundated from sea-level rise. Although this generally reflects a change from one type of ecosystem or habitat to another (e.g., terrestrial to estuarine or marine), it is arguable whether one can simply substitute one type of habitat for another with no net loss of natural amenity (Parmesan and Galbraith, 2004).

Assessing the adaptive capacity of natural ecosystems to climate change poses some significant challenges, not the least of which is limited knowledge regarding the ability of individual species or event communities of species to adapt to changes in the climate system. Therefore, as with sensitivity, the conceptual model for ecosystem vulnerability to climate change focused on the relationship between adaptive capacity and resilience. In other words, to what extent does adaptive capacity convey the potential to increase the resilience of natural ecosystems to various pressures including, but not limited to, climate change. In this context, resources enable households and communities to manage and reduce their impact upon the landscape. For example, investments in technology and infrastructure at the household and community level can reduce water consumption and improve water quality in surface waters.

Yet obviously, there are a range of social/cultural barriers that exist to making such investments. First, as with bushfire management, responsibility for managing and conserving natural ecosystems is often split among different agencies. For example, catchment management authorities, local Councils, State government, and Federal government all have some degree of responsibility for environmental management, but coordination and cooperation among such different institutions may be sub-optimal to achieve consistent results. In addition, competing interests may place constraints on environmental management. For example, in areas associated with intensive land-use, there are likely to be inherent trade-offs between maintenance of human activities and land uses and conservation of natural ecosystems and resources. Particularly in heavily urbanised areas, it is clear that regardless of the effort invested in environmental protection, such areas will invariably be associated with diminished biodiversity and natural amenity relative to less urban environments. Hence, the history of urban settlements and the societal commitment to the maintenance and growth of such developments is a fundamental limit on the resilience of the natural environment.

5. Methodology for Vulnerability Mapping

Chapter Summary

- ✓ ***The conceptual models presented in Section 4.3 were used to identify relevant indicators of exposure, sensitivity and adaptive capacity for each of the five impact areas.***
- ✓ ***Indicators were obtained from a diverse array of sources and included data on current and future climate conditions; topography, land use and land cover; landscape condition; demographics; and SCCG member Council characteristics and performance metrics.***
- ✓ ***The various indicators were converted to a quantitative scale and normalised to a standard spatial reference prior to their integration.***

5.1 Indicator Selection and Sourcing

The conceptual models described in Section 4.3 were utilised to inform the selection of relevant data sets that could be used to map exposure, sensitivity and adaptive capacity for the five impact areas. A large number of indicators were drawn from a broad range of sources. However, to ensure comparability in vulnerability estimates derived from indicators, indicators had to provide complete coverage over the entire SCCG region. This excluded a number of potential indicators including some data sets maintained by individual SCCG member Councils.

5.2 Vulnerability Indicators

Identification of the indicators used for vulnerability mapping appear in the following tables (Table 5–Table 9). Each table contains a list of indicators used to represent exposure, sensitivity and adaptive capacity for each of the five impact areas. In addition, the spatial extent or resolution of the original data set appears in parentheses following the indicator. Additional details regarding vulnerability indicators are provided in Appendix I.

Table 5. Vulnerability Indicators for Extreme Heat and Human Health

Exposure Indicators	Sensitivity Indicators	Adaptive Capacity Indicators
1) Present average January maximum temperature (BOM stations) 2) Present average January minimum temperature (BOM stations) 3) Present # Days > 30°C (BOM stations) 4) Projected change in average DJF maximum temperature in 2030 (25 km grid) 5) Land cover (14 m grid) 6) Population density (census districts) 7) Road density (5 km grid)	1) % population≥65 years of age (census districts) 2) % population≥65 years of age & living alone (census districts) 3) % population≤4 years of age (census districts) 4) % of housing as multi-unit dwellings (census districts) 5) Projected population growth to 2019 (statistical local areas)	1) % population completing year 12 (census district) 2) % population that speaks language other than English (census district) 3) Median home loan repayment (census district) 4) % home ownership (census district) 5) Median household income (census district) 6) % households requiring financial assistance (Census district) 7) % population with internet access (census district) 8) Current ratios (local government areas) 9) Per capita business rates (local government areas) 10) Per capita residential rates (local government areas) 11) Per capita community service expenses (local government areas) 12) Per capita

		environment and health expenses (local government areas)

Table 6. Vulnerability Indicators for Extreme Rainfall and Stormwater Management		
Exposure Indicators	**Sensitivity Indicators**	**Adaptive Capacity Indicators**
1) Present average annual rainfall (BOM stations) 2) Present average 90th percentile annual rainfall (BOM stations) 3) Projected change in extreme rainfall events in 2030 (5 km grid)	1) Land cover (12 m grid) 2) Elevation (90 m grid) 3) Slope (90 m grid) 4) Drainage (90 m grid) 5) Average soil water holding capacity (5 km grid) 6) Population density (census districts) 7) Road density (5 km grid) 8) Projected population growth to 2019 (statistical local areas)	1) % population completing year 12 (census district) 2) % population that speaks language other than English (census district) 3) Median home loan repayment (census district) 4) % home ownership (census district) 5) Median household income (census district) 6) % households requiring financial assistance (Census district) 7) % population with internet access (census district) 8) Current ratios (local government areas) 9) Per capita business rates (local government areas) 10) Per capita residential rates (local government areas) 11) Per capita community service expenses (local government areas)

Table 7. Vulnerability Indicators for Sea-Level Rise and Coastal Management		
Exposure Indicators	**Sensitivity Indicators**	**Adaptive Capacity Indicators**
1) Distance to coastline (90 m grid) 2) Present relative storm surge along SCCG coast (100 m grid) 3) SEPP 71-defined sensitive coastal locations (polygon file) 4) Coastal elevation (90 m grid)	1) Land cover (90 m grid) 2) Population density (census districts) 3) Road density (census districts) 4) Projected population growth to 2019 (statistical local areas) 5) Acid sulphate soils (polygon file)	1) % population completing year 12 (census district) 2) % population that speaks language other than English (census district) 3) Median home loan repayment (census district) 4) % home ownership

5) Slope (90 m grid)		(census district) 5) Median household income (census district) 6) % households requiring financial assistance (Census district) 7) % population with internet access (census district) 8) Current ratios (local government areas) 9) Per capita business rates (local government areas) 10) Per capita residential rates (local government areas) 11) Per capita community service expenses (local government areas)

Table 8. Vulnerability Indicators for Bushfires		
Exposure Indicators	**Sensitivity Indicators**	**Adaptive Capacity Indicators**
1) Present average maximum January temperature (BOM stations) 2) Present # Days > 30°C (BOM stations) 3) Projected change in average maximum DJF temperature in 2030 (25 km grid) 4) Present average annual rainfall (BOM stations) 5) Present average annual 10th percentile rainfall (BOM stations) 6) Projected average annual rainfall change in 2030 (25 km grid)	1) Annual primary production (1 km grid) 2) Land cover (14 m grid) 3) Slope (90 m grid) 4) Aspect (90 m grid) 5) Population density (census districts) 6) Road density (5 km grid)	1) % population completing year 12 (census district) 2) % population that speaks language other than English (census district) 3) Median home loan repayment (census district) 4) % home ownership (census district) 5) Median household income (census district) 6) % households requiring financial assistance (Census district) 7) % population with internet access (census district)Current ratios (local government areas) 8) Per capita business rates (local government areas) 9) Per capita residential rates (local government areas) 10) Per capita community service expenses (local government areas)

Table 9. Vulnerability Indicators for Ecosystems and Natural Resources		
Exposure Indicators	**Sensitivity Indicators**	**Adaptive Capacity Indicators**
1) Projected change in annual average temperature in 2030 (25 km grid) 2) Projected change in average DJF maximum (25 km grid) temperature in 2030 3) Projected change in annual average JJA minimum temperature in 2030 (25 km grid) 4) Projected change in average annual rainfall in 2030 (25 km grid)	1) Elevation (90 metre grid) 2) Land cover (14 m grid) 3) % Native vegetation (5 km grid) 4) Water condition (1 km grid) 5) Land condition (1 km grid) 6) Population density (census districts) 7) Road density (5 km grid) 8) Projected population growth to 2019 (statistical local areas) 9) SEPP 14 wetland areas (polygon file)	1) % population completing year 12 (census district) 2) % population that speaks language other than English (census district) 3) Median home loan repayment (census district) 4) % home ownership (census district) 5) Median household income (census district) 6) % households requiring financial assistance (Census district) 7) % population with internet access (census district) 8) Current ratios (local government areas) 9) Per capita business rates (local government areas) 10) Per capita residential rates (local government areas) 11) Per capita community service expenses (local government areas) 12) Per capita environment and health expenses (local government areas) 13) Per capita annual recycling (local government areas)

5.3 Integration of Data Layers

The diversity of data sources, formats, and spatial scales necessitated reconciliation to a common spatial reference before data could be integrated. A spatially homogenous data scale of a 90 metre grid over the SCCG Councils was used.[3] This represented one of the highest resolution data sets available for the region, corresponding with the SRTM digital elevation model. Other data sets were processed to match this spatial reference using one of the following methods:

[3] *The WGS 1984 datum was utilised for all data layers in vulnerability mapping.*

- ***For gridded data***. Data were resampled to 90 metre resolution and the spatial extent was matched to that of the baseline grid.

- ***For vector/polygon data***.[4] Vector polygon data were converted to a 90 metre resolution grid and its spatial extent was matched to the spatial extent of the base grid.

- ***For vector/point data***. Vector point data were used to interpolate a 90 metre gridded surface using a spatial interpolation technique.[5]

Data conversion introduced uncertainty into the indicators. However, the implications of data heterogeneities for vulnerability estimates were judged to be negligible because a) all indicators were converted to a qualitative ranking (see below) and b) maps represent relative vulnerability, as opposed to absolute measures of consequence or impact.

Once data layers were converted to a common spatial reference, data were assigned a qualitative ranking from 1 to 5, with 1 representing low exposure, low sensitivity or high adaptive capacity and 5 representing high exposure, high sensitivity or low adaptive capacity. In most instances, scoring was accomplished by dividing the frequency distribution for data into quintiles, which were then scored. In some instances, particularly indicators of exposure for sea-level rise, exponential scaling was used (see Appendix I for details). This scoring method was utilised for continuous data. However, some data were categorical, such as the presence or absence of a particular indicator or indicator type for a given grid cell. Identification of these data sets and description of how they were scored appear in Appendix II.

The spatial extent of indicators was restricted for the assessment of sea-level rise and coastal hazards, due to the fact that exposure to coastal processes is a precondition for vulnerability. As such, an arbitrary elevation limit was selected and the extent of all indicators was restricted to this area. The selected elevation limit was 16 meters. This allowed for five exposure categories for elevation, based upon an exponential scale (i.e., in the scoring of elevation, exposure was assumed to decline with the square of elevation). The selection of this upper limit was guided by historical information regarding storm surge and wave heights. Some of the highest recorded storm wave heights observed in Sydney occurred during Cyclone Colin in 1976, when waves of 12 metres were observed at Sydney heads (Callaghan, 2007). This height falls in the middle of the lowest exposure category for elevation (i.e., 8–16 metres). In reality, the relationship between elevation and exposure will vary throughout the SCCG region, depending upon proximity to the coast, and whether a location is located on an estuary or ocean frontage. However, this height limit provided a means of restricting the study area to focus on areas associated with a plausible exposure to coastal hazards. Accordingly all indicators used in the sea-level rise assessment were restricted to this region of elevation and the qualitative scoring of indicators was based upon values falling within this region.

For each impact area, net vulnerability was assessed through the aggregation of three maps representing the different components of vulnerability – exposure, sensitivity, and adaptive capacity – for each impact (Figure 13). Due to differences in the number of indicators available for each component of vulnerability for each impact area, data had to first be integrated for each component to prevent any one component from biasing the results.

[4] *Vector/polygon data refers to all data based upon ARCGIS shapefiles or MAPINFO .tab files.*
[5] *Ordinary kriging (see Clark, 1979).*

Integration of indicators for each component of vulnerability was achieved simply by calculating the sum of all indicators. Individual indicators not weighted due to a lack of knowledge about their relative importance or the quantitative relationships among variables.[6] Sums were then rescored to a scale from 1 to 9 based upon quintiles, with 1 representing low exposure, low sensitivity or high adaptive capacity and 9 representing high exposure, high sensitivity or low adaptive capacity. Integration of the three component layers was then accomplished by summing the scores from the three vulnerability layers, with the result again being rescored to a scale from 1 to 9.

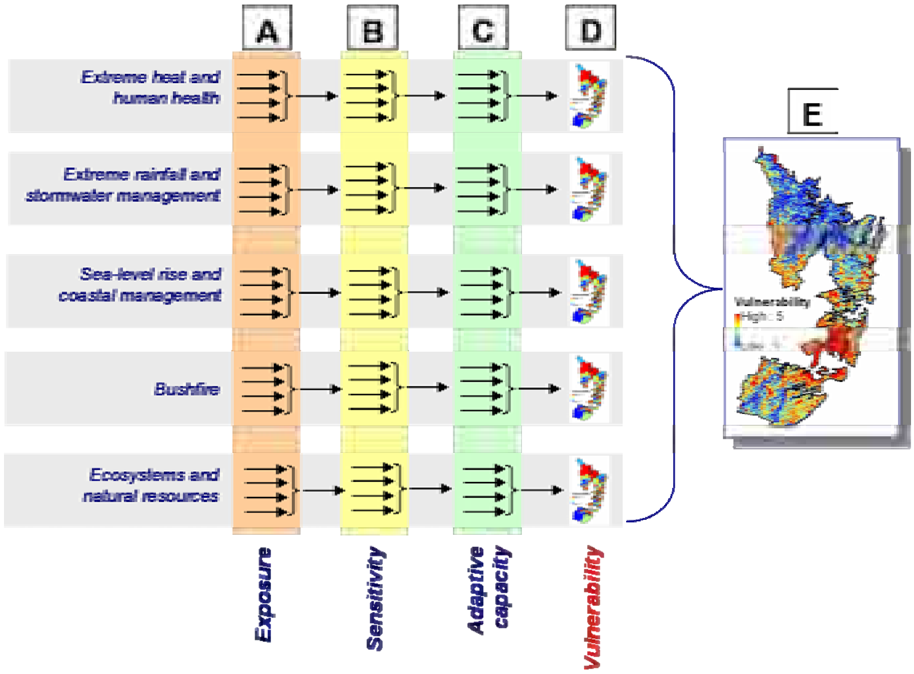


Figure 13. *Conceptual model of the approach for assembling vulnerabilty maps for each of the five impact areas, and net climate change vulnerability for the region. Maps of the components of vulnerability (A,B,and C) were developed from multiple indicators (see Table 5–Table 9), and summed to develop vulnerability maps (D). The five vulnerability maps were subsequently weighted and summed to develop a map of net climate change vulnerability for the Sydney Coastal Councils Group region (E).*

Different components were weighted in the calculation of vulnerability due to expert judgment of the investigators regarding their relative importance (Table 10). For example, in some instances, the climate conditions to which an area is exposed may be a secondary consideration with respect to vulnerability than the sensitivity of the people or infrastructure inhabitant the land. Similarly, the capacity to adapt doesn't necessarily mean that vulnerability does not exist, particularly for those areas routinely exposed to unavoidable hazards.

Generally, components were assigned a common weight of 1. However, components judged to have a low influence on vulnerability were assigned a weight of 0.5, while components judged to have a particularly high influence on vulnerability were assigned a weight of 2. For all impact areas, adaptive capacity was assigned a weight of 0.5 due to the fact that a) adaptive capacity does not necessarily contribute to effective adaptation; b) the complete

[6] *For example, while it is safe to assume that higher summer temperatures contribute to a greater risk of heat-related illness and that greater urbanisation may contribute to an urban heat island, building a model that can account for each of these variables in a projection of actual numbers of deaths was beyond the scope of this study.*

elimination of vulnerability through adaptive capacity is unlikely (Easterling et al., 2004); c) responsibility for management of some risks may lie beyond the household or local government level; and d) the adaptive capacity of some systems (e.g., natural ecosystems) is quite limited.

Table 10. Weights Utilised in Calculation of Net Vulnerability

Component	Extreme Heat	Extreme Rainfall	Sea-Level Rise	Bushfire	Natural Ecosystems
Exposure	1	1	2	1	0.5
Sensitivity	1	1	1	2	2
Adaptive Capacity	0.5	0.5	0.5	0.5	0.5

Exposure for sea-level rise was assigned a weight of 2, due to the fact that the existence of coastal impacts presupposes proximity to the coastline. Exposure for natural ecosystems was assigned a weight of 0.5, because exposure was a function of projected changes in temperature and rainfall which, though variable over the study area, were associated with rather shallow gradients (i.e., projected differences among the 15 member Councils were relatively small). Sensitivity for natural ecosystems and bushfire were assigned a weight of 2. For the former, land condition and use were assumed to be the dominate factors influencing future resilience of ecosystems. For the latter, the distribution of fuel sources was seen to be a limiting step on bushfire risk, independent of climate conditions, which are generally suitable throughout the region for bushfire ignition and spread. Changes to these assumptions would alter the vulnerability score for a given grid cell for a particular impact area.

Application of this approach resulted in five maps of net relative vulnerability for each of the impact areas. These five maps were subsequently integrated to generate a map of overall climate change vulnerability across the different impact areas (Figure 13). The difficulty in integrating across different vulnerabilities is the fact that they are often incommensurate. For example, how does one balance the effects of climate change on ecosystem resilience against effects on flood damages from stormwater runoff? Information is needed on the relative importance of these different impacts, so that they can be weighted appropriately. Here, this weighting was accomplished by the use of results from a stakeholder survey of vulnerability (see Box 2, page 62). The vulnerability maps for each impact were multiplied by the Councils' self-reported perceptions of vulnerability (expressed as the ratio of vulnerability to management capacity) to each impact in each Council, and this product was summed across each impact area. This sum was then rescored to a scale from 1 to 9 based upon quantiles, with 1 representing low vulnerability and 9 high.

6. Regional Results

Chapter Summary

- ✓ ***The spatial distribution of climate change vulnerability varied significantly from location to location depending upon the impact under consideration.***
- ✓ ***For some impacts, such as extreme heat and health effects, vulnerability was highly fragmented across the SCCG landscape due to the spatial heterogeneity of sensitive subpopulations. Vulnerability for other impacts tended to conform to general spatial gradients (e.g., bushfire and ecosystems) or was concentrated in certain areas (e.g., sea-level rise and coastal management).***
- ✓ ***The spatial pattern of vulnerability was often dominated by demographic and/or socio-economic indicators associated with sensitivity or adaptive capacity.***
- ✓ ***Net climate change vulnerability in the SCCG region was particularly high in those areas with significant vulnerability to multiple climate hazards.***

6.1 Heat-Related Health Effects

6.1.1 Exposure

The exposure component of extreme heat events suggests that temperature extremes generally increase with distance from the coastline, due to the moderating effect that large bodies of water have on daily temperatures (Figure 14). As a consequence, exposure to extreme heat events was greatest in southern Hornsby Council, as well as Willoughby, North Sydney, Leichhardt, and Rockdale Councils. These also represent regions where there are not only relatively high temperatures, but also significant development that may contribute to an urban heat-island effect. Notice, for example, that the exposure map was sensitive to the presence of large green spaces, such as Centennial Park. Less developed and/or more coastal areas such as northern Hornsby and southern Sutherland were generally associated with limited exposure.

6.1.2 Sensitivity

The spatial diversity of extreme heat sensitivity in the SCCG region was largely dictated by demographic factors that affect the distribution of sensitive subpopulations (e.g., infants, small children and the elderly) as well as future increases in population that are likely to result in large, exposed populations. This resulted in a highly variable pattern of sensitivity across the region. Pockets of relatively high sensitivity were observed in all of the inner-city Councils, and particularly parts of far northern and far southern Hornsby Shire Council, where census data suggest a relatively high proportion of elderly individuals (despite overall low population densities). In contrast, southern Sutherland Shire and much of northern Warringah Shire Councils were associated with low sensitivities.

6.1.3 Adaptive Capacity

The adaptive capacity of the SCCG region to address the vulnerabilities associated with extreme heat events suggested capacities in a number of at-risk areas were relatively high. For example, the high adaptive capacity of the inner-city Councils and those of Warringah and Pittwater offset some of the vulnerability generated by exposure and sensitivity. However, other areas, such as Rockdale and Botany Bay City Councils, southeast Sutherland Council and isolated areas within Hornsby Shire Council had lower adaptive capacities. This is particularly problematic for Rockdale and Botany Bay, which are also associated with significant exposure and sensitivity.

6.1.4 Vulnerability

When combined with their associated weights, the net vulnerability of the SCCG region to extreme heat events was largely attributed to the interaction between exposure, sensitivity and adaptive capacity. As such, almost all of Rockdale City and Botany Bay City Councils were associated with high vulnerability. A number of additional Councils had more spatially variable hotspots of vulnerability, including southern Hornsby Shire Council, eastern Pittwater Council, the Councils of central Sydney north and south of the harbour, as well as northern Sutherland Council. Meanwhile, much of western Pittwater Council, northern Warringah Council as well as eastern and southern Sutherland Council were associated with relatively low vulnerability.

6.2 Sea-Level Rise and Coastal Management

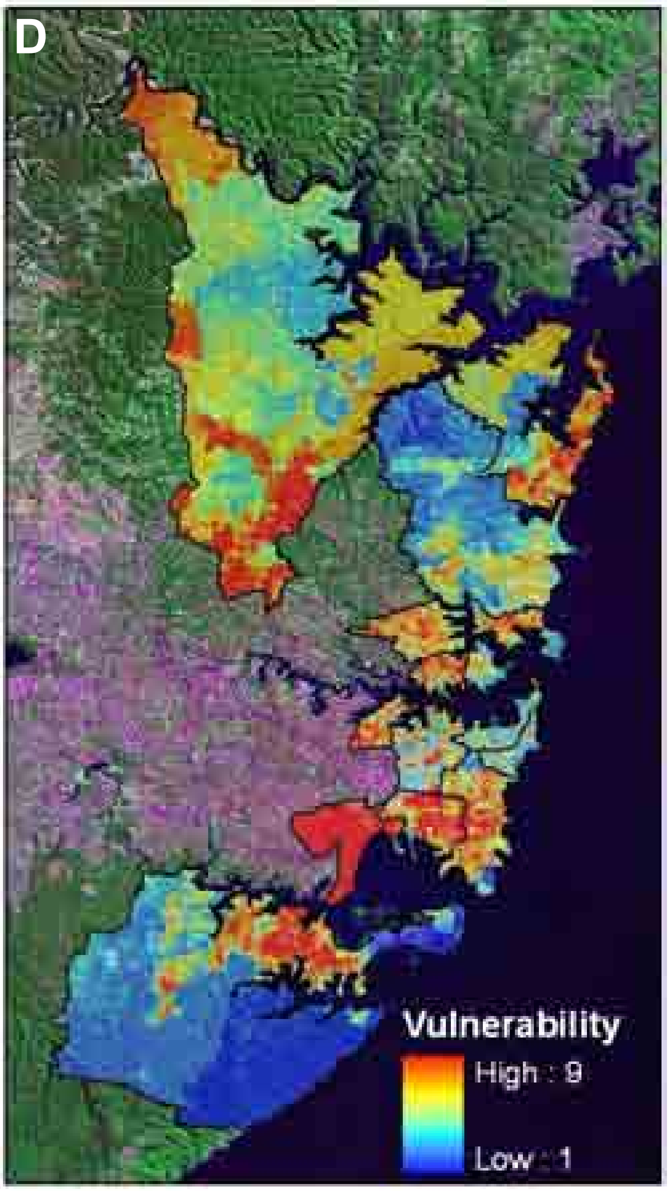
6.2.1 Exposure

The exposure component of coastal vulnerability logically indicates that plausible areas of exposure to coastal hazards are constrained by proximity to the coastline and topography (Figure 15, Figure 16). The vast majority of the region lies at elevations judged sufficiently high to prevent significant exposure. The areas of greatest exposure occurred around the low-lying areas in Councils surrounding Botany Bay (i.e., Botany Bay and Rockdale City Councils and Sutherland Shire Council) as well as the northern beaches from Manly Council to Warringah and Pittwater Councils. Exposure generally declined as one moves away from the coast or upstream, although one area in northern Hornsby Council along the Hawkesbury River was also identified as having a relatively high degree of exposure.

6.2.2 Sensitivity

The sensitivity of the SCCG region to coastal impacts was assessed for those areas identified as being plausible areas of exposure. Sensitivity was largely a function of development patterns that may place assets and populations in harm's way. In addition, some measures of sensitivity were directly associated with proximity to the coast, such as the presence of acid sulphate soils (ASS), due to the affect of ASS on the citing and design of buildings and infrastructure (including coastal defences). Therefore, the highly developed areas of Rockdale and Botany Bay Councils, Sydney Harbour, and Warringah and Pittwater Councils were judged to be the most sensitive. In contrast, northern Sutherland, though associated with significant exposure, was assessed as having relatively low sensitivity.

Figure 14. *Vulnerability of the SCCG region to extreme heat events and adverse health effects. Figures A, B, and C represent the three components of vulnerability: exposure, sensitivity, and adaptive capacity, respectively. D represents the integration of these components into net vulnerability. High values indicate a relatively high degree of vulnerability to future extreme heat events while low values indicate a low degree of vulnerability.*



6.2.3 Adaptive Capacity

The adaptive capacity of the SCCG region to coastal impacts indicated that well-resourced coastal Councils around central Sydney had the highest capacity to cope with their exposure and sensitivity to coastal hazards. However, this capacity declined as one moved north or south of Sydney or upstream. For example, the Councils surrounding Botany Bay including northern Sutherland Shire Council generally had lower levels of adaptive capacity. Rockdale and Botany Bay Councils in particular had very low adaptive capacity suggesting management of the coastal zone may be a particular challenge.

6.2.4 Vulnerability

When combined with their associated weights, the net vulnerability of the SCCG region's coastal zone is concentrated around the east coast from Manly to Pittwater Councils and, particularly, Botany Bay and Rockdale City Councils. For these latter Councils, their high vulnerability is function of multiple challenges including topography, high levels of development and low adaptive capacity. As a consequence, assets, infrastructure and coastal amenities (e.g., beaches) in vulnerable areas must be carefully managed in the future to protect both development and amenity. To this end, local governments' adaptive capacities and their ability to partner with each other and state government to achieve management goals may be particularly important.

6.3 Extreme Rainfall and Stormwater Management

6.3.1 Exposure

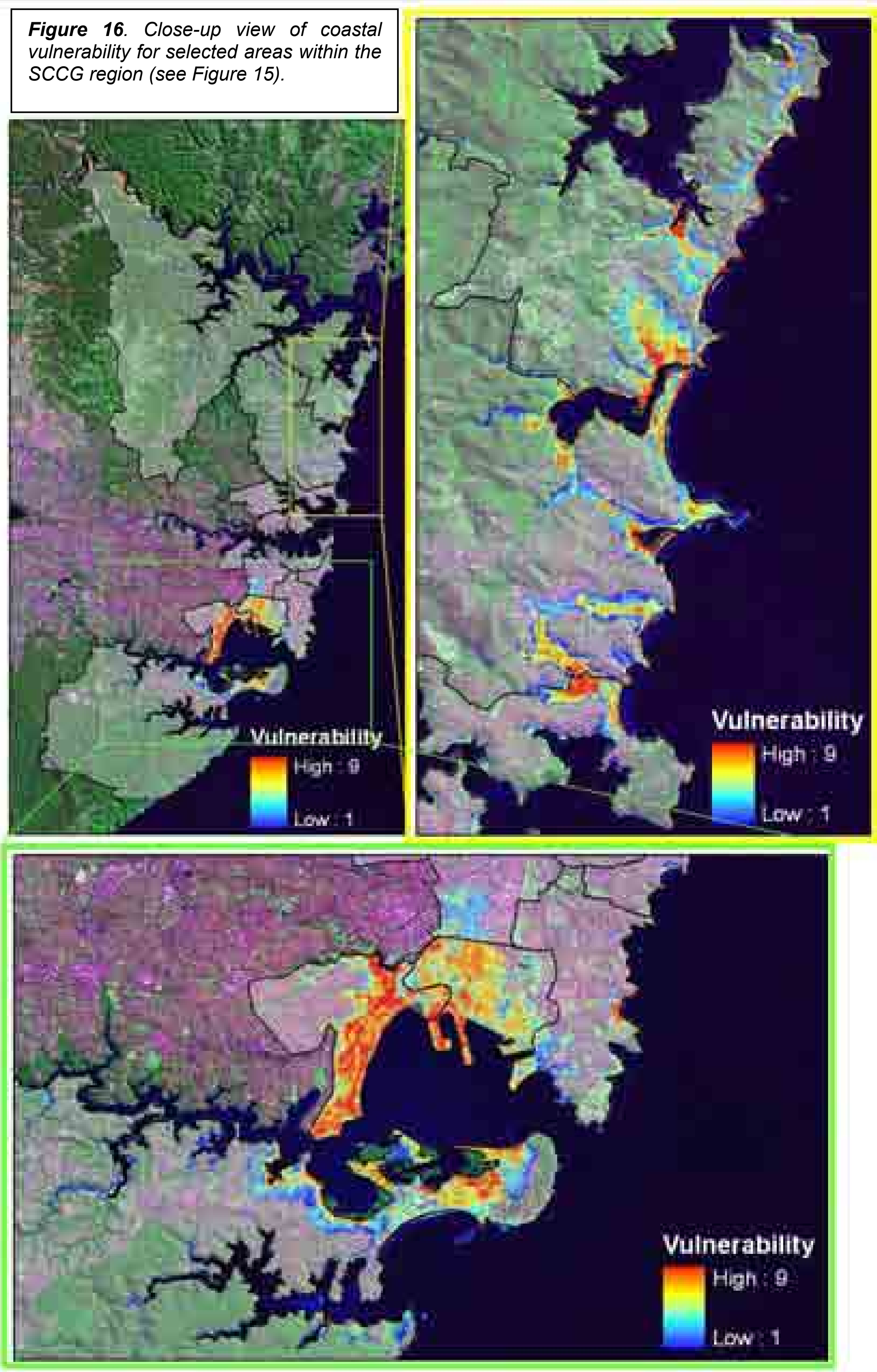
The exposure component of extreme rainfall suggested that exposure generally increases from west to east, with hotspots from Warringah and Pittwater Councils south across Sydney Harbour to Woollahra Council as well as southern Sutherland (Figure 17). These are regions where average annual rainfall as well 90th percentile rainfall is particularly high. Furthermore the Sydney Harbour to Botany Bay region is one where extreme rainfall events are projected to increase over the next few decades. Meanwhile, western Hornsby and western Sutherland Councils have the lowest exposure.

6.3.2 Sensitivity

The sensitivity of the SCCG region to extreme rainfall and the potential effects of the resulting stormwater runoff were largely associated with urban areas, due to their higher proportions of development and, subsequently, impervious surfaces (e.g., buildings and roads) that contribute to high rates of runoff. Hence, those Councils around the CBD as well as eastern Pittwater Council have relatively high sensitivity compared to the more rural and less developed areas of Sutherland and Hornsby Councils. However, the effects of topography resulted in a high degree of small-scale variability in vulnerability. Low-lying areas that act as collection points for runoff were located throughout the region.

Figure 15. *Vulnerability of the SCCG coastline to climate change, sea-level rise and storm surge events. Figures A, B, and C represent the three components of vulnerability: exposure, sensitivity, and adaptive capacity, respectively. D represents the integration of these components into net vulnerability. High values indicate a relatively high degree of coastal vulnerability to future sea-level rise and storm surge events while low values indicate a low degree of vulnerability. Areas greater than 16 metres in elevation have been excluded from the analysis. See Figure 16 for close-up views of key areas.*

***Figure 16**. Close-up view of coastal vulnerability for selected areas within the SCCG region (see Figure 15).*



6.3.3 Adaptive Capacity

The adaptive capacity of the SCCG region to address vulnerability to extreme rainfall events varied significantly from one location to another. Multiple indicators of capacity and Council performance suggest the most developed and urbanised areas of Sydney (including Warringah and Pittwater Councils to the north) have relatively greater wealth, education, and technical resources to invest in infrastructure to manage stormwater drainage. In particular, Councils in central Sydney north to Pittwater have a relatively high degree of adaptive capacity. In contrast, Hornsby Shire Council, Rockdale City Council and eastern Sutherland Shire Council were judged to have relatively limited adaptive capacity.

6.3.4 Vulnerability

When combined with their associated weights, the net vulnerability of the SCCG region to extreme rainfall and the resulting runoff is closely correlated with development patterns that contribute to impervious surface and high runoff rates. For example, Councils associated with central Sydney generally had high levels of vulnerability. Nevertheless, a number of less urbanised areas were also judged to be vulnerable including areas of eastern Hornsby and northeast Sutherland Shire Council. These hotspots were largely the product of high levels of exposure and/or topographies and development patterns that enhance the sensitivity of the landscape. Furthermore, there were areas of isolated high vulnerability scattered throughout southern Sutherland Council that were also due to the relatively high exposure of the region and localised topographic effects. Low vulnerability was largely restricted to far northern Hornsby, northern Warringah, and western Pittwater Councils along with western Sutherland Shire Council, although some areas of vulnerability were identified along the northern edge of Hornsby Council along the Hawkesbury River. In addition, these regional areas may remain vulnerable to riverine flooding, which was not assessed in this study.

6.4 Bushfire

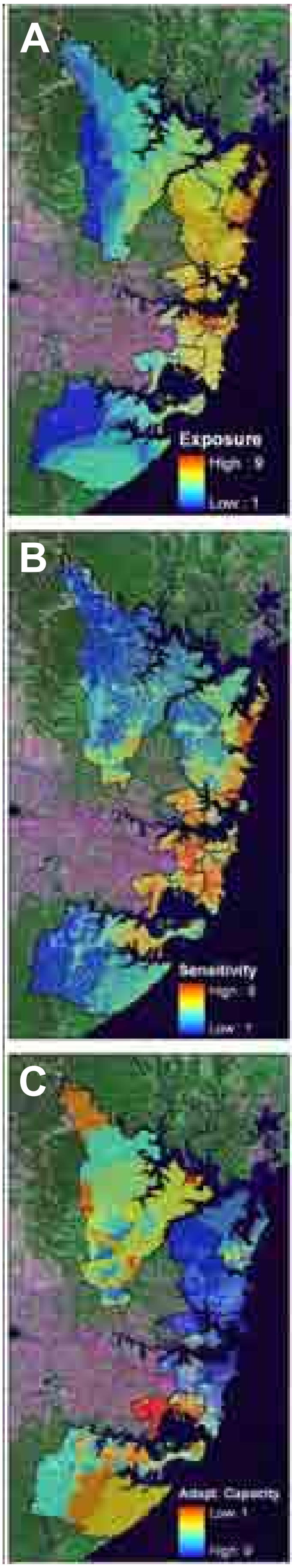
6.4.1 Exposure

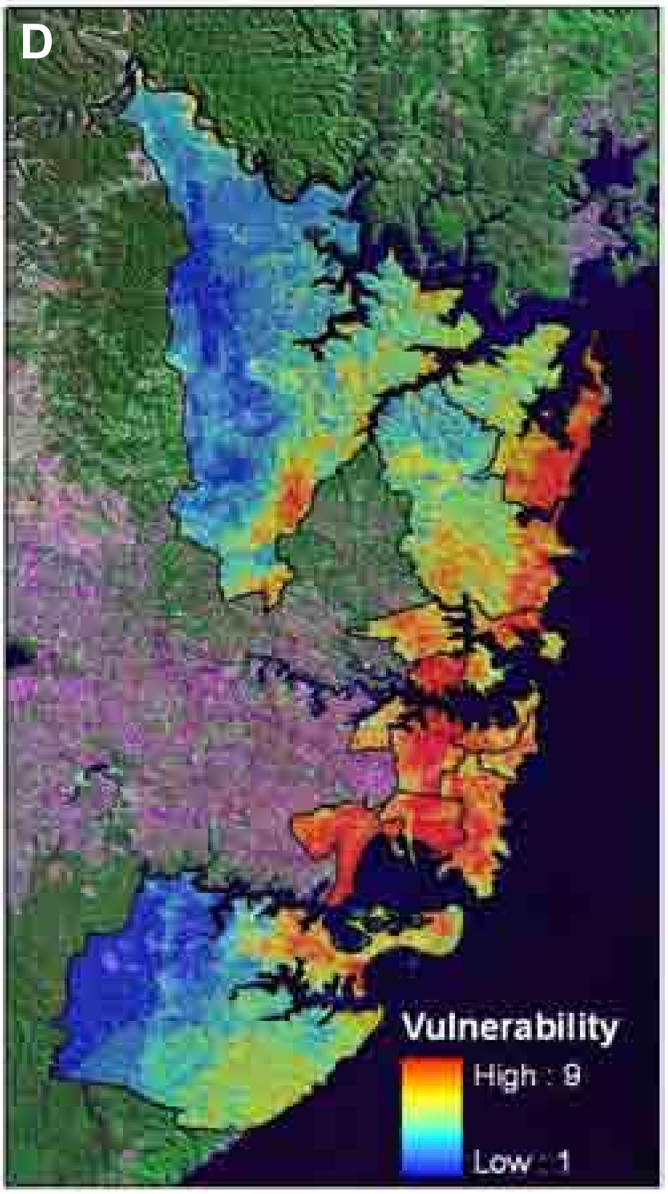
The exposure component of bushfire vulnerability suggests that exposure generally decreases from west to east, consistent with the exposure profile for extreme heat and health effects (Figure 18). Hotspots occur around western Hornsby and western Sutherland Shire Councils. These are regions where summer (DJF) temperatures are relatively high as are the number of days above 30°C. Meanwhile, average annual rainfall is low and these areas also are associated with some of the lowest values for 10^{th} percentile annual rainfall, increasing the risk of aridity. Meanwhile, much of the east of the SCCG region has relatively low exposure.

6.4.2 Sensitivity

Areas of the SCCG region that were identified as being particularly sensitive to bushfire generally occurred in rural areas, including northern Hornsby and Warringah Councils as well as western Pittwater and southern Sutherland Shire Councils. Dense development throughout much of the SCCG region, and central Sydney in particular, resulted in an overall relatively low sensitivity to bushfire for much of the region and the majority of Councils.

Figure 17. *Vulnerability of the SCCG region to extreme rainfall and resulting runoff. Figures A, B, and C represent the three components of vulnerability: exposure, sensitivity, and adaptive capacity, respectively. D represents the integration of these components into net vulnerability. High values indicate a relatively high degree of vulnerability to extreme rainfall events in the face of future climate change while low values indicate a low degree of vulnerability.*





6.4.3 Adaptive Capacity

Estimates of the adaptive capacity of the SCCG region to bushfire were generally similar to those for other impact areas. High adaptive capacity was identified in some of the wealthier inner-city Councils around central Sydney as well as Hornsby, Warringah and Pittwater Councils and western Sutherland Shire Council. The exceptions were Rockdale and Botany Bay Councils which are urbanised Councils with low adaptive capacity. Due to the importance of State government in managing and responding to bushfire risk, measures of household and Council adaptive capacity may not be particularly relevant. In more rural areas, however, it could be argued that household adaptive capacity could be quite important in decision-making regarding bushfire risk.

6.4.4 Vulnerability

When combined with their associated weights, net bushfire vulnerability for the SCCG region was closely correlated with available fuel loads as well as areas where climate conditions are projected to become more favourable for fire weather conditions. Hence, much of Hornsby Council was identified as being of considerably high vulnerability, with some moderate to high vulnerability in neighbouring Warringah and Pittwater Councils as well. The only other areas of significant vulnerability occurred in the south of the SCCG region in Sutherland Shire Council. Here, as with Hornsby, significant bushlands create a fire hazard, which is exacerbated by low adaptive capacity. However, projected changes in the climate are projected to be less severe as in the north.

6.5 Natural Ecosystems and Assets

6.5.1 Exposure

The exposure component of ecosystem vulnerability suggests that exposure increases from east to west (Figure 20). The greatest area of exposure was associated with Hornsby Council where the greatest increases in average annual, summer maximum and winter minimum temperatures are projected. In addition, changes in rainfall (predominately reductions) were also greatest in those SCCG Councils in the west of the region. As one moves closer to the coastline, the magnitude of projected climate change declines, with the Councils associated with central Sydney and eastern Sutherland Council having the lowest exposure.

6.5.2 Sensitivity

As the vulnerability of ecosystems was largely viewed in the context of resilience to disturbance, ecosystem sensitivity in the SCCG region was closely associated with urbanisation and land use, which also influenced water quality and land degradation. Sensitivity was greatest in the most urbanised Councils around the CBD and north of Sydney Harbour (e.g., North Sydney, Willoughby, Mosman and Manly Councils). Secondary hotspots occurred in southern Hornsby and eastern Pittwater Councils as well as the northern fringe of Sutherland Council. Resilience was deemed highest in those areas where development is minimal and significant bushland, native vegetation, and conservation lands occur such as northern Hornsby and Warringah Councils and southern Sutherland Shire Council.

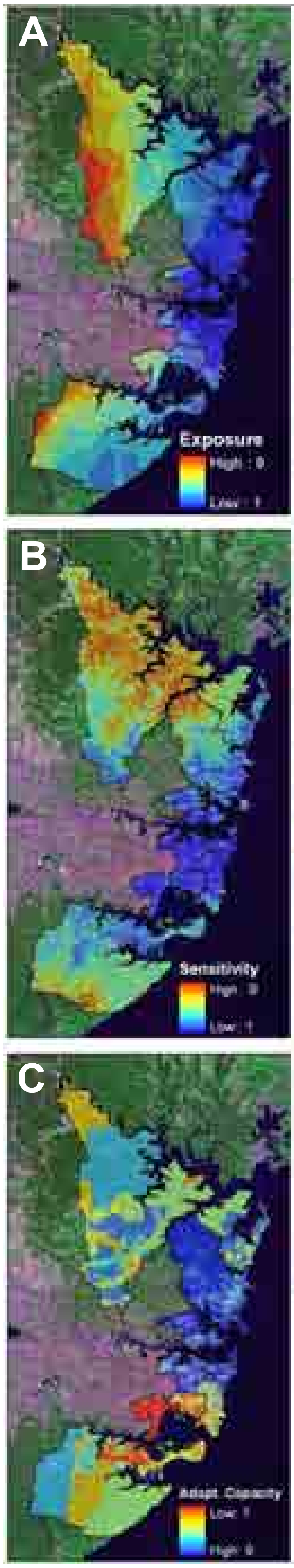
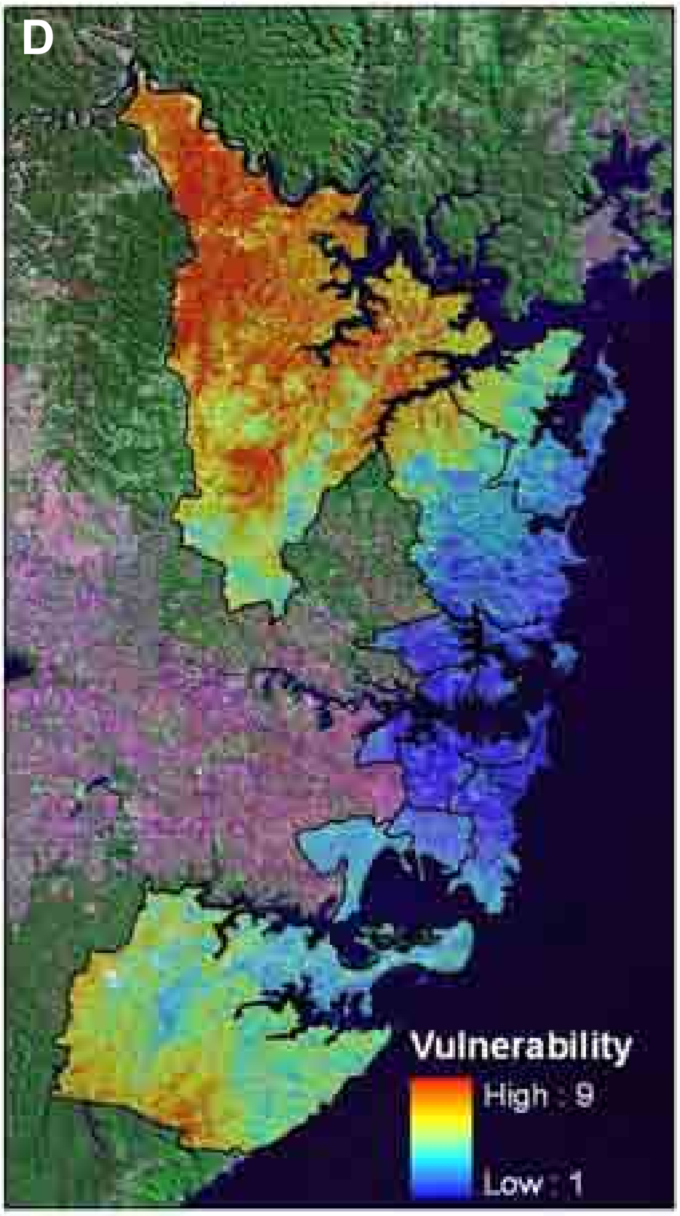


Figure 18. *Vulnerability of the SCCG region to bushfire. Figures A, B, and C represent the three components of vulnerability: exposure, sensitivity, and adaptive capacity, respectively. D represents the integration of these components into net vulnerability. Low values indicate low vulnerability to bushfire while high values indicate high vulnerability.*



Box 1. Validating Results of Vulnerability Assessments

The process of undertaking a vulnerability assessment can be a useful tool for communicating complexity and the diversity of determinants of vulnerability. However, another important consideration is the extent to which individual indicators and/or the assessment as a whole provides a plausible and, ideally robust, representation of vulnerability and risk. This raises the question of available methods by which assessment results can be validated against a given set of criteria and how well they perform in this regard. Validation of climate change vulnerability assessments is challenged by the fact that they tend to be forward-looking, and there are inherent uncertainties and unknowns about future states that cannot be validated. Given that the current state of affairs is often an important determinant of future vulnerability, as a minimum, there should be some level of consistency among spatial patterns of vulnerability at present and those that are estimated to be vulnerable in the future. Even this can be complicated by the fact that appropriate information by which to validate assessment results may not be readily available due to limited knowledge about the current nature or spatial distribution of risk. Here, we present an approach to validation of the bushfire vulnerability assessment, based upon two independent data sets.

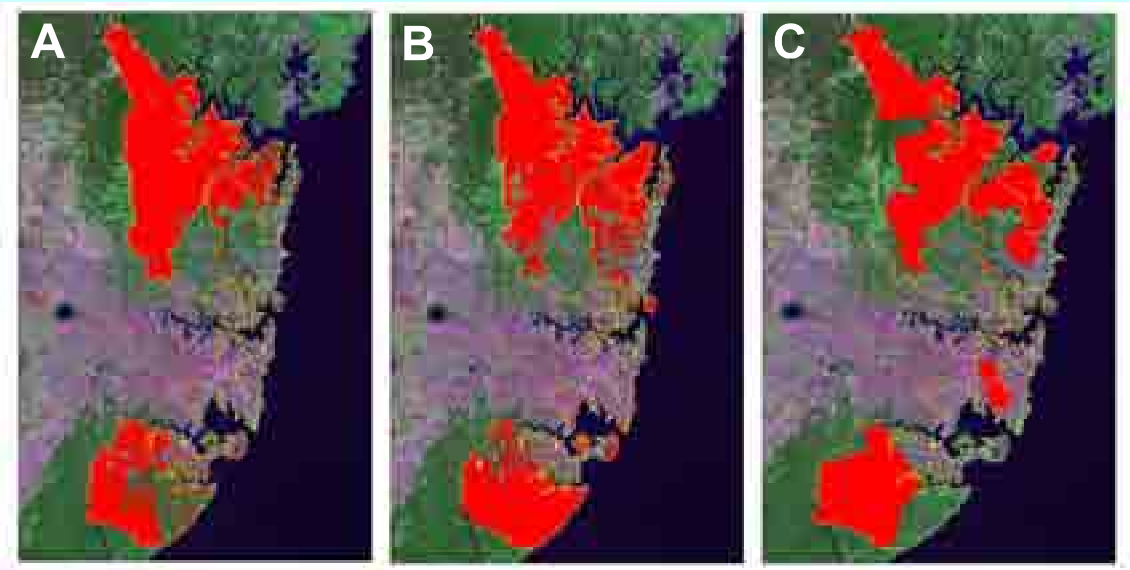


Figure 19. *Comparison of the assessment of bushfire vulnerability with other indicators of bushfire hazard. A) areas with moderate to high vulnerability as assessed in the current study. B) Bushfire hazard areas identified by local government planning overlays, vegetation mapping or land use. C) Pattern of bushfires (2000-2007) as detected by satellite.*

Validation against Local Government Bushfire Hazard Planning Schemes

As part of local government planning and risk management activities, a number of the local councils within the SCCG have developed and utilise bushfire hazard or bushfire management spatial data sets. Ten of the 15 Councils supplied digital geographic data (in vector polygon format) useful for the direct or indirect identification of bushfire hazard areas, while the remaining five either didn't undertake such assessments (due to the high levels of urbanisation) or did not provide such data to the investigators. Of the ten for which data were available, bushland areas at risk were identified based upon proxy information for four of the Councils, which were subsequently compared with regional Landsat satellite imagery to check for consistency.

For Randwick and Warringah, vegetation maps were used to identify at-risk areas. For Randwick, bushfire hazard areas corresponded with "remnant bushland vegetation," while hazard areas in Warringah corresponded with "Duffy's Forest", "sandstone gully forest," and "sandstone ridgetop woodland." For Sutherland and Woollahra Councils, bushfire hazard areas were estimated from land-use planning data. For Sutherland Council, relevant land uses included "national parks and nature reserves", "regional open space reservations," "environmental housing in bushland," "public open space bushland," and "special uses." For Woollahra, relevant land uses included "national parks and nature reserves."

The qualitative scores generated throughout the SCCG region were reclassified to identify all areas corresponding with the ten Council bushfire hazard data layers. Grid cells associated with scores of 5 to 9 (reflecting 'moderate' to 'very high' vulnerability) were assigned a value of 1, while all grid cells within the SCCG region that did not correspond with a bushfire management layer were assigned a value of 0. Meanwhile the data for bushfire hazard areas were converted to a grid and this grid was reclassified as above, with bushfire hazard areas assigned a value of 1 and all other areas assigned a value of 0 (Figure 19).

To quantitatively assess the level of agreement between the spatial pattern of vulnerability identified by the assessment and the Councils' bushfire hazard areas, Pearson's product moment pattern correlation was calculated for the two data sets (excluding those areas where LGA data for bushfire hazard areas were not available; Table 3). The result of 0.70 ($p<0.05$) indicates a relatively high degree of spatial correlation between the two data sets, despite differences in how they were derived. This provides evidence that the vulnerability assessment is yielding relatively robust results, even at fine spatial resolution of 90 metres.

Validation against Satellite Detections of Bushfires

A further validation test was conducted by comparing results of the vulnerability assessment with geographic data on the spatial distribution of actual bushfire events based upon seven years of remote sensing observations with the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite (Justice et al., 2002; NASA/UMD, 2002). MODIS fire detection data at 1 km resolution were obtained for the time period November 2000 through November 2007. The pattern of bushfire detections for the total time period was imported into ArcGIS 9.2 as an image file, which was subsequently georeferenced against the SCCG study area. A point density algorithm was then applied to this pattern of points to obtain an interpolated bushfire detection density data layer, and density values were scored on a scale from 1 to 9 by dividing the data into quantiles. This bushfire density layer was reclassified such that scores of 5 to 9 were assigned a value of 1 and all other scores were assigned a value of 0. The resulting data layer was assumed to represent those areas within the region where there was a 'moderate' to 'very high' degree of fire activity over the seven year period of observations (Figure 4). The pattern correlation between the vulnerable areas identified thorough the assessment process and those identified from MODIS data was calculated, with a result of 0.66 ($p<0.05$) (Table 3).

In addition, the correlation between bushfire hazard areas and fire detections was calculated, yielding a similar degree of correlation (0.69; $p<0.05$) (Table 3). The relative similarity among the three data sets with respect to their spatial pattern generally indicates that each provides a reasonable representation of vulnerability and risk. Given that the degree of correlation between two independent and commonly used indices of bushfire risk was quite similar to correlations between those data and the vulnerability assessment suggests that the pattern identified through the vulnerability assessment is about as robust a method as one might expect.

6.5.3 Adaptive Capacity

The adaptive capacity of the SCCG region to address the resilience of ecological communities suggests some significant ironies. Multiple indicators of capacity and Council performance suggest the most developed and urbanised areas of Sydney have the capacity to facilitate environmental management to conserve ecosystem resilience. Yet clearly, these are also areas where significant ecosystem degradation has already occurred and resilience is at a minimum indicating a fundamental limit to adaptation (Hulme et al., 2007). Low adaptive capacity, particularly in western Sutherland Council may contribute to future degradation of natural landscapes. Realistically, however, natural resource management functions are split among various tiers of government, with State government and the Catchment Management Authorities playing a critical role.

6.5.4 Vulnerability

When combined with their associated weights, the net vulnerability for the SCCG region's ecosystems and natural resources was closely correlated with the sensitivity component of vulnerability. The most vulnerable areas were southern Hornsby and southeast Pittwater Councils, Councils associated with central Sydney north and south of the harbour, and northern Sutherland Shire Council. Vulnerability within the region's peri-urban areas may be more critical as these represent transitional areas, where some natural amenity persists, but is under significant pressure. The high conservation value areas found throughout most of northern Hornsby and southeast Sutherland appear to be potential ecological refugia that may be most resilient to the effects of climate change. This suggests a potential strong need to continue to maintain the environmental health of these regions in the future.

6.6 Net Regional Vulnerability

The five individual maps of vulnerability for the different impact areas were subsequently combined using the stakeholder risk perceptions as integration weights to generate a view of overall regional vulnerability to climate change (Figure 21). This view certainly does not consider all aspects of climate change vulnerability, as it is limited to the vulnerability layers and associated impacts upon which it is based. Furthermore, it must be treated cautiously as it assumes that the different vulnerability scores are comparable and can be meaningfully combined, which is arguable. Nevertheless, it provides a quick snapshot of where the SCCG region's hotspots for vulnerability lie. The combination of various vulnerability layers results in a pattern that largely resembles the development patterns of metropolitan Sydney. The greatest regions of vulnerability are associated with population centres and dense development: southern Hornsby Shire Council, eastern Pittwater Shire Council, Sydney Harbour to Botany Bay (particularly Rockdale and Botany Bay City Councils), and northern Sutherland Shire Council. The drivers of this pattern are largely two-fold:

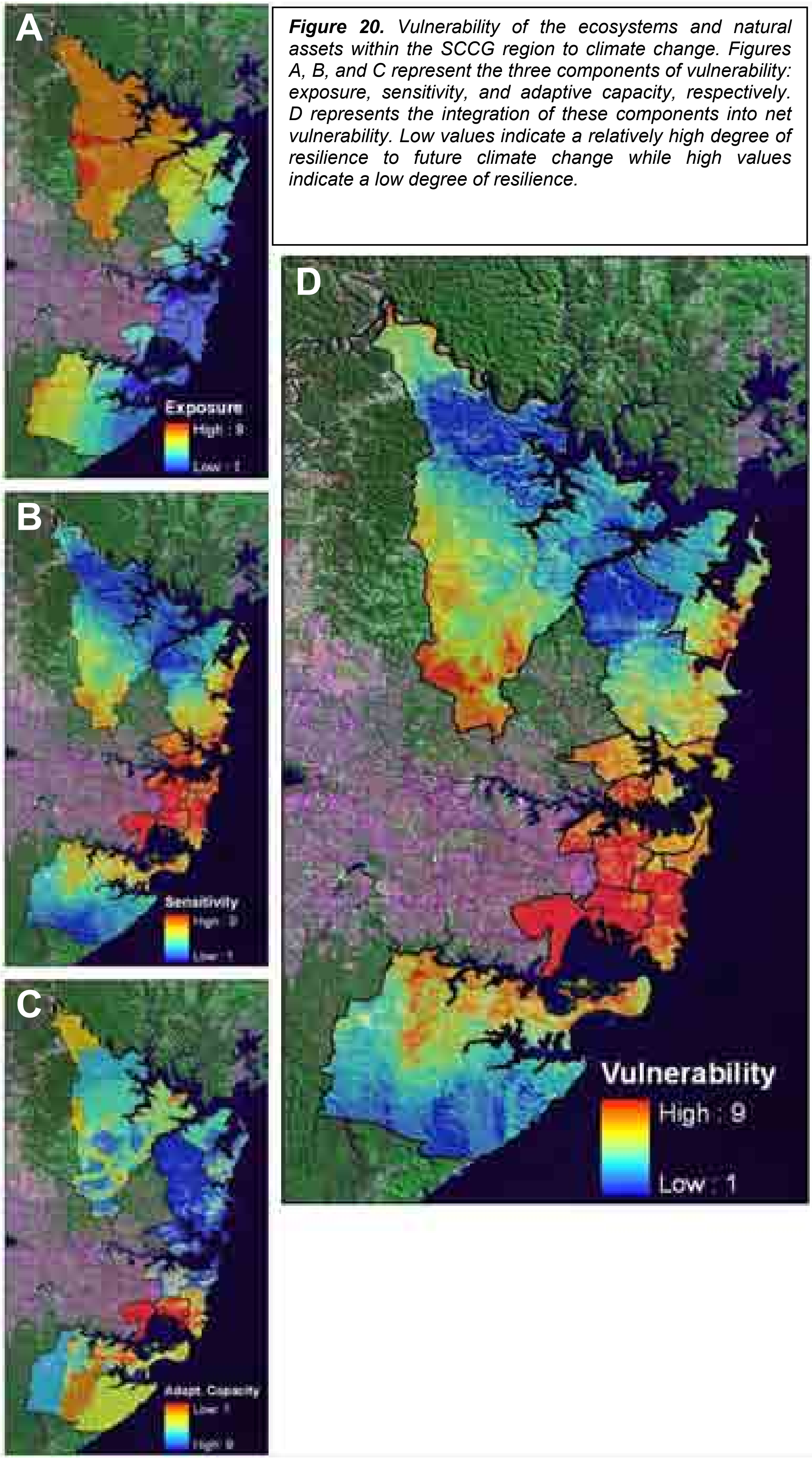


Figure 20. *Vulnerability of the ecosystems and natural assets within the SCCG region to climate change. Figures A, B, and C represent the three components of vulnerability: exposure, sensitivity, and adaptive capacity, respectively. D represents the integration of these components into net vulnerability. Low values indicate a relatively high degree of resilience to future climate change while high values indicate a low degree of resilience.*

1) Emphasis in the assessment of vulnerability on people and infrastructure in harm's way (e.g., extreme heat and coastal impacts) and/or development patterns that increase runoff or degrade ecosystems. These factors were generally associated with the sensitivity components of vulnerability.

2) The spatial distribution of adaptive capacity, which was relatively uniform among different impact areas, and therefore had a consistent and relatively significant influence on net vulnerability. In particular, this contributes significantly to overall vulnerability in southern Hornsby Council, Pittwater Council, Rockdale Council, Botany Bay Council and northern Sutherland Shire Council.

In contrast, the exposure component of vulnerability, though significant for individual impact areas, was highly variable from one impact to another. Extreme heat, bushfire, and ecosystem exposures were concentrated in the west of the SCCG region, extreme rainfall in the northeast, and coastal exposure along the coastal fringe. In the estimation of net vulnerability, the occurrence of regional winners and losers with respect to exposure offset one another to some extent, allowing the sensitivity and adaptive capacity drivers to dominate. This highlights the fact that despite the importance of climate variability and change in driving adverse consequences, the severity and capacity to cope with those consequences is the product of social and economic considerations.

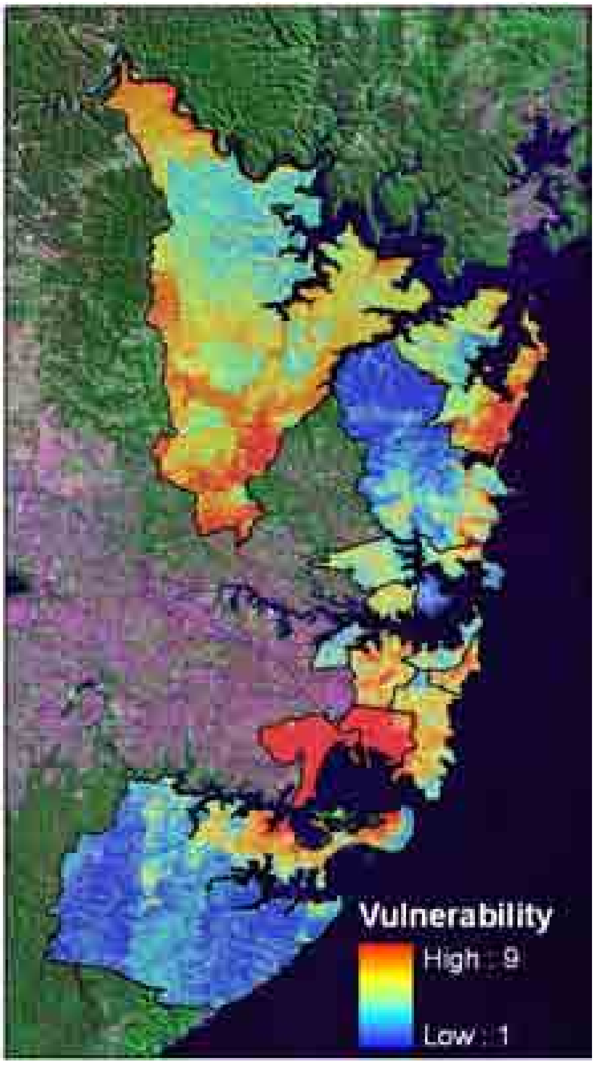


Figure 21. *Overall vulnerability of the SCCG region to climate change, based upon the vulnerability layers for the five impact areas. Low values indicate a relatively high degree of vulnerability to future climate change while low values indicate low vulnerability.*

7. Council-Specific Results

Chapter Summary

- ✓ ***When vulnerability maps were averaged over the 15 SCCG member Councils, a number of Councils stood out as being particularly vulnerable.***
- ✓ ***Overall, the inner-city Councils between Sydney Harbour and Botany Bay (i.e., Botany Bay, Leichhardt, North Sydney, Randwick, Rockdale and Sydney) had the highest levels of climate change vulnerability.***
- ✓ ***In contrast, Sutherland and Warringah Councils generally had relatively low levels of vulnerability.***
- ✓ ***Despite these generalisations, almost every Council had at least one impact area to which it had a high degree of vulnerability and at least one to which it was particularly resilient.***

The region-wide maps of vulnerability for the SCCG were averaged over the 15 SCCG member Councils to generate internally consistent, but Council-specific aggregate estimates of vulnerability for each of the five impact areas. An additional modifier was applied to sea-level rise vulnerability scores to account for the fact that the proportion of the land area plausibly exposed to sea-level rise and coastal processes varies from one Council to another. As such, the vulnerability scores generated by the combination of exposure, sensitivity and adaptive capacity for sea-level rise assessment were subsequently divided by the percentage of the Council's land area that fell with the exposure area (based upon the elevation limit). The resulting product was then rescored on a scale from 1 to 9 based upon quantiles.

A quick inspection of Table 11 reveals the relative importance of different vulnerabilities among the 15 Councils. For example, whereas vulnerability for bushfire is relatively low for the majority of Councils, for extreme rain events and ecosystems, vulnerability is relatively high for most of the SCCG Councils. Size disparities among different Councils accounted for some of the observed patterns of vulnerability. For example, despite extensive areas of land in the SCCG region being identified as vulnerable to bushfire (Figure 18), the majority of this land is concentrated in just a few Councils: Hornsby, Sutherland and Warringah Shire Councils, of which the first two are quite large. Therefore, the bulk of regional bushfire vulnerability as well as any associated responsibilities for management are isolated within a small number of Councils. Similarly, while the majority of Councils had significant localised vulnerability to sea-level rise and coastal hazards, the normalisation of the Councils' vulnerability scores to the proportion of the land area within Councils considered exposed to such hazards reduced vulnerability in a number of instances (e.g., particularly those with large geographic area relative to the extent of the coastline such as Hornsby, Warringah, and Sutherland Shire Councils). In contrast, ecosystem and extreme rainfall vulnerability were largely associated with multiple, small inner-city Councils, and thus efforts in regional conservation and storm water management are divided among a large number of institutions.

Table 11. Mean Vulnerability Scores for the 15 SCCG Councils.

Council	Impact Area					
	Extreme Heat	Sea-Level Rise	Extreme Rain	Bushfire	Ecosystems	Net
Botany Bay	7	9	8	2	9	9
Hornsby	6	1	4	7	4	5
Leichhardt	7	8	7	2	8	7
Manly	6	7	8	2	7	6
Mosman	4	3	7	1	7	4
North Sydney	7	2	9	1	8	7
Pittwater	6	5	7	4	5	6
Randwick	6	6	8	2	8	7
Rockdale	9	9	9	3	9	9
Sutherland	3	4	4	5	4	3
Sydney	5	8	8	1	8	7
Warringah	3	2	6	3	4	3
Waverley	4	4	7	1	7	5
Willoughby	7	1	7	2	7	6
Woollahra	4	6	8	1	7	5
Average	***6***	***5***	***7***	***3***	***7***	***6***
High values indicate a relatively high degree of vulnerability to future climate change while low values indicate low vulnerability. Colours reflect relative degrees of vulnerability, with blue (low vulnerability) associated with scores of 1 to 3, green (moderate vulnerability) with scores of 4-6, and red (high vulnerability) with scores of 7 to 9.						

The landscape diversity associated with large Councils creates the additional burden of having to cope with different types of vulnerability scattered over large geographic areas. Southern Hornsby has high ecosystem and extreme heat vulnerability, while bushfire vulnerability is greater in the north. Smaller, inner-city Councils are more homogenous, and thus benefit from a smaller number of vulnerabilities more evenly distributed over a smaller area. These issues of scale as well as the division of governance responsibilities likely have important implications for adaptation planning.

When the net vulnerability of Councils was considered, only Sutherland and Warringah Shire Councils stood out as having low vulnerability to the impacts of climate change. This is not to say that these Councils have no vulnerabilities, just that key vulnerabilities are few in number and/or are associated with a relatively small area relative to the size of the Council when compared with other parts of the SCCG region. These Councils benefit from relatively limited exposure to significant climatic changes, limited development of the landscape, and limited exposure to the Tasman Sea. Nevertheless, low levels of adaptive capacity in northern Sutherland Shire Council contribute to this being one of the SCCG region's vulnerability hotspots.

Those Councils associated with particularly high net vulnerability included Botany Bay, Leichhardt, North Sydney, Pittwater, Randwick, Rockdale and Sydney (Table 11). Overall these are relatively urbanised Councils with significant exposure to the coast, and for Botany Bay and Rockdale City Councils, with generally low adaptive capacity (particularly when compared with other Councils; see Appendix III). This demonstrates that urban landscapes are not necessarily immune to the effects of climate change. On the contrary, unless carefully managed, the greater the magnitude of population, wealth, assets and infrastructure, the larger the target for climate hazards.

8. Interpreting Vulnerability Maps

Chapter Summary

- ✓ ***Vulnerability maps should be interpreted in the context of the assumptions of the analysis and the limitations imposed by the methodology.***
- ✓ ***Here, vulnerability scores represent areas with a relatively greater or lesser burden of risk factors, but do not reflect predictions of absolute consequence or outcomes.***
- ✓ ***The most informative application of vulnerability estimates is to diagnose the various factors that contribute to a vulnerability.***

As discussed in Section 3, one drawback of using vulnerability to explore the implications of climate change and adaptation is the lack of a specific quantitative prediction of outcomes or impact. As a result, it is not always self-evident how measures of vulnerability should be interpreted. For example, one could readily view the vulnerability of the SCCG's natural ecosystems from two different perspectives. On one hand, one would be justified in identifying the more high conservation value areas of the region as the most vulnerable, in the sense that changes induced by climate change in these areas would have greater ecological significance than those in areas already disturbed by human activities and development. On the other hand, as is done here, one could view ecosystem vulnerability from the standpoint of which areas are likely to have the greatest inherent resilience and coping capacity to future climate change. In this light, the high conservation value areas are the least vulnerable, as they are relatively undisturbed and maintain some degree of natural ecosystem structure and function. A map of vulnerability based upon vulnerability framed from this latter point of view will look quite different from, and in fact may be in direct opposition to, one framed from the former perspective (see also Box 2). Therefore, vulnerability maps must be interpreted cautiously in the context of the conceptual model and framework used to generate the estimates of vulnerability.

One must also be cautious in how one interprets 'high' or 'low' estimates of vulnerability. First and foremost, it is important to remember that vulnerability reflects potential susceptibility to harm, but does not necessarily mean that adverse outcomes may occur nor does it communicate the magnitude or severity of the outcome. Vulnerability estimates should not be viewed here in such absolute terms, but rather in a more relative context. For example, areas identified as being of high vulnerability are presumed to have a greater likelihood of experiencing an adverse impact than those of low vulnerability, even if the nature, absolute probability, or severity of the impact remains unknown. Therefore, vulnerability cannot necessarily provide information on where a hazard management planning overlay should be placed or where development should be restricted, but it can aid in identifying areas where such issues require further examination and investigation.

Perhaps the most informative application of vulnerability estimates is to diagnose the various factors that contribute to a vulnerability score (Adger and Vincent, 2005; Smit and Wandel, 2007), rather than focusing on the score itself. For example, some areas may be vulnerable due to a significant exposure to a climate hazard, while the vulnerability of other areas may lie in the lack of adaptive capacity to manage the consequences of such hazards. Hence, areas may be equally vulnerable, but that vulnerability may be driven by different causes that require different management and adaptive strategies. The deconstruction of vulnerability into its individual components and even individual indicators is likely to be useful in building a greater understanding of the particular issues facing a given area or local government. In fact, the serial construction and deconstruction of vulnerability using different assumptions, indicators and methods would probably be a useful exercise for diagnosing critical issues affecting the future implications of climate change and the adaptive management of climate risk. This mindset was taken-up and utilised as a core principle in the communication of vulnerability maps to SCCG stakeholders.

9. Stakeholder Responses to Vulnerability Mapping

Chapter Summary

- ✓ ***Through a series of workshops with the SCCG member Councils, stakeholders were provided the opportunity to review and comment on the results of the vulnerability analysis and associated maps.***
- ✓ ***Stakeholder feedback suggested the approach taken to mapping vulnerability offered a number of advantages, particularly with respect to readily communicating the spatial dynamics of risk as well as the diversity of factors that contribute to vulnerability.***
- ✓ ***Nevertheless, a number of challenges were identified in communicating the vulnerability assessment including stakeholder preoccupation with scores, failure to incorporate information stakeholders considered relevant, and difficulties in meeting expectations of stakeholders with respect to perceptions and provision of solutions.***

Vulnerability maps were presented to stakeholders in all 15 of the SCCG member Councils through a variety of methods. The primary vehicle was a 45 minutes presentation to Council stakeholders that provided an overview of the concepts of vulnerability, methods utilised in the current vulnerability assessment, and regional as well as Council-specific results (in short, an overview of the material contained within this report). These presentations focused on the diversity of drivers that may contribute to vulnerability rather than the resulting scores generated by the analysis.

Stakeholders were encouraged to provide feedback during and after the presentation, and were presented with the opportunity to provide follow-up comments at any point after the workshops. Such feedback was used to identify perceived inconsistencies in the estimates of vulnerability. This led to review of the various indicators utilised and in some instances revisions of the analysis. Through this process, a number of strengths and challenges of the assessment stood out as being particularly relevant to future assessment applications and their use in conjunction with stakeholders. These are discussed in more detail on subsequent pages.

Box 2. Comparison of Objective and Subjective Council Vulnerability Scores

In addition to the vulnerability scores calculated for individual Councils based upon mapping of vulnerability across the five impact areas, Council staff were independently surveyed to obtain their initial subjective perceptions of vulnerability and adaptive capacity (Figure 22; Appendix VI). This provided an independent evaluation of vulnerability based upon a different approach and criteria, which provides an interesting comparison to the vulnerability mapping (see also Box 1). For example, sea-level rise was identified as the area of greatest vulnerability relative to adaptive capacity across Councils (Figure 22). However, as with the case of bushfire, a number of Councils perceived their adaptive capacity to be high relative to their vulnerability. The correlation between the objective assessment of vulnerability from vulnerability mapping and these subjective perceptions of Councils (average value for vulnerability among survey participants) was moderately high for three areas: sea-level rise, extreme rainfall, and bushfire (Table 12). However, vulnerability mapping generated divergent estimates for extreme heat events and natural ecosystems in particular.

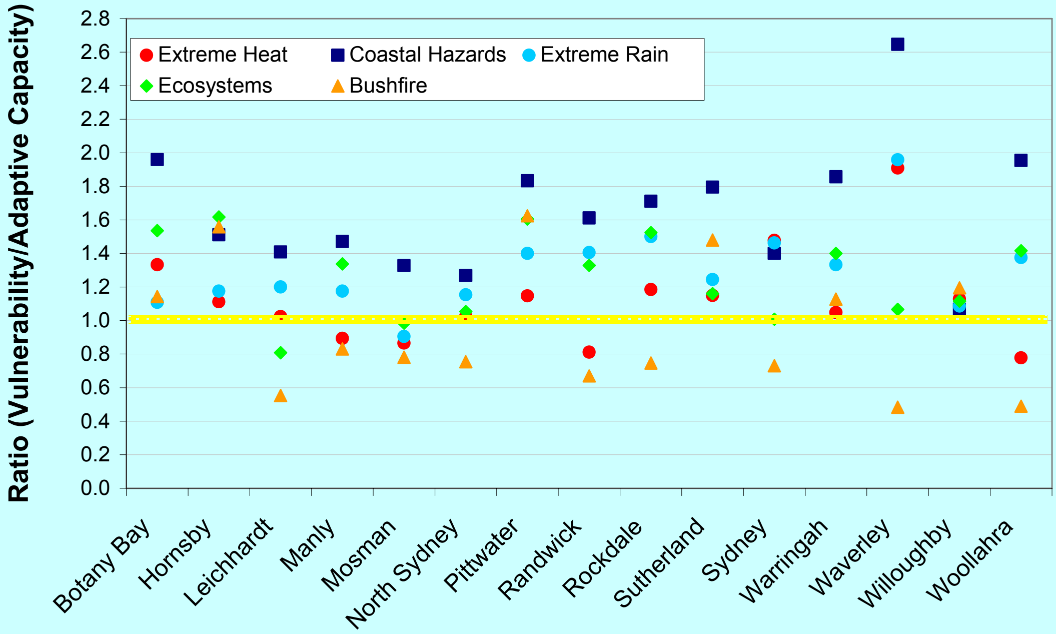


Figure 22. *Stakeholder perceptions of vulnerability from the 15 SCCG member Councils. Vulnerability is expressed as the ratio of mean vulnerability to mean adaptive capacity, based upon survey results from Council staff (Appendix VI). Values greater than 1 indicate that mean vulnerability scores were greater than the mean scores for adaptive capacity, suggesting the impact may be a challenge for Council. Values less than 1 indicate adaptive capacity is greater than vulnerability, suggesting Councils feel they have an adequate capacity to cope with a particular hazard or impact.*

A number of explanations can be offered for the level of agreement/disagreement. First, some Councils noted that assessing vulnerability was a difficult task. Participants were not given a prior briefing on definitions of vulnerability, were not allowed to view vulnerability maps, and were not instructed on the manner in which to assess vulnerability (e.g., relative or absolute basis and/or against what baseline). This largely explains the divergent estimates for vulnerability associated with extreme heat events and ecosystems. For the former, some respondents reported low vulnerability due to the proximity of the SCCG region to the coastline, overlooking the fact that heat-related mortality is nevertheless an annual occurrence in the region (Woodruff et al., 2005). For the latter, ecosystem vulnerability was likely associated with having significant ecosystem assets and natural landscapes. Hence, urbanised areas were assigned low vulnerability due to a paucity of natural assets, while more rural areas were perceived as having more assets that could be in harm's way.

In contrast, coastal vulnerability as well as vulnerability to bushfire and extreme rain events were more consistent with objective vulnerability measures from mapping, due to the more intuitive nature of vulnerability as well as the benefit of past experience. For example, those communities on the coast and/or with more coastal frontage are likely to perceive a higher vulnerability to sea-level rise and coastal hazards. Similarly those rural areas with more bushland and which have experienced significant bushfire events in recent years are more likely to perceive bushfire vulnerability to be high.

Table 12. Comparison between Council Vulnerability Scores and Council Self-Reported Perceptions of Vulnerability

Impact Area	Correlation[a]
Extreme heat	-0.09
Sea-level rise	0.42
Extreme rainfall	0.40
Bushfire	0.70
Natural ecosystems	-0.44

[a] *Correlation represents the level of agreement between the aggregate vulnerability scores calculated for each Council as part of this assessment and Council stakeholders' self-reported perceptions of vulnerability. Values greater than 0.51 are statistically significant at the 95% confidence level.*

Sample size=159

While this comparison provides some real-world validation of some of the vulnerability mapping, in that some results were consistent with the perceptions of local governments with local knowledge, it also highlights the high degree of disparity that can result from different ways of framing and/or assessing vulnerability. This represents a potential challenge in not only communicating climate change vulnerability and risk, but also adaptation, which will likely be driven by a combination of objective indicators but also subjective perceptions of risk.

9.1 Strengths

1) The concept of mapping vulnerability created significant interest among stakeholders, with some citing this as a principle motivation for attending the workshops. The combination of spatially explicit information in a visual format had obvious appeal. It also enabled stakeholders to readily compare analysis results with their own subjective perceptions of vulnerability given local knowledge of the landscape and how it responds to natural hazards.

2) Some stakeholders noted that the vulnerability-based approach offered the opportunity to think about vulnerability and risk in a novel manner. Specifically, stakeholders cited the value in thinking about the importance of different drivers, some of which were not ones typically considered. In particular, there was interest in the assessment of adaptive capacity and its incorporation as an integral part of vulnerability, as this was a novel framework for thinking about vulnerability and risk for many stakeholders.

3) Stakeholders appreciated the complexity of the vulnerability assessment in its incorporation of a diverse array of indicators and drivers. Though challenging to

comprehend and perhaps overwhelming without more detailed guidance, it proved effective in communicating the diversity of factors that could potentially influence vulnerability.

4) There was obvious interest in thinking more about how vulnerability assessments could be expanded. For example, it was proposed that the vulnerability maps could be used to expand existing geographic data sets and mapping tools within Councils, further examine assets and resources falling within different vulnerability categories (which may be an approach for better harmonising the concepts of vulnerability and risk), communicate with Council stakeholders, and undertaken additional analyses focused exclusively on individual Councils.

9.2 Challenges

1) The spatially explicit nature of vulnerability maps invariably led to stakeholder focus on areas identified as high or low vulnerability and associated semi-quantitative scores. Multiple Councils expressed concern about public or political responses to scores that were perceived to be either too high or too low, and particularly the risk of decision-makers drawing erroneous conclusions about risk and the allocation of management resources. This created the potential for stakeholders to deviate into thinking about the assessment as a final product or output, as opposed to an introduction into thinking about complex systems. Facilitators often led inquiries and questions in this regard toward a discussion of the drivers of vulnerability maps and highlighting the underlying questions that shape vulnerability. Disagreement and question-raising was encouraged.

2) As evidenced by the survey of stakeholder perceptions of vulnerabilities (Box 2), there often appeared to be differences in perceptions of vulnerability between stakeholders and the vulnerability assessment. Regionally, this appeared to stem from differences in how vulnerability was framed, although more fundamental discrepancies were observed at more local scales. Experienced hazard managers struggled with the incorporation of adaptive capacity or other socio-economic indicators into vulnerability assessment. In addition, differences emerged regarding whether vulnerability should be based upon geographic areas or people and assets at-risk. Facilitators attempted to be inclusive, acknowledging the validity of different framing methods, reiterating the assumptions of the current study, and acknowledging that other valid methods could yield different outputs.

3) Stakeholders sometimes struggled with the concept of relative risk, assuming that significant differences in relative risk necessarily translate into significant differences in absolute risk. This often contributed to disparities in stakeholder and investigator perceptions of risk (above), particularly at the local level.

4) Stakeholders were also able to identify a number of variables or potential indicators that were not reflected in the analysis (e.g., non-resident populations or small-scale policy or management decisions) due to lack of readily available data or ignorance among investigators regarding its importance. Facilitators acknowledged apparent limitations of the analysis and stakeholders were encouraged to incorporate such information into their own mental models of systems and their vulnerability.

5) A number of stakeholders raised the issue of weights associated with individual indicators or components of vulnerability (exposure, sensitivity, and adaptive capacity). Although stakeholders did not object to the weights that were utilised, they were quick to recognise the potential importance of differential weighting of individual indicators.

6) The attempt to conduct a top-down objective assessment of vulnerability invariably overlooked institutional cultures and local contextual knowledge that can have a profound influence on perceptions of vulnerability and adaptive capacity as well as the effectiveness with which management decisions can be implemented. Therefore, objective measures of adaptive capacity may have little relationship with subjective perceptions.

7) Some stakeholders retreated to a position of expecting ‘experts’ to provide ‘solutions’. With such an expectation, vulnerability assessment was judged inadequate as its emphasis on expansionist views of complexity and diversity of drivers was inconsistent with the desired outcome of reductionist identification of explicit impacts and management solutions delivered by external experts.

10. Conclusions and Discussion

Chapter Summary

- ✓ ***Vulnerability assessments should be interpreted within the context of the conceptual models, frameworks, and assumptions in which they were conducted. While vulnerability does not predict specific outcomes or their likelihoods, it can prove beneficial for identifying and diagnosing the drivers of vulnerability and their interactions.***

- ✓ ***Without being overly prescriptive regarding the significance and meaning of the vulnerability maps, a number of robust conclusions can be drawn. Climate change vulnerability varies significantly across the SCCG landscape and this vulnerability is often dominated by socio-economic factors. In addition, the insight gained through the process of executing a vulnerability assessment may often be just as useful, if not more, than the results of the assessment itself.***

The addition to its role as a communication tool for engaging with local governments, the execution of the assessment reported here raises a number of questions that could and should be addressed through future research efforts (see Box 3). Despite the need for further investigation, the following conclusions emerge as robust outcomes of the mapping exercise that may prove to be useful messages for the SCCG member Councils:

1) There is significant spatial variability throughout the SCCG region with respect to climate change vulnerability. Not only does vulnerability vary from Council to Council, it also varies from city block to city block and, realistically, from household to household.

    a) The relative vulnerability of different areas to climate change varies considerably depending upon the consequences under consideration. This is predominantly a function of different areas being more or less exposed and/or the sensitivity of the exposed population or system shifting depending on the consequence.

b) Almost every Council has at least one area of critical vulnerability that may be a focal point for management efforts. Similarly, every Council has at least one impact to which it appears to be particularly resilient. Generally, however, the majority of Councils appear to face multiple vulnerabilities.

c) The vulnerabilities of urban, peri-urban, and rural communities vary significantly. While urban communities are particularly vulnerable to extreme rainfall and suffer from limited ecosystem resilience, rural communities are particularly vulnerable to the effects of bushfire. Meanwhile, transitional communities such as outer suburbs appear most vulnerable to heat-related health effects.

d) Spatial scale and the fragmentation of vulnerability may create challenges for managing risk. Large Councils must manage vulnerability to diverse impacts occurring over large spatial areas. Meanwhile, regional impacts that are fragmented among large numbers of Councils may confound attempts to harmonise effective response strategies.

2) Despite accounting for the significant changes in the climate system projected for the region in the decades ahead, the social and economic circumstances of the SCCG landscape emerge as key factors affecting future vulnerability.

   a) For most impact areas, vulnerability was closely correlated with human development patterns, indicating human agency and decision-making as core components of vulnerability. The placement of people, wealth and infrastructure in areas exposed to climate hazards combined with ecosystem alternations that reduce resilience account for a significant fraction of observed vulnerability. Such exposure to natural hazards is the legacy of past decision-making, highlighting the importance of thinking long-term about future management decisions.

3) Despite the deliberate bias against adaptive capacity in the weighting of components of vulnerability, adaptive capacity nevertheless proved to be important in influencing vulnerability in certain areas. In particular, the very low levels of adaptive capacity identified for Rockdale City and Botany Bay City Councils and northern Sutherland Shire Council consistently interacted with the exposure and sensitivity of these areas to enhance vulnerability. This suggests these may be high priority areas for targeting efforts to improve adaptive capacity.

4) A number of qualities of the vulnerability assessment and mapping lend themselves well to communicating with stakeholders. However, care must be exercised in the presentation of vulnerability and stakeholders must be guided in the interpretation of results. Furthermore, challenges will invariably arise due to real or perceived inconsistencies between assessed vulnerability and stakeholder beliefs. Transparency in addressing such challenges and providing stakeholders the opportunity to suggest potential revisions is essential to securing stakeholder buy-in of the assessment process.

5) Arguably, the true value of vulnerability mapping is the insight that is gained through the process of conducting the assessment. While the final results may indeed be useful for

identifying and prioritising at-risk areas, building an understanding of different systems and how they respond to and interact with climate change and other drivers is ultimately a limiting step in developing and implementing robust adaptation strategies. Hence, vulnerability assessment alone, without a 'learning-by-doing' ethos and/or a concerted effort to work with stakeholders in the communication and decomposition of vulnerability, is likely of limited utility in developing a rigorous understanding of adaptive capacity or the pursuance of adaptive decision-making.

Box 3. Key Research Questions Emerging from this Study

The learning associated with the execution of this vulnerability assessment in conjunction with the aforementioned conclusions raises a number of research questions that could be profitably targeted by future research efforts. Although the following list is likely not exhaustive, it highlights some key considerations.

1) What is an appropriate framework for assessing and communicating vulnerability? Should researchers continue to rely upon constructs such as exposure, sensitivity and adaptive capacity in participatory environments, or should these concepts be translated and incorporated into more traditional hazard models to ease stakeholder communication?

2) What are the data and information requirements for conducting a vulnerability assessment? How much information is required to achieve different goals and what are appropriate/relevant indicators that can be used for vulnerability assessment?

3) What is the relative importance of different components or individual indicators of vulnerability (i.e., significance of climate versus landscape characteristics versus adaptive capacity) and to what extent can more rigorous statistical treatment of vulnerability indicators aid in their prioritisation and integration?

4) How do researchers and stakeholders quantify and manage the uncertainties inherent in vulnerability assessment in using assessment outcomes for prioritisation and decision-making? To what extent can vulnerability assessments be validated to build confidence in their representations of future states?

5) At what scale should vulnerability assessments be conducted to provide useful information to stakeholders? Is the tendency to pursue increasingly high-resolution data and assessment outputs warranted or necessary to inform stakeholders about vulnerability and risk?

6) What is the relationship between climate change vulnerability and the risk of adverse consequences? Is there utility for stakeholders in the identification of spatial areas associated with greater susceptibility to adverse impacts, or are efforts better invested in developing tools fore more predictive analyses of specific outcomes (natural hazards, economic damages, or social consequences) and their probabilities?

REFERENCES

Abbs, D., Aryal, S., Campbell, E., McGregor, J., Nguyen, K., et al. (2006) *Projections of Extreme Rainfall and Cyclones*. Report to the Australian Greenhouse Office, Canberra, Australia, 97 pp.

ABS (Australian Bureau of Statistics) (1999) *Population Projections, Australia, 1996 to 2021*. Cat. No. 3222.0, Canberra, Australia.

Adger, W.N., Brooks, N., Kelly, M., Bentham, G., Agnew, M., and Erisen, S (2004) *New Indicators of Vulnerability and Adaptive Capacity*. Technical Report Number 7, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

Adger, W.N. and Vincent, K. (2005) Uncertainty in adaptive capacity. *C.R. Geoscience* 337, 399-410.

Allen Consulting. (2005) *Climate Change Risk and Vulnerability*. Australian Greenhouse Office, Department of the Environment and Heritage, Canberra, Australia, 159 pp.

Australian Standards (2004) *Australian Standard: Risk Management*. Council of Standards Australia and Council of Standards New Zealand, AS/NZA 4360:2004, Standards Association of Australia, Strathfield, NSW, Australia.

Callaghan, J. (2007) *Tropical Cyclone Impacts along the Australian East Coast from November to April 1867 to 2000*. Bureau of Meteorology, Brisbane, QLD.

BMBMC (Blue Mountains Bushfire Management Committee) (2000) *Bushfire Risk Management Plan*. Prepared by the Bushfire Management Committee of New South Wales, Sydney, 86 pp.

CSIRO and BOM (Bureau of Meteorology) (2007) *Climate Change in Australia*. CSIRO and the Bureau of Meteorology. Melbourne, VIC, in preparation.

Bogardi, J.J., Billagran, J.C., Birkmann, J., Renaud, F., Sakulski, D., Chen, X., Affeltranger, AB., Mensa, A., and Kaplan, M. (2005) Vulnerability in the context of climate change. *Human Security and Climate Change: An International Workshop*, Oslo, 21-23 June, 2005.

Bradstock, R.A., Gill, A.M., Kenny, B.J., and Scott, J. (1998) Bushfire risk at the urban interface estimated from historical weather records: consequences for the use of prescribed fire in the Sydney region of south-eastern Australia. *Journal of Environmental Management* 52, 259-271.

Bridgman, H., Warner, R., and Dodson, J. (1995) *Urban Biophysical Environments*. Oxford University Press, Oxford, UK, 152 pp.

BOM (Bureau of Meteorology) (2006) *The Australian Baseline Sea Level Monitoring Project: Annual Sea Level Data Summary Report, July 2006-June 2006*. National Tidal Centre, Kent Town, SA, Australia, 40 pp.

Bronstert, A., Niehoff, D., and Bürger, G. (2002) Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. *Hydrological Processes* 16, 509-529.

Brooks, M.L. and Esque, T.C.. (2002) Alien annual plants and wildfire in desert tortoise habitat: status, ecological effects, and management. *Chelonian Conservation and Biology* 4, 330-340.

Brooks, M., Matchett, J., Wallace, C., and Esque, T. (2004) Fuels mapping and fire hazard assessment in a desert ecosystem. *Arid Lands*, May/June.

Brooks, N., Adger, W.N., Kelly, P.M. (2005) The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change* 15, 151-163.

Brown, T.J., Hall, B.L. and Westerling, A.L. (2004) The impacts of 21st century climate change on wildland fire danger in the western United States: an application perspective. *Climatic Change* 62, 365-388.

Buechley, R.W., Van Bruggen, J., and Truppi, L.E. (1972) Heat island equals death island? *Environmental Research.* 5, 85-92.

BTE (Bureau of Transport Economics) (2001) *Economic Costs of Natural Disasters in Australia*. Report 103, Bureau of Transport Economics, Commonwealth of Australia, Canberra.

Burke, E.J., Brown, S.J., and Christidis, N. (2006) Modelling the recent evolution of global drought and projections for the twenty first century with the Hadley Centre climate model. *Journal of Hydrometeorology* 7, 1113-1125.

Centers for Disease Control (1981) Heatstroke – United States: 1980. *MMWR* 30, 277-279.

Carlson, T.N. and Arthur, S.T. (2000) The impact of land use — land cover changes due to urbanization on surface microclimate and hydrology: a satellite perspective. *Global and Planetary Change* 26, 49-65.

Chen, X.-L., Zhao, H.-M., Li, P.-X., and Yin, Z.-Y. (2006) Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote Sensing of Environment* 104, 133-146

Chen, W. and Zhou, G. (2004) Comparison of the effects of selected variables on urban surface temperature. *IEEE International Geoscience and Remote Sensing Symposium*, Anchorage, Alaska, USA.

Chapman, D. (2000) Hazardous Sydney. In J. Connell (ed), *Sydney: The Emergence of a World City*. Oxford Unviersity Press, South Melbourne, Victoria, Australia.

Church, J.A. and White, N.J. (2006) A 20^{th} century acceleration of sea-level rise. Geophysical Research Letters 33, L01602, doi:10.1029/2005GL024826

Clark, I. (1979) *Practical Geostatistics*. Applied Science, London, UK.

Clarke, J.F. (1972) Some effects of the urban structure on heat mortality. *Environmental Research* 5, 93-104.

Coutis, A.M., Beringer, J., and Tapper, N.J. (2007) Impact of increasing urban density on local climate: spatial and temporal variations in the surface energy balance in Melbourne, Australia. *Journal of Applied Meteorology and Climatology* 46, 477-493.

Cowell, P.J., Thom, B.G., Jones, R.A., Everts, C.H., and Simanovic, D. (2006) Management of uncertainty in predicting climate-change impacts on beaches. *Journal of Coastal Research* 22, 232-245.

CSIRO and BOM (Bureau of Meteorology) (2007) *Climate Change in Australia: Technical Report 2007*. CSIRO Marine and Atmospheric Research and Bureau of Meteorology, Melbourne, VIC, Australia.

DNR (Department of Natural Resources) (2006) *NSW Department of Natural Resources Annual Report 2005-06*. Government of New South Wales, Sydney, Australia, 113 pp.

DNR (Department of Natural Resources) (2007) *Estuaries in NSW: Physical Characteristics and Behaviour*. Available at http://www.dnr.nsw.gov.au/estuaries/factsheets/physical/tidal-behaviour.shtml.

Dixon, P.G., Brommer, D.M., Hedquist, B.C., Kalkstein, A.J., and Goodrich, G.B., et al (2005) Heat mortality vs. cold mortality: a study of conflicting databases in the United States. *Bulletin of the American Meteorological Society* 7, 937-943.

Easterling III, W.E., Hurd, B.H., and Smith, J.B. (2004) *Coping with Global Climate Change: The Role of Adaptation in the United States.* Pew Centre on Global climate Change, Arlington, VA, USA, 39 pp.

Erten, E., Kurgun, V., and Musaoglu, N. (2004) Forest fire risk zone mapping from satellite imagery and GIS. A case study. International Society for

Photogrammetry and Remote Sensing, XXth ISPRS Congress, Istanbul, Turkey, 12-23 July 2004.

Fowler, H.J. and Kilsby, C.G. (2006) Implications of changes in seasonal and annual extreme rainfall. *Geophysical Research Letters* 30, NO. 13, 1720, doi:10.1029/2003GL017327

Füssel, H.-M., Klein, R.J.T. (2006) Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change* 75:301-329.

Gillen, M. (2005) Urban vulnerability in Sydney: policy and institutional ambiguities in bushfire protection. *Urban Policy and Research* 23, 465-476.

Goldammer, J.G. and Price, C. (1998) Potential impacts of climate change on fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightning model. *Climatic Change* 39, 273-296.

Guest, C.S., Wilson, K., Woodward, A.J., Hennessy, K., Kalkstein, L.S., et al. (1999) Climate and mortality in Australia: retrospective study, 1979-1990, and predicted impacts in five major cities in 2030. *Climate Research* 13, 1-5.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., and Medina-Elizade, M. (2006) Global temperature change. *Proceedings of the National Academies of Science, USA* 103, 14288-14293.

Hennecke, W.G. (2004) GIS modelling of sea-level rise induced shoreline changes inside coastal re-entrants - two examples from southeastern Australia. *Natural Hazards* 31, 253-276.

Hennessy, K., Page, C., McInnes, K., Jones, R., Bathols, J., Collins, D., and Jones, D. (2004a) *Climate Change in New South Wales. Part 1. Past Climate Variability and Projected Changes in Average Climate*. Consultancy report for the New South Wales Greenhouse Office by CSIRO and the Australian Bureau of Meteorology.

Hennessy, K., Page, C., McInnes, K., Jones, R., Bathols, J., Collins, D., and Jones, D. (2004b) *Climate Change in New South Wales. Part 2. Projected Changes in Climate Extremes*. Consultancy report for the New South Wales Greenhouse Office by CSIRO and the Australian Bureau of Meteorology.

Hennessy, K.J. Lucas, C., Nicholls, N., Bathols, J., Suppiah, R., and Ricketts, J. (2005) *Climate Change Impacts on Fire-Weather in Southeast Australia*. CSIRO Atmospheric Research. Consultancy report jointly funded by the Commonwealth of Australia and the governments of New South Wales, Victoria, Tasmania, and the Australian Capital Territory, 91 pp.

Howden, S.M., Reyenga, P.J., and Gorman, J.T. (1999) *Current Evidence of Global Change and its Impacts: Australian Forests and Other Ecosystems*. CSIRO Wildlife and Ecology Working Paper 99/01, 23 pp.

Hulme, M., Adger, W.N., Dessai, S., Goulden, M., Lorenzoni, I., Nelson, D., Naess, L.-O., Wolf, J., Wreford, A. (2007) *Limits and Barriers to Adaptation: Four Propositions.* Tyndall Briefing Note No. 20, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK.

IPCC (Intergovernmental Panel on Climate Change) (2001a) *Climate Change 2001: The Scientific Basis.* Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 881 pp.

IPCC (Intergovernmental Panel on Climate Change) (2001b) *Climate Change 2001: Impacts and Adaptation*. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1000 pp.

IPCC (Intergovernmental Panel on Climate Change) (2002) *Climate Change and Biodiversity*. Technical Paper V. H. Gitay, A. Suárez, R.T. Watson, and D.J. Dokken (eds), IPCC Secretariat, Geneva, Switzerland, 85 pp.

IPCC (Intergovernmental Panel on Climate Change) (2007) *Climate Change 2007: The Physical Science Basis. Summary for Policymakers*. Contribution of Working Group I to the

Third Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, Switzerland, 21 pp.

IDRO (International Disasters Response Organisation) (2006) *Major Disasters Since June 1967 - Revised to March 2006.* Accessed 14 April 2006.

ISO (2002) *Risk management. Vocabulary. Guidelines for Use in Standards*. Guide 73:2002, International Organization for Standardization, Geneva, Switzerland.

Jarvis, A., Rubiano, J., Nelson, A., Farrow, A., and Mulligan, M. (2004) *Practical Use of SRTM Data in the Tropics: Comparisons with Digital Elevation Models Generated from Cartographic Data*. Centro Internacional de Agricultura Tropical, Cali, Colombia, 32 p.

Kalkstein, L.S. and Greene, J.S. (1997) An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change. *Environmental Health Perspectives* 105, 84-93.

Kleinosky, L.R., Yarnal, B., and Fisher, A. (2006) Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea-level rise. *Natural Hazards* 40, 43-70.

Lawson and Treolar (2004) *Estuarine Planning Level Mapping: Pittwater Estuary*. Report Prepared for Pittwater Council, Lawson and Treolar Pty Ltd, Gordon, NSW.

Lindley, S.J., Handley, J.F., Theuray, N., Peet, E., and McEvoy, D. (2006) Adaptation strategies for climate change in the urban environment: assessing climate change related risk in UK urban areas. *Journal of Risk Research* 9, 543-568.

Liu, Z. and Todini, E. (2002) Towards a comprehensive physically-based rainfall-runoff model. *Hydrology and Earth System Sciences* 6, 859-881.

MHL (Manly Hydraulics Laboratory) (1991) *Storm Surges Monitored along the New South Wales Coast March-April 1990*. Report MHL 591, Public Works Department, New South Wales.

Martens, W.J.M. (1998) Climate change, thermal stress and mortality changes. *Social Science and Medicine* 46, 331-344.

McInnes, K.L. and Hubbert, G.D. (2001) The impact of eastern Australian cut-off lows on coastal sea levels. *Meteorological Applications* 8, 229-243.

McInnes, K.L., Macadam, I., Hubbert, G.D., Abbs, D.J., and Bathols, J. (2005) *Climate Change in Eastern Victoria, Stage 2 Report: The Effect of Climate Change on Storm Surges*. A consultancy report undertaken for the Gippsland Coastal Board by the Climate Impacts Group, CSIRO Atmospheric Research, Aspendale, VIC, Australia, 37 pp.

McMichael, A., Woodruff, R., Whetton, P.H., Hennessy, K., Nicholls, N., Hales, S., Woodward, A., and Kjellstrom, T. (2003) *Human Health and Climate Change in Oceania: A Risk Assessment*. Commonwealth Department of Health and Ageing, Canberra, Australia.

Metzeger, M.I.J., Leemans, R., Schröter, D. (2005) A multidisciplinary multi-scale framework for assessing vulnerability to global change. International *Journal of Applied Earth Observation and Geoinformation* 7, 253-267.

Minnery, J.R. and Smith, D.I. (1994) Climate change, flooding and urban infrastructure. *Australian-New Zealand Conference on Climate Change*, Wellington, New Zealand.

Minnery, J.R. and Smith, D.I. (1996) Climate change, flooding and urban infrastructure. In W.J. Bouma, G.I. Pearman, and M.R. Manning (eds), *Greenhouse: Coping with Climate Change*. CSIRO Publishing, Collingwood, Victoria, Australia, pp. 235-247.

NOAA (National Oceanic and Atmospheric Administration) (2007) Trends in Atmospheric Carbon Dioxide. Available at http://www.esrl.noaa.gov/gmd/ccgg/trends/.

NSW (2006) *Comparative Information on NSW Local Government Councils 2004/2005.* Department of Local Government, Government of New South Wales, Sydney. J

O'Brien, K., Leichenko, R., Kelkar, U.I., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., West, J. (2004) Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change* 14, 303-313.

Office of the Prime Minister (2003) *Statistical Evidence to Support the Housing Health and Safety Rating System. Volume II – Summary of Results.* University of Warwick, London School of Hygiene & Tropical Medicine, London, UK, 75 pp.

Page, C.M. and Jones, R.N. (2001) OzClim: the development of a climate scenario generator for Australia. *Modelling and Simulation Society of Australia and New Zealand*, Canberra.

Parmesan, C., and Galbraith, H. (2004) *Observed Impacts of Global Climate Change in the United States*. Pew Centre on Global Climate Change, Arlington, VA, USA, 56 pp.

Patt, A., Klein, R.J.T., de la Vega-Leinert, A. (2005) Taking the uncertainty in climate-change vulnerability assessment seriously. *C.R. Geoscience* 337, 411-424.

Patz, J.A., McGeehin, M.A., Bernard, S.M., Ebi, K.L., Epstein, P.R. (2001) Potential consequences of climate variability and change for human health in the United States. Chapter 15 in *US National Assessment of the Potential Consequences of Climate Variability and Change.* U.S. Global Change Research Program, Washington, DC.

Pearce, G., Mullan, A.B., Salinger, M.J., Opperman, T.W., Woods, D. and Moore, J.R. (2005) *Impact of Climate Variability and Change on Long-Term Fire Danger.* Report to the New Zealand Fire Service Commission, 75 pp.

Pickering, C.M., Good, R., and Green, K. (2004) *Potential Effects of Global Warming on the Biota of the Australian Alps*. A report for the Australia Greenhouse Office.

Port of Melbourne Authority (1992) *Victorian Coastal Vulnerability Study*. Coastal Investigations Unit, Port of Melbourne Authority, Port Melbourne, VIC.

Preston, B.L. (2007) *Climate Change in the Sydney Metropolitan Catchments*. Prepared by CSIRO Marine and Atmospheric Research for the New South Wales Greenhouse Office, Sydney, NSW, Australia, 12 pp.

Rahmstorf, S. (2006) A semi-empirical approach to projecting future sea-level rise. *Science* 315, 368-370.

Sarewitz, D., Pilke Jr, R., Keykhah, M. (2003) Vulnerability and risk: some thoughts from a political and policy perspective. *Risk Analysis* 23, 805-810.

Scheers-Masters, J.R., Schootman, M., Thach, B.T. (2004) Heat stress and sudden infant death syndrome incidence: a United States population epidemiologic study. *Paediatrics* 113, e586-e592.

Schreider, S.Y., Smith, D.I., and Jakeman, A.J. (2000) Climate change impacts on urban flooding. *Climatic Change* 47, 91-115.

Semenza, J.C., McCullough, J.E., Flanders, W.D., McGeehin, M.A., Lumpkin, J.R. (1999) Excess hospital admissions during July 1995 heat wave in Chicago. *American Journal of Preventive Medicine* 16, 269-277.

Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, W.D., Howe, H.L., and Wilhelm, J.L. (1996) Heat-related deaths during the July 1996 heat wave in Chicago. *New England Journal of Medicine* 335(2), 84-90.

Sharples, C., (2004) *Indicative Mapping of Tasmania Coastal Vulnerability to Climate Change and Sea Level Rise: Explanatory Report*. Department of Primary Industries, Water & Environment (Tasmania), 126 pp.

Siegenthaler, U., Stocker, T.F., Monnin, E., Luthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fisher, H., Masson-Delmotte, V., and Jouzel, J. (2005) Stable carbon cycle-climate relationship during the late Pleistocene. *Science* 310, 1313-1317.

Smit, B. and Wandel, J. (2006) Adaptation, adaptive capacity and vulnerability. *Global Environmental Change* 16, 282-292.

Smith, D.I. (1998) Urban flood damage under greenhouse conditions: what does it mean for policy? *Australian Journal of Emergency Management* 13(2), 56-61.

Smoyer, K.E. (1998) Putting risk in its place: methodological consideration for investigating extreme event health risk. *Social Science and Medicine* 47(11), 1809-1824.

Spahni, R., Chappellaz, J., Stocker, T.F., Loulergue, L., Hausammann, G., Kawamura, K., Fluckiger, J., Schwander, J., Raynaud, D., Masson-Delmotte, V., and Jouzel, J. (2005) Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* 310, 1317-1321.

State of Victoria (2004) *Adapting to Climate Change: Enhancing Victoria's Capacity*. Victoria Department of Sustainability and Environment, East Melbourne, Victoria, Australia. Available at: http://www.greenhouse.vic.gov.au/impacts/Consultation_Paper_14_07.pdf

Steffen, W., Sanderson, A., Tyson, P., Jäger, J., Matson, P., Moore, B., III, Oldfield, F., Richardson, K., Schellnhuber, H-J., Turner, BL., II, and Wasson, R. (2004) *Global Change and the Earth System: A Planet Under Pressure*. IGBP Global Change Series. Springer-Verlag, Berlin, Heidelburg, New York.

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wooton, B.M. *et al* (1998) Climate change and forest fire potential in Russian and Canadian boreal forests. *Climatic Change*, 38, 1-13.

Thorton, P.K., Jones, P.G., Owiyo, T., Druska, R.L., Herrero, M., et al. (2006) Mapping climate vulnerability and poverty in Africa. Report to the Department of International Development, ILRI, Nairobi, Kenya.

Titus, J.G. and Richman, C. (2001) Maps of lands vulnerable to sea level rise: modelled elevations along the US Atlantic and Gulf coasts. *Climate Research* 18, 205-228.

Thieler, E.R., Williams, J., and Hammar-Klose, E. (2000) *National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast*. U.S. Geological Survey, Open-File Report 99-593, Woods Hole, USA.

Tol, R.S.J. (2006) Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science and Policy* 8, 572-578.

Turner II, B.L., Kasperson, R.E., Matson, P.A. et al (2006) A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academies of Science USA* 100, 8074-8079.

UK NHS (United Kingdom National Health Service) (2005) *Heatwave Plan for England: Protecting Health and Reducing Harm from Extreme Heat and Heatwaves*. National Health Service, London, UK.

Vandentorren, S., Bretin, P., Zeghnoun, A. Mandereau-Bruno, L. Croisier, A. *et al* (2006) August 2003 heat wave in France: risk factors for death of elderly people living at home. *European Journal of Public Health* 16, 583-591.

Voice, M., Harvey, N. and Walsh, K. (Eds.) (2006) *Vulnerability to Climate Change of Australia's Coastal Zone: Analysis of Gaps in Methods, Data and System Thresholds*. Report to the Australian Greenhouse Office, Canberra, Australia.

Wessel, P. and Smith W.H.F., (1996) A global self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research, 101*, 8741-8743, 1996.

White, G.F. (1974) *Natural Hazards: Local, National, Global*. Oxford University Press, New York, USA, 288 pp.

Woodruff, R., Hales, S., Butler, C., and McMichael, A. (2005) *Climate Change Health Effects in Australia: Effects of Dramatic CO2 Emission Reductions*. Report for the Australian Conservation Foundation and the Australian Medical Association, Canberra, Australia, 44 pp.

WMA (Webb, McKeown, and Associates) (2005) *Green Square and West Kensington (Sheas Creek-Victoria Branch) Flood Study*. City of Sydney and Randwick City Councils, Webb, McKeown, and Associates Pty Ltd, Sydney, NSW.

Wotton, B.M., Martell, D.L. and Logan, K.A. (2003) Climate change and people-caused fire occurrence in Ontario. *Climatic Change* 60, 275-295.

Yang, L., Guang, C., Homer, C.G., Wylie, B.K., and Coan, M.J. (2003) An approach for mapping large-area impervious surfaces: synergistic use of Landsat-7 ETM+ and high spatial resolution imagery. *Canadian Journal of Remote Sensing* 29, 230-240.

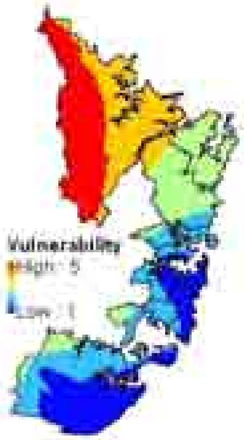
Yeo, S.W. (2002) Flooding in Australia: a review of events in 1998. *Natural Hazards* 25, 177-191.

Yohe, G., Neumann, J., and Marshall, P. (1999) The economic damage induced by sea level rise in the United States. In R. Mendelsohn and J.E. Neumann (eds), *The Impact of Climate Change on the United States Economy*. Cambridge University Press, New York, NY, pp 178-208.

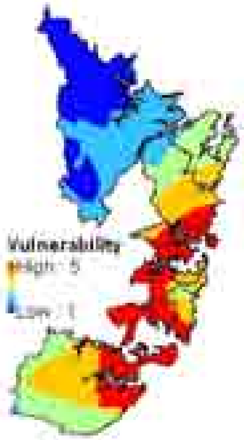
APPENDIX I. VULNERABILITY DATA LAYERS

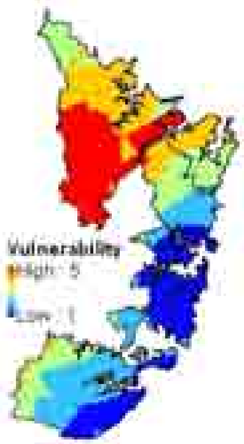
This appendix contains further information regarding the data utilised as indicators of vulnerability for different impacts in the SCCG region. Each indicator is identified along with the original source of the data, the impact areas for which it was used and why it was used. Regional maps illustrating the distribution of different indicators across the SCCG region are also presented, with areas in red associated with a relatively high contribution to overall vulnerability (reflecting high exposure, high sensitivity or low adaptive capacity) and areas in blue associated with a relatively low contribution to overall vulnerability (reflecting low exposure, low sensitivity or high adaptive capacity).

EXPOSURE LAYERS

<table>
<tr><th colspan="3">Present Average January Maximum Temperature</th></tr>
<tr><td colspan="3">Source: Original data were derived from BOM stations in and around the SCCG region. Station data were interpolated to yield a gridded estimate of temperature across the 15 SCCG member Councils.[7]</td></tr>
<tr><th>Indicator Map</th><th>Impact Area</th><th>Justification</th></tr>
<tr><td rowspan="2">
</td><td>Extreme Heat and Health Effects</td><td>Indicator of the relative differences in high temperatures across the SCCG region.</td></tr>
<tr><td>Bushfires</td><td>Indicator of the relative differences in high temperatures across the SCCG region that contribute to fire weather.</td></tr>
</table>

[7] *See Appendix IV.*

Present Average January Minimum Temperature		
Source: *Original data were derived from BOM stations in and around the SCCG region. Station data were interpolated to yield a gridded estimate of temperature across the 15 SCCG member Councils.*[7]		
Indicator Map	**Impact Area**	**Justification**
	Extreme Heat and Health Effects	Indicator of the relative differences in the urban heat-island effect across the SCCG region.

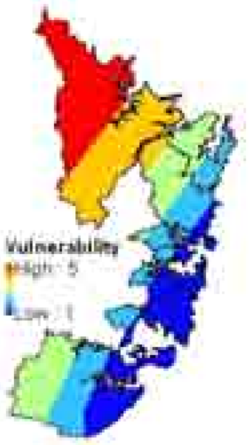
Present Average Annual Days>30 degrees		
Source: *Original data were derived from BOM stations in and around the SCCG region. Station data were interpolated to yield a gridded estimate of temperature across the 15 SCCG member Councils.*[7]		
Indicator Map	**Impact Area**	**Justification**
	Extreme Heat and Health Effects	Indicator of the relative differences in the variability of extreme temperatures across the SCCG region.

<table>
<tr><th colspan="3">Projected Change in Average DJF Maximum Temperature in 2030</th></tr>
<tr><td colspan="3">Source: Original data were derived from the OZCLIM scenario generator (v.2).[8] An estimate of projected temperature change was based upon average results from 10 climate models utilising three climate sensitivities and three emissions scenarios.</td></tr>
<tr><th>Indicator Map</th><th>Impact Area</th><th>Justification</th></tr>
<tr><td rowspan="3">
</td><td>Extreme Heat and Health Effects</td><td>Indicator of future increases in maximum summer daily temperatures in 2030 that will affect the severity of future extreme heat events.</td></tr>
<tr><td>Bushfire</td><td>Indicator of future increases in maximum summer daily temperatures in 2030 that will affect fire weather.</td></tr>
<tr><td>Ecosystems and Natural Resources</td><td>Indicator of increase in summer maximum temperatures that may affect species distributions</td></tr>
</table>

[8] *See Page and Jones (2001).*

Projected Change in Average Annual Temperature in 2030

Source: *Original data were derived from the OZCLIM scenario generator (v.2).*[8] *An estimate of projected temperature change was based upon average results from 12 climate models utilising three climate sensitivities and three emissions scenarios.*

Indicator Map	Impact Area	Justification
	Ecosystems and Natural Resources	Indicator of the change in average annual temperatures that will affect ecosystem structure and function.

Projected Change in JJA Minimum Temperature in 2030

Source: *Original data were derived from the OZCLIM scenario generator (v.2).* [8] *An estimate of projected temperature change was based upon average results from10 climate models utilising three climate sensitivities and three emissions scenarios.*

Indicator Map	Impact Area	Justification
	Ecosystems and Natural Resources	Indicator of the change in average winter minimum temperatures that will affect the lower temperature constrain on species distributions.

Present Average Annual Rainfall		
Source: *Original data were derived from BOM stations in and around the SCCG region. Station data were interpolated to yield a gridded estimate of temperature across the 15 SCCG member Councils.*[7]		
Indicator Map	**Impact Area**	**Justification**
	Extreme Rainfall and Storm Water Management	Indicator of the spatial distribution of annual rainfall that affects total runoff.
	Bushfire	Indicator of the spatial distribution of annual rainfall that affects landscape aridity that contributes to fire conditions.

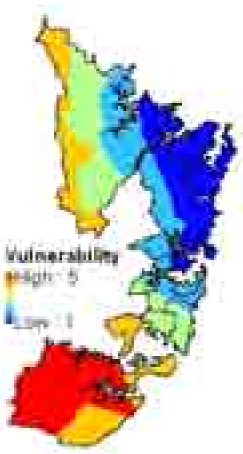
Projected Average Annual Rainfall in 2030

***Source:** Original data were derived from the OZCLIM scenario generator (v.2).[8] An estimate of projected temperature change was based upon average results from16 climate models utilising three climate sensitivities and three emissions scenarios.*

Indicator Map	Impact Area	Justification
	Bushfire	Indicator of the spatial distribution of annual rainfall changes in 2030 that affect landscape aridity that contributes to fire conditions.
	Ecosystems and Natural Resources	Indicator of the spatial distribution of annual rainfall changes in 2030 that affect landscape productivity and ecosystem structure and function.

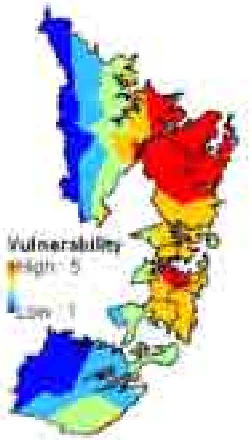
Present 10th Percentile Rainfall

***Source:** Original data were derived from BOM stations in and around the SCCG region. Station data were interpolated to yield a gridded estimate of temperature across the 15 SCCG member Councils.[7]*

Indicator Map	Impact Area	Justification
	Bushfire	Indicator of the spatial distribution of rainfall variability associated with anomalously low rainfall events that enhance aridity and bushfire risk.

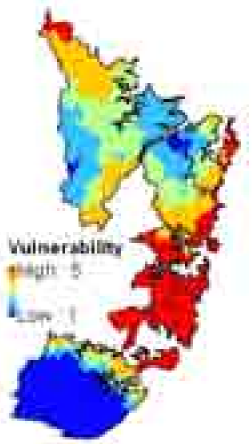
Present 90th Percentile Rainfall

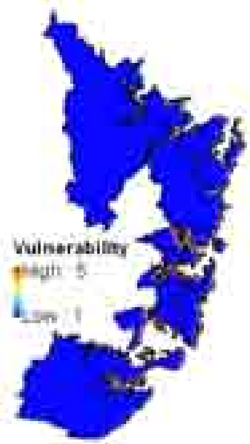
Source: *Original data were derived from BOM stations in and around the SCCG region. Station data were interpolated to yield a gridded estimate of temperature across the 15 SCCG member Councils.* [7]

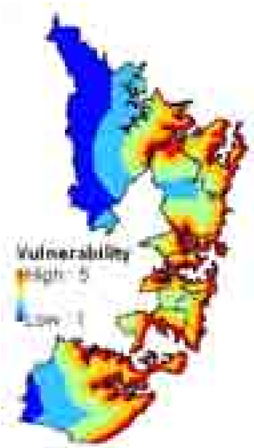
Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of the spatial distribution of rainfall variability associated with anomalously high rainfall events associated with high runoff.

Projected Changes in 2030 Extreme Rainfall Events

Source: *Original data were derived from Abbs et al. (2006), based upon fractional changes in extreme rainfall events.*

Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of the spatial distribution of changes in extreme rainfall events that will affect future runoff amounts.

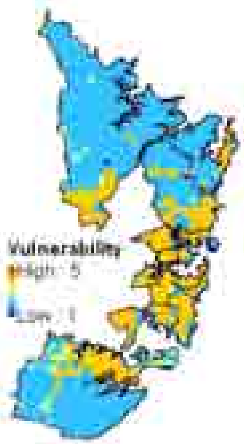
Present Relative Storm Surge Heights		
Source: *Original data were derived from simulation of observed rank storm surge events along the NSW coastline, with subsequent downscaling to the SCCG region (see Appendix V).*		
Indicator Map	**Impact Area**	**Justification**
	Sea-Level Rise and Coastal Management	Storm surge events are associated with periodic coastal inundation and erosion.

Distance to the Coastline		
Source: *Original data were derived from a Euclidean distance calculation using the GSHHS shoreline data set to represent the coastline of the SCCG region.*[9]		
Indicator Map	**Impact Area**	**Justification**
	Sea-Level Rise and Coastal Management	Indicator of the relative distance to the coastline that reflects exposure to coastal hazards.

[9] *Globally Consistent Hierarchical High-Resolution Shoreline Database (Wessel et al., 1996)*

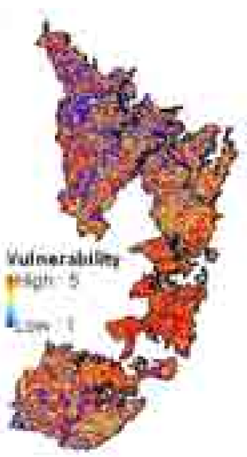
Land Use

Source: *Original data were derived from the 1996/97 Land Use of Australia Version 2.0, developed for the 2001 National Land and Water Resources Audit. Information regarding how scores were assigned appears in Appendix II.*

Indicator Map	Impact Area	Justification
	Extreme Heat and Human Health	Indicator of the relative distribution of human development of the landscape that contributes to urban heat islands.

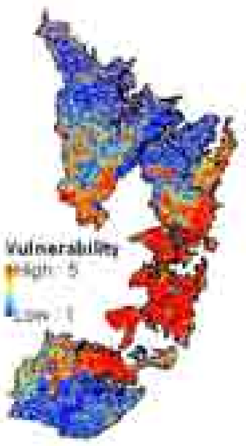
Landsat Vegetation

Source: *Original data were derived from Landsat 7 ETM+ (1999-2002) with a 14.25 metre resolution. Darker colours were associated with water and vegetation while lighter colours, with higher levels of reflectance were indicative of cleared lands, buildings and infrastructure. See also Yang et al. (2002)*

Indicator Map	Impact Area	Justification
	Extreme Heat and Human Health	Indicator of the relative distribution of vegetation that reflects a measure of human development of the landscape that contributes to urban heat islands.

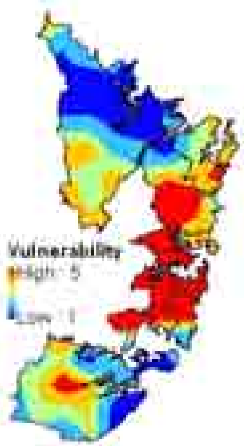
Land Cover

Source: *Data were derived by multiplying the data layers for vegetation cover (see above) by the land use data layer (see above) to produce a land use-adjusted vegetation map across the SCCG area.*

Indicator Map	Impact Area	Justification
	Extreme Heat and Human Health	Indicator of the relative distribution of human development of the landscape that contributes to urban heat islands.

Road Density

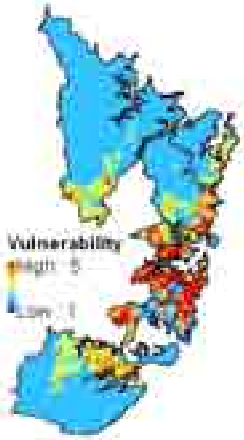
Source: *Original data were derived from the 2001 Land and Water Resource Audit.*[10] *Road density represents the average spatial density of roads per unit area.*

Indicator Map	Impact Area	Justification
	Extreme Heat Events and Human Health Effects	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with a greater urban heat-island effect

[10] Data from the 2001 Land and Water Resources Audit were obtained through the Australian Natural Resources Data Library (http://adl.brs.gov.au/anrdl/php/).

Population Density

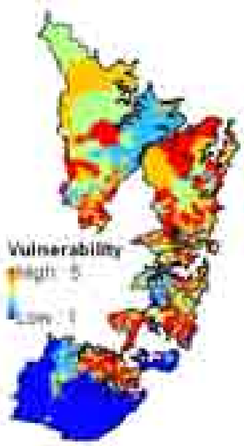
Source: *Original data were derived from the 2006 Census (ABS, 2007). Population densities were calculated by dividing population sizes for individual census collection districts within the SCCG region by their associated areas.*

Indicator Map	Impact Area	Justification
	Extreme Heat and Health Effects	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with a greater urban heat-island effect

SENSITIVITY LAYERS

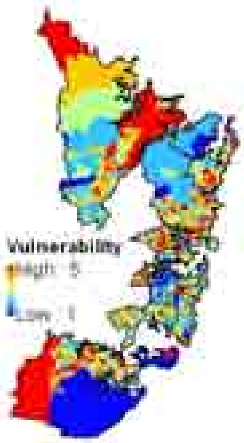
Present Density of Individuals ≥65 Years of Age

Source: *Original data were derived from the 2006 Census (ABS, 2007).*

Indicator Map	Impact Area	Justification
	Extreme Heat and Health Effects	Indicator of the relative size of the elderly population occurring with census collection districts within the SCCG region.

Present Density of Individuals ≤4 Years of Age

Source: *Original data were derived from the 2006 Census (ABS, 2007).*

Indicator Map	Impact Area	Justification
	Extreme Heat and Health Effects	Indicator of the relative size of the population of infants and young children occurring with census collection districts within the SCCG region.

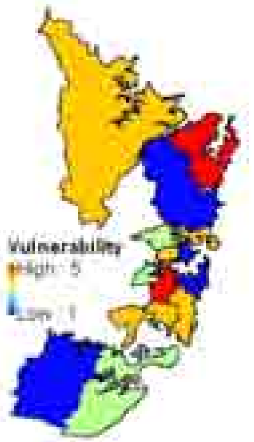
Present Density of Individuals Living Alone

Source: *Original data were derived from the 2006 Census (ABS, 2007).*

Indicator Map	Impact Area	Justification
	Extreme Heat and Health Effects	Indicator of the relative size of the elderly population living alone occurring with census collection districts within the SCCG region.

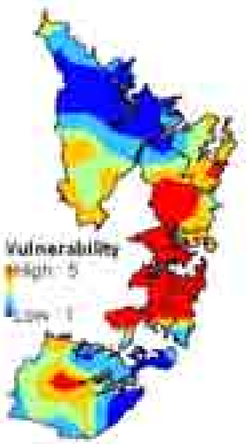
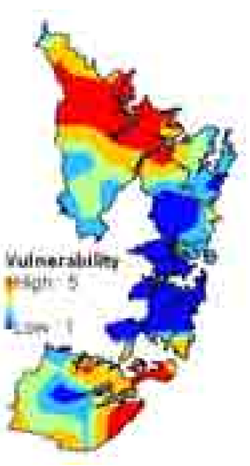
Projected Population Growth to 2019

Source: *Original data were derived from the Australian Bureau of Statistics, and represent projections of population growth between 2001 and 2019 for statistical local areas (ABS, 1999).*

Indicator Map	Impact Area	Justification
	Extreme Heat and Health Effects Sea-Level Rise and Storm Water Management Extreme Rainfall and Stormwater Management Ecosystems and Natural Resources	Indicator of population growth and development among statistical local areas of the SCCG region. More rapid rates of growth are indicator of greater pressure on ecosystems; larger populations exposed to extreme heat; or greater development and infrastructure on the landscape.
	Bushfire	Indicator of population growth and development among statistical local areas of the SCCG region. More rapid rates of growth increase the likelihood of additional land clearance that would reduce bushfire risk.

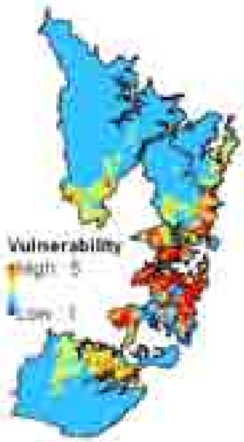
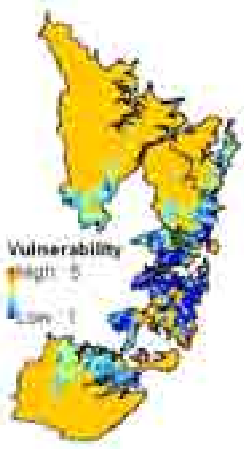
Road Density

Source: *Original data were derived from the 2001 Land and Water Resource Audit.*[10] *Road density represents the average spatial density of roads per unit area.*[10]

Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of the relative differences in the density of impervious surface across the SCCG region. Greater density was associated with greater runoff.
	Sea-Level Rise and Coastal Management	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with a greater development and infrastructure exposed to coastal hazards.
	Ecosystems and Natural Resources	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with greater development and therefore lower ecosystem resilience.
	Bushfire	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with greater development and therefore lower bushfire risk.

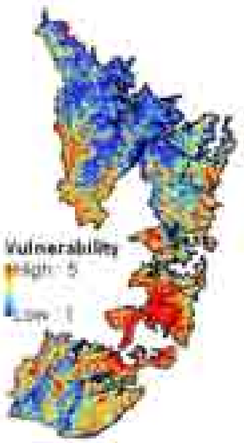
Present Population Density

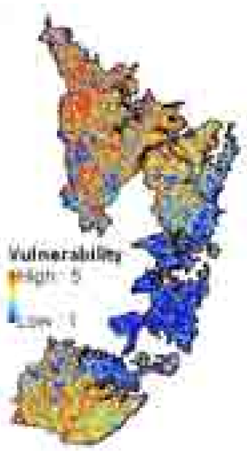
Source: *Original data were derived from the 2006 Census (ABS, 2007). Population densities were calculated by dividing population sizes for individual censuses collection districts within the SCCG region by their associated areas.*

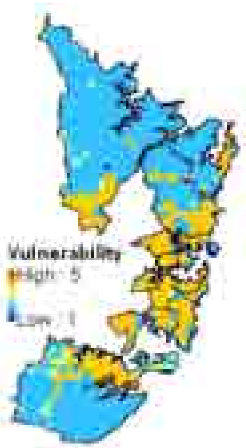
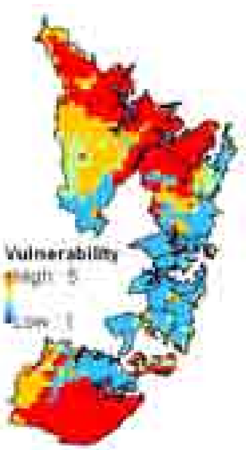
Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with a greater proportion of impervious surface and hence runoff.
	Sea-Level Rise and Coastal Management	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with greater development and infrastructure exposed to coastal hazards.
	Ecosystems and Natural Resources	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with degraded natural ecosystems.
	Bushfire	Indicator of the relative differences in the density of the built environment across the SCCG region. Greater density was associated with more hardened infrastructure and less fuel for bushfires.

Average Soil Water Content

Source: *Original data were derived from the 2001 National Land and Water Resources Audit. Soil water content expresses the water content of the full soil column as a proportion of its saturated capacity.*

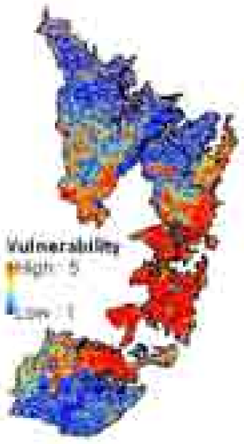
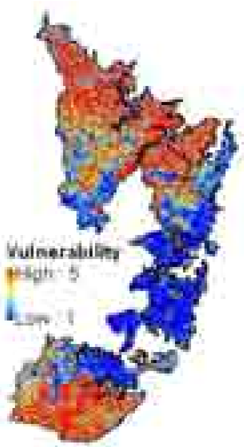
Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of the average relative saturation of soils across the SCCG area. More saturated soils are assumed more prone to flooding due to higher water content than less saturated soils.

Landsat Vegetation		
Source: *Original data were derived from Landsat 7 ETM+ (1999-2002) with a 14.25 metre resolution. Darker colours were associated with water and vegetation while lighter colours, with higher levels of reflectance were indicative of cleared lands, buildings and infrastructure.*		
Indicator Map	**Impact Area**	**Justification**
	Extreme Rainfall and Stormwater management	Indicator of the relative distribution of vegetation that reflects the proportion of impervious surface on the landscape.
	Sea-level Rise and Coastal Management	Indicator of the relative distribution of vegetation that reflects a measure of human development which is associated with increased damages from coastal hazards.
	Ecosystems and Natural Resources	Indicator of the relative distribution of vegetation that reflects a measure of landscape disturbance.
	Bushfire	Indicator of the relative distribution of vegetation that serves as a fuel source.

Land Use		
Source: *Original data were derived from the 1996/97 Land Use of Australia Version 2.0, developed for the 2001 National Land and Water Resources Audit.*[10] *Information regarding how scores were assigned appears in Appendix II.*		
Indicator Map	**Impact Area**	**Justification**
	Extreme Rainfall and Stormwater Management	Indicator of the relative distribution of impervious surface on the landscape that contributes to runoff.
	Sea-Level Rise and Coastal Management	Indicator of the relative distribution of human development and infrastructure, which is associated with increased damages from coastal hazards.
	Ecosystems and Natural Resources	Indicator of the relative distribution of landscape disturbance.
	Bushfire	Indicator of the relative distribution rural bushlands that serves as a fuel source.

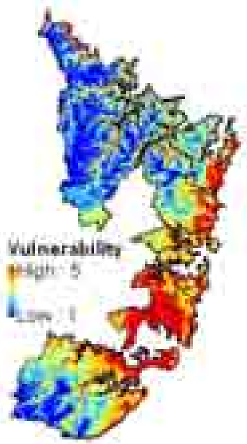
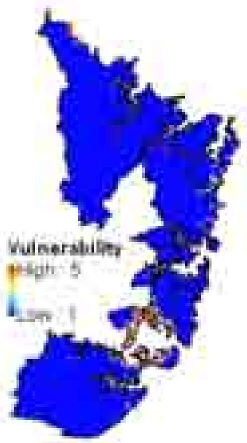
Land Cover

Source: *Data were derived by multiplying the data layers for vegetation cover (see above) by the land use data layer (see above) to produce a land use-adjusted vegetation map across the SCCG area.*

Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of the relative distribution of impervious surface on the landscape that contributes to runoff.
	Sea-Level Rise and Coastal Management	Indicator of the relative distribution of human development and infrastructure, which is associated with increased damages from coastal hazards.
	Ecosystems and Natural Resources	Indicator of the relative distribution of landscape disturbance.
	Bushfire	Indicator of the relative distribution rural bushlands that serves as a fuel source.

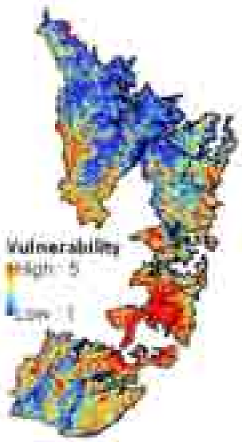
Elevation

Source: *Original data were derived from the SRTM 90 metre resolution digital elevation model (Jarvis et al., 2004).*

Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of low-lying areas that may be more susceptible to flooding.
	Sea-Level Rise and Coastal Management	Indicator of low-lying areas that may be more susceptible to inundation and erosion.
	Ecosystems and Natural Resources	Indicator of low-lying coastal ecosystems and wetlands that may be more susceptible to inundation and erosion.

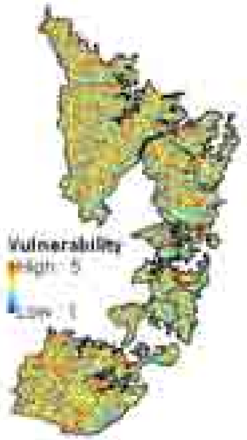
Slope

Source: *Original data were derived from SRTM 90 metre resolution digital elevation model (Jarvis et al., 2004).*

Indicator Map	Impact Area	Justification
	Sea-Level Rise and Coastal Management; Extreme Rainfall and Stormwater Management	Indicator of landscape topography reflecting where water is more likely to runoff or collect. The higher the slope, the greater the potential for runoff, whereas low slopes suggest plains where water is more likely to collect. On the foreshore of the coastal zone, steeper slopes indicate lower susceptibility to sea-level rise.
	Bushfire	Indicator of landscape topography reflecting where there is greater or lesser risk of bushfire spread. Bushfire spreads more rapidly up slopes and the steeper the slope, the higher the rate of spread.

Aspect

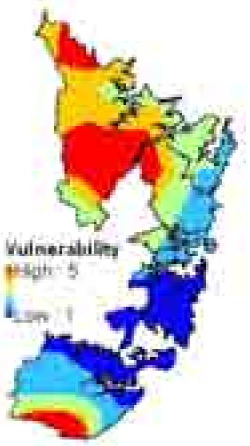
Source: *Original data were derived from the SRTM 90 metre resolution digital elevation model (Jarvis et al., 2004). Details regarding how different aspects were coded appears in Appendix II.*

Indicator Map	Impact Area	Justification
	Bushfire	Indicator of directional slope of regional topography. In the southern hemisphere, northern facing slopes tend to be drier than southern facing slopes, increasing fire risk. In addition, northern facing slopes in NSW are exposed to warm northern winds during summer that may exacerbate fire risk.

Drainage

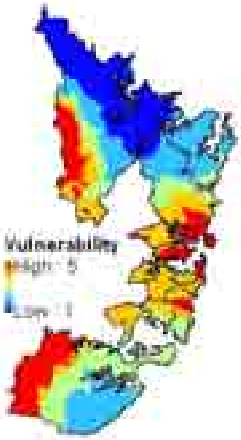
Source: *Original data were derived from SRTM 90 metre resolution digital elevation model (Jarvis et al., 2004).*

Indicator Map	Impact Area	Justification
	Extreme Rainfall and Stormwater Management	Indicator of likely drainage pathways based upon a digital elevation model.

Present Annual Primary Production		
Source: *Original data were derived from the 2001 National Land and Water Resources Audit.*		
Indicator Map	**Impact Area**	**Justification**
	Bushfire	Indicator of annual growth/regrowth of vegetation that may serve as fuel for bushfires.
	Ecosystems and Natural Resources	Indicator of the natural productivity of the landscape and potential for recovery from disturbance.

Present Land Condition

Source: *Original data were derived from the 2001 Land and Water Resources Audit.*[10] *Land condition index is comprised of an aggregation of several indicators such as land-use intensity and vulnerability due to sulphidic, saline, waterlogged, and sodic soils.*

Indicator Map	Impact Area	Justification
	Ecosystems and Natural Resources	Indicator of soil degradation that may affect the productivity and resilience of the landscape.

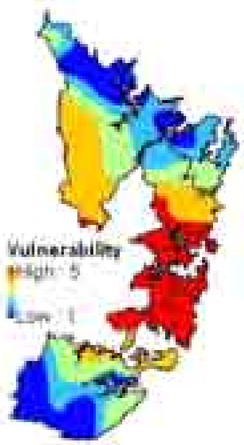
Present Water Condition

Source: *Original data were derived from the 2001 Land and Water Resources Audit.*[10] *Water condition indicator is comprised of an aggregation of several surface water quality hazards including the suspended sediment ratio, pesticide hazard, industrial point source hazard, and impoundment density.*

Indicator Map	Impact Area	Justification
	Ecosystems and Natural Resources	Indicator of Council performance in recycling and progressive waste management

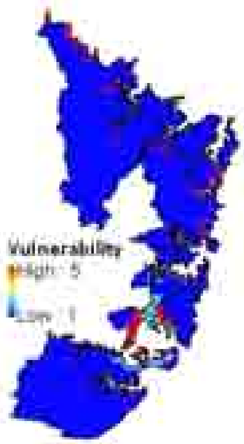
Present Extent of Native Vegetation

Source: *Original data were derived from the 2001 Land and Water Resources Audit,[10] based upon the percentage of native vegetation found on the landscape.*

Indicator Map	Impact Area	Justification
	Ecosystems and Natural Resources	Indicator of the spatial distribution of undisturbed ecosystems of high conservation value.

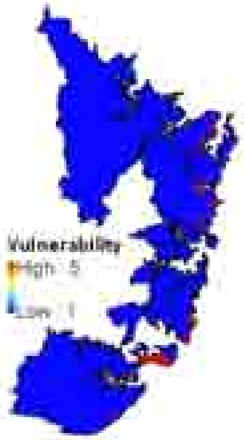
Present Distribution of Acid Sulphate Soils

Source: *Original data were obtained from the NSW Department of Planning. Information regarding how scores were assigned appears in Appendix II.*

Indicator Map	Impact Area	Justification
	Sea-Level Rise and Coastal Management	Indicator of the spatial distribution of acid sulphate soils that may affect the siting of coastal development and/or increase development and/or maintenance costs.
	Ecosystems and Natural Resources	Indicator of the spatial distribution of acid sulphate soils that may adversely affect coastal ecosystems.

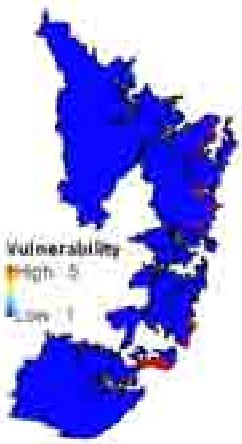
Present Extent of Coastal Protection Areas

Source: *Original data were derived from NSW Department of Planning, and represent coastal areas that are included within the SEPP 71 planning framework. Information regarding how scores were assigned appears in Appendix II.*

Indicator Map	Impact Area	Justification
	Sea-Level Rise and Coastal Management	Indicator of areas within the SCCG region that fall under SEPP 71 protection.

Present Extent of Coastal Wetland Areas

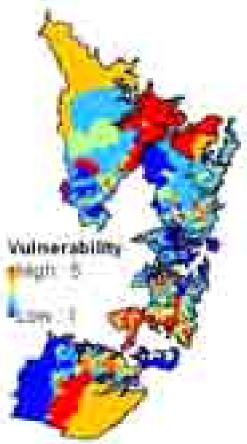
Source: *Original data were derived from NSW Department of Planning, and represents coastal areas that are included with the SEPP 14 planning framework. Information regarding how scores were assigned appears in Appendix II.*

Indicator Map	Impact Area	Justification
	Ecosystems and Natural Resources	Indicator of areas within the SCCG region that are consistent with wetlands as categorised by SEPP 14. SEPP 14 wetlands in the Sydney region from protection, and thus such wetlands represent areas particularly sensitive to the pressures of sea-level rise and development.

ADAPTIVE CAPACITY LAYERS

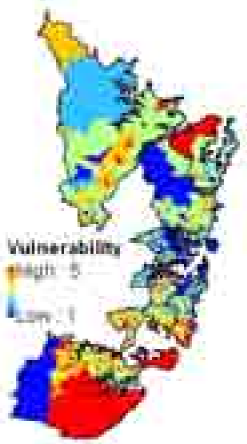
Present Average Household Income

Source: *Original data were derived from the 2006 Census (ABS, 2007). Income estimates were obtained by multiplying the frequency of different income categories by the midpoint for each category range and then averaging the results across the number of respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of household financial resources available for adaptation and risk management

Present Average Home Loan Repayment

Source: *Original data were derived from the 2006 Census (ABS, 2007). Mortgage estimates were obtained by multiplying the frequency of different mortgage categories by the midpoint for each category range and then averaging the results across the number of respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of household financial resources available for adaptation and risk management

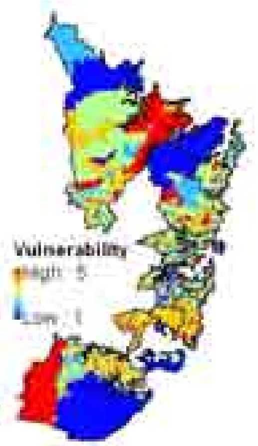
Present Home Ownership

Source: *Original data were derived from the 2006 Census (ABS, 2007). Home ownership was calculated as a percentage of respondents reporting home ownership relative to all respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of household financial resources available for adaptation and risk management

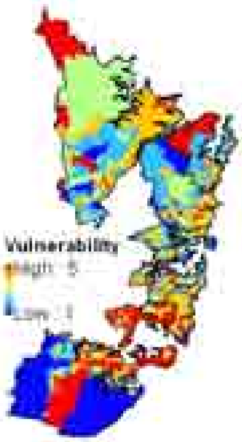
Present Needs Financial Assistance

Source: *Original data were derived from the 2006 Census (ABS, 2007). Home ownership was calculated as a percentage of respondents reporting home ownership relative to all respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of limitation on household financial resources available for adaptation and risk management

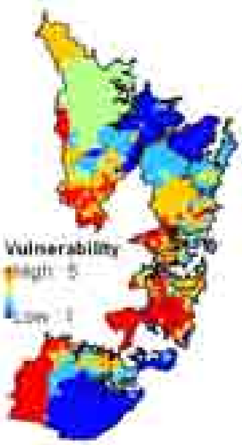
Present Internet Usage

Source: *Original data were derived from the 2006 Census (ABS, 2007). Internet usage was calculated as a percentage of respondents reporting internet usage relative to all respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of household access and use of technology including modern telecommunications infrastructure

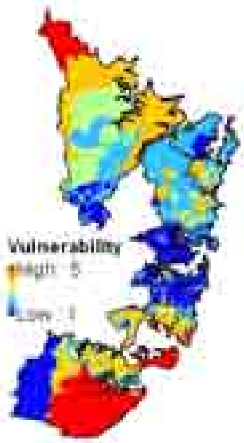
Present English Literacy

Source: *Original data were derived from the 2006 Census (ABS, 2007). English literacy was calculated as a percentage of respondents reporting problems in communicating in English relative to all respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas (Table)	Indicator of household capacity to access common communication channels and media.

Present Completion of Year 12 Education

Source: *Original data were derived from the 2006 Census (ABS, 2007). Education was calculated as a percentage of respondents reporting completion of a year 12 education relative to all respondents for each census collection district.*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of household education levels.

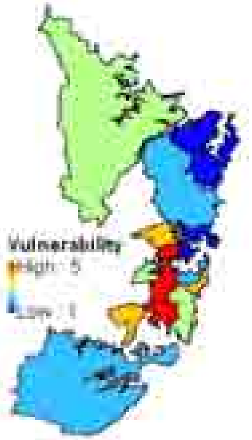
Council Current Ratios

Source: *Original data were derived from "Comparative Information on NSW Local Government Councils 2004/2005 (NSW, 2006)"*

Indicator Map	Impact Area	Justification
	All Areas	Indicator of Council capacity to meet financial obligations and discretionary spending

Per Capita Residential Rates

Source: *Original data were derived from "Comparative Information on NSW Local Government Councils 2004/2005"*

Indicator Map	Impact Area	Justification
	All Areas (Table)	Indicator of community affluence and extent of Council revenue generation

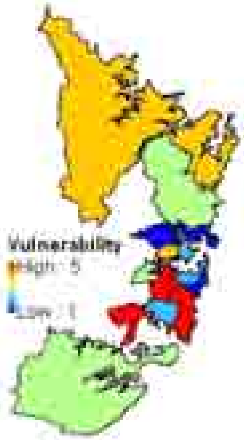
Per Capita Business Rates

Source: *Original data were derived from "Comparative Information on NSW Local Government Councils 2004/2005"*

Indicator Map	Impact Area	Justification
	All Areas (Table)	Indicator of community affluence and extent of Council revenue generation

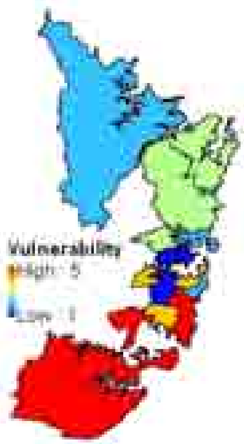
Per Capita Community Services Expenditures

Source: *Original data were derived from "Comparative Information on NSW Local Government Councils 2004/2005"*

Indicator Map	Impact Area	Justification
	All Areas (Table)	Indicator of Council investment in provisioning of services

Per Capita Environment and Health Expenditures

Source: *Original data were derived from "Comparative Information on NSW Local Government Councils 2004/2005"*

Indicator Map	Impact Area	Justification
	Extreme Heat and Health Effects (Table 5))	Indicator of community investment in environmental safety and public health
	Ecosystems and Natural Resources	Indicator of community investment in environmental health and conservation

Per Capita Volume of Recycling		
Source: *Original data were derived from "Comparative Information on NSW Local Government Councils 2004/2005"*[11]		
Indicator Map	**Impact Area**	**Justification**
	Ecosystems and Natural Resources	Indicator of Council performance in recycling and progressive waste management.

[11] *Data for Sydney were obtained from City of Sydney environmental indicators, available through* http://www.cityofsydney.nsw.gov.au/

APPENDIX II. SCORING OF CATEGORICAL DATA

- ***Coastal Elevation Data.*** Coastal elevation data used in the estimation of natural ecosystem and coastal management vulnerability were scored based upon an exponential scale of declining risk. Hence, elevations were scored as indicated in the following table (at right).

Elevation	Score
<1 metre	5
1 to 2 metres	4
2 to 4 metres	3
4 to 8 metres	2
8 to 16 metres	1

Reported high water levels in the Sydney Harbour are commonly in excess of 1 metre, making elevations less than 1 metre above the mean tidal level highly vulnerable to inundation and erosion, particularly in light of future sea-level rise (Figure 7). Heights of 1 to 2 meters are common given storm surges and extreme tides (Figure 7). Storm surge heights in excess of 2 metres are rare, but have been reported at various locations along the NSW coast (Callaghan, 2007). Storm surges beyond 4 meters would appear to be unlikely for the SCCG area, although wave action may be significant. When the effects of waves are included, additional exposure occurs for higher elevations. For example, waves of 12 metres have been reported at Sydney Heads (Callaghan, 2007), although throughout most of the region, such elevations appear to be at low risk from coastal storms, storm surge and sea-level rise, except in the most catastrophic of storm events.

- ***Acid Sulphate Soils.*** Data for acid sulphate soils obtained from NSW were comprised of three vector polygon features representing three different categories of risk due to acid sulphate soils. Categories were listed as either "high [risk]", "low [risk]", or "disturbed [soils]". Areas corresponding with high risk were assigned a score of 5. Areas corresponding with low risk were assigned a score of 1. Areas corresponding with disturbed soils were assigned a score of 3, due to the fact that further analysis of such areas is required to determine actual risk. Areas not associated with acid sulphate soils were assigned a score of 0.

- ***Coastal Protection.*** State Environmental Planning Policy (SEPP) No. 71 - Coastal Protection, was implemented in 2002 to ensure:
    - development in the NSW coastal zone is appropriate and suitably located;
    - there is a consistent and strategic approach to coastal planning and management; and
    - there is a clear development assessment framework for the Coastal Zone.

  Data for areas corresponding with SEPP 71 were available as vector polygons. Areas with the SCCG region either fell inside or outside of SEPP 71 planning regions. Areas that fell inside were assigned categorical sensitivity rankings of 5, reflecting sensitive coastal land areas, while areas outside were assigned rankings of 1.

- ***Coastal Wetlands.*** State Environmental Planning Policy (SEPP) No. 14 places planning and development controls under the Environmental Planning and Assessment Act, 1979 over the wetlands identified in The Coastal Wetlands Survey Report. However, wetlands within the Sydney region (Hawkesbury River to

Wollongong) are exempt from regulatory guidelines. Data for areas corresponding with SEPP 14 were available as vector polygons. Areas with the SCCG region either fell inside or outside of SEPP 14 planning regions. Areas that fell inside were assigned categorical sensitivity rankings of 1 while areas outside were assigned rankings of 5.

- ***Land Use.*** Data for land use obtained from the BRS were assigned two different classification schemes, reflecting the sensitivity of different land uses in the context of different climate change impacts. Scores were assigned to different land use types based upon the table below:

Land Use Designation	Scores
Extreme heat and health effects, sea-level rise and coastal hazards, extreme rainfall and urban stormwater management, ecosystems and natural assets	
Water	**1**
Minimal Use, Nature Conservation, Potential Ag Land,	**2**
Livestock Grazing, Irrigated Horticulture, Woodland	**3**
Residential	**4**
Transport and Communication	**5**
Bushfire	
Transport and Communication, Water	**1**
Residential	**2**
Livestock Grazing, Irrigated Horticulture	**3**
Minimal Use, Potential Ag Land	**4**
Nature Conservation, Woodland	**5**

- ***Slope Aspect.*** Slope aspect data derived from the SRTM digital elevation model and used in the estimation of bushfire vulnerability were scored based upon compass headings in degrees. Northern facing slopes were assigned the greatest sensitivity while southern facing slopes were assigned the lowest (e.g., Erten et al., 2004). Hence, elevations were scored as according to the following table (at right).

Aspect	Score
337.5–22.5°	**5**
22.5–67.5°; 292.5–337.5°	**4**
67.5–112.5°; 247.5–292.5°	**3**
112.5–157.5°; 202.5–247.5°	**2**
157.5–202.5°	**1**

APPENDIX III. COUNCIL COMPARISON OF COMPONENTS OF VULNERABILITY

EXPOSURE

Table 13. Mean Exposure Scores for the 15 SCCG Councils.

Council	Impact Area				
	Extreme Heat	Sea-Level Rise	Extreme Rain	Bushfire	Ecosystems
Botany Bay	5	5	6	2	2
Hornsby	5	5	3	6	8
Leichhardt	7	4	5	2	3
Manly	5	5	7	1	3
Mosman	5	4	7	1	2
North Sydney	7	4	7	1	3
Pittwater	4	5	7	1	5
Randwick	4	4	6	1	2
Rockdale	7	5	4	4	4
Sutherland	3	5	3	4	4
Sydney	6	4	6	1	2
Warringah	5	5	7	2	5
Waverley	5	5	7	1	2
Willoughby	7	4	6	2	4
Woollahra	6	4	7	1	2

High values indicate a relatively high degree of exposure to future climate change while low values indicate low exposure. Colours reflect relative degrees of exposure, with blue (low exposure) associated with scores of 1 to 3, green (moderate exposure) with scores of 4-6, and red (high exposure) with scores of 7 to 9.

SENSITIVITY

Table 14. Mean Sensitivity Scores for the 15 SCCG Councils.

Council	Impact Area				
	Extreme Heat	Sea-Level Rise	Extreme Rain	Bushfire	Ecosystems
Botany Bay	7	7	7	1	9
Hornsby	6	4	3	6	3
Leichhardt	6	7	7	1	8
Manly	7	6	7	2	8
Mosman	5	5	5	2	8
North Sydney	6	8	7	1	9
Pittwater	7	7	6	4	5
Randwick	7	5	7	2	8
Rockdale	8	8	7	1	9
Sutherland	3	3	3	4	4
Sydney	5	5	8	1	9
Warringah	4	4	4	4	4

Waverley	5	5	6	1	8
Willoughby	7	5	6	2	8
Woollahra	5	7	6	1	8
High values indicate a relatively high degree of sensitivity to future climate change while low values indicate low sensitivity. Colours reflect relative degrees of sensitivity, with blue (low sensitivity) associated with scores of 1 to 3, green (moderate sensitivity) with scores of 4-6, and red (high sensitivity) with scores of 7 to 9.					

ADAPTIVE CAPACITY

Table 15. Mean Adaptive Capacity Scores for the 15 SCCG Councils.

Council	***Impact Area***				
	Extreme Heat	***Sea-Level Rise***	***Extreme Rain***	***Bushfire***	***Ecosystems***
Botany Bay	7	6	7	7	8
Hornsby	5	4	5	4	4
Leichhardt	3	1	3	3	4
Manly	1	1	1	1	1
Mosman	1	1	1	2	2
North Sydney	3	1	3	2	3
Pittwater	3	3	3	4	3
Randwick	5	4	5	5	6
Rockdale	9	8	9	9	9
Sutherland	6	5	6	5	5
Sydney	3	2	3	2	4
Warringah	1	2	1	1	1
Waverley	2	1	2	2	3
Willoughby	1	1	1	1	2
Woollahra	2	1	2	2	2
High values indicate a relatively low degree of adaptive capacity to future climate change while low values indicate high adaptive capacity. Colours reflect relative degrees of adaptive capacity, with blue (high adaptive capacity) associated with scores of 1 to 3, green (moderate adaptive capacity) with scores of 4-6, and red (low adaptive capacity) with scores of 7 to 9.					

APPENDIX IV. BUREAU OF METEROLOGY STATIONS USED FOR INTERPOLATION OF OBSERVED CLIMATE VARIABLES

Table 15. Bureau of Meteorology Weather Stations Used in the Interpolation of Observed Climate Data (BOM, 2007)

	Name	Latitude (S)	Longitude (E)	Elevation (m)
1	Badgerys Creek	-33.8683	150.7278	65.0
2	Bankstown	-33.9181	150.9864	6.5
3	Camden	-34.0391	150.6890	73.9
4	Glenfield	-33.9667	150.9000	23.0
5	Gosford	-33.3949	151.3290	20.0
6	Katoomba	-33.7135	150.2983	1030.0
7	Kulnura	-33.2333	151.2000	312.0
8	Liverpool	-33.9272	150.9128	20.0
9	Lucas Heights	-34.0517	150.9800	140.0
10	Manly	-33.8000	151.3000	?
11	Marsfield	-33.7791	151.1121	65.0
12	Orchard Hills	-33.8020	150.7069	93.0
13	Paramatta	-33.8167	151.0000	15.2
14	Paramatta North	-33.7917	151.0181	55.0
15	Peats Ridge	-33.3102	151.2443	280.0
16	Pennant Hills	-33.7333	151.0667	183.0
17	Prospect Dam	-33.8193	150.9127	61.0
18	Richmond	-33.6165	150.7477	20.0
19	Riverview	-33.8258	151.1556	40.0
20	Seven Hills	-33.7704	150.9318	50.0
21	Sydney	-33.9000	151.2333	38.0
22	Sydney Airport	-33.9411	151.1725	6.0
23	Sydney Observatory	-33.8607	151.2050	39.0
24	Wollongong	-34.4030	150.8795	25.0

APPENDIX V. STORM SURGE MODEL SIMULATIONS FOR THE SYDNEY COASTAL COUNCIL'S PROJECT

For the current study, estimates of extreme storm surge levels were developed throughout the SCCG study region. Estimates were generated by simulating a series of observed storm surge events, using observed ocean and atmospheric forcing parameters. A set of 30 extreme sea level events were selected from tide gauge data in the 1990's and from a Manly Hydraulics Laboratory report prior to the 1990s (MHL, 1991). Table 16 provides the list of events.

Table 16. The start and end dates selected for modelling

Event number	Event start date (*yyyymmdd*)	Event end date (*yyyymmdd*)	Duration (*days*)
1	19630702	19630706	4
2	19650621	19650625	4
3	19660429	19660503	4
4	19660519	19660523	4
5	19660611	19660615	4
6	19740524	19740528	4
7	19740608	19740612	4
8	19750619	19750623	4
9	19780127	19780131	4
10	19780531	19780604	4
11	19780613	19780617	4
12	19900202	19900206	4
13	19900423	19900429	6
14	19900801	19900805	4
15	19920609	19920613	4
16	19940105	19940109	4
17	19940411	19940415	4
18	19941105	19941109	4
19	19950324	19950328	4
20	19950408	19950412	4
21	19960208	19960212	4
22	19970508	19970512	4
23	19980305	19980309	4
24	19980805	19980809	4
25	19981024	19981028	4
26	19981207	19981211	4
27	19981224	19981228	4
28	19990426	19990430	4
29	20000905	20000909	4
30	20030917	20030921	4
31	20051005	20051009	4
32	20051210	20051214	4

For each simulated event, the storm surge model was set up on 3 model grids at 1.25 km, 250 m, 100 m respectively. The details of each model grid are summarised in Table 17 while the extent of each grid is presented in Figure 23. The atmospheric fields required to force the storm surge model were obtained from 6 hourly NCEP wind and pressure fields which were interpolated spatially and temporally to provide initial and boundary conditions for each model simulation. For the 250 km model grid, oceanic boundary conditions (currents and sea surface heights) were obtained from the 1.25 km simulation while the 100 m storm surge simulations obtained oceanic boundary conditions from the 250 m grid.

Table 17. Details of three model grids used for storm surge simulation

Grid resolution	**Number of grid points**	
(m)	***east-west***	***north-south***
1250	328	896
250	860	869
100	495	925

The approach in this modelling exercise was to model each of the extreme events and store the maximum grid point sea level heights attained during the simulation. After completion of all simulations, each of the events was ranked to obtain a single maximum sea level height. The spatial pattern of this maximum value would provide qualitative guidance to the locations relatively more vulnerable to extreme sea levels and those that were less vulnerable.

However, some problems were encountered in the surge modelling. On the 1.25 km grid the results contained some noise that was generated on the computational grid at the edge of the continental shelf. This is a problem of the rapidly changing total depth. This influenced the inner grids, but in addition to this, on the higher resolution grids, there were also some problems of spuriously high values occurring in the vicinity of the complex coastline near and in the estuaries. A simulation that appeared to be less affected by noise and which produced among the top three highest values of sea levels at Sydney was event 22 which occurred in May 1997. The spatial structure of the sea levels in this particular simulation is similar to that obtained by ranking all 32 events. However, the pockets of spuriously high values which appear to be caused by the complex coastline are confined to just a small region on this particular grid and so it was decided to proceed with just the results of this simulation. The spatial structure of the peak storm surge height in these simulations is presented in Figure 24. Regions where computational noise is believed to be influencing the results are indicated. This particular event was one I modelled previously at much lower resolution in McInnes and Hubbert (2001). The actual event produced a sea level residual at Sydney of just under 0.4 m. In McInnes and Hubbert (2001) the modelled surge was only 0.15 m. In the current simulation it is producing a peak of around 0.25m. As discussed in McInnes and Hubbert (2001), it's possible that wave breaking processes such as wave set up may be contributing to the total residuals that are measured. This is something that is likely to be explored further in future simulations.

To assess coastal vulnerability in response to these storm surge simulations, the storm surge heights for event 22 were georeferenced against the baseline 90 m grid used for mapping the various vulnerability indicators. Storm surge heights were then assigned to each of the grid cells of the baseline grid by assigning the storm surge height value of the closest grid cell, resulting in a storm surge indicator layer throughout the SCCG region. This layer was subsequently adjusted by dividing each grid cell by its distance to the coastline. This resulted in a layer with the following characteristics:

a) grid cells adjacent to sites with higher simulated storm surge heights had higher raw storm surge vulnerability scores; and

b) grid cells closer to the coast had higher raw storm surge vulnerability scores.

As a result of the distance adjustment, storm surge exposure generally declined rapidly as one moved away from the coastline. Yet vulnerability was still higher in those grid cells adjacent to high storm surge values than those with lower storm surge values. This grid was then normalised to a scale from 1 to 5 using an exponential scale.

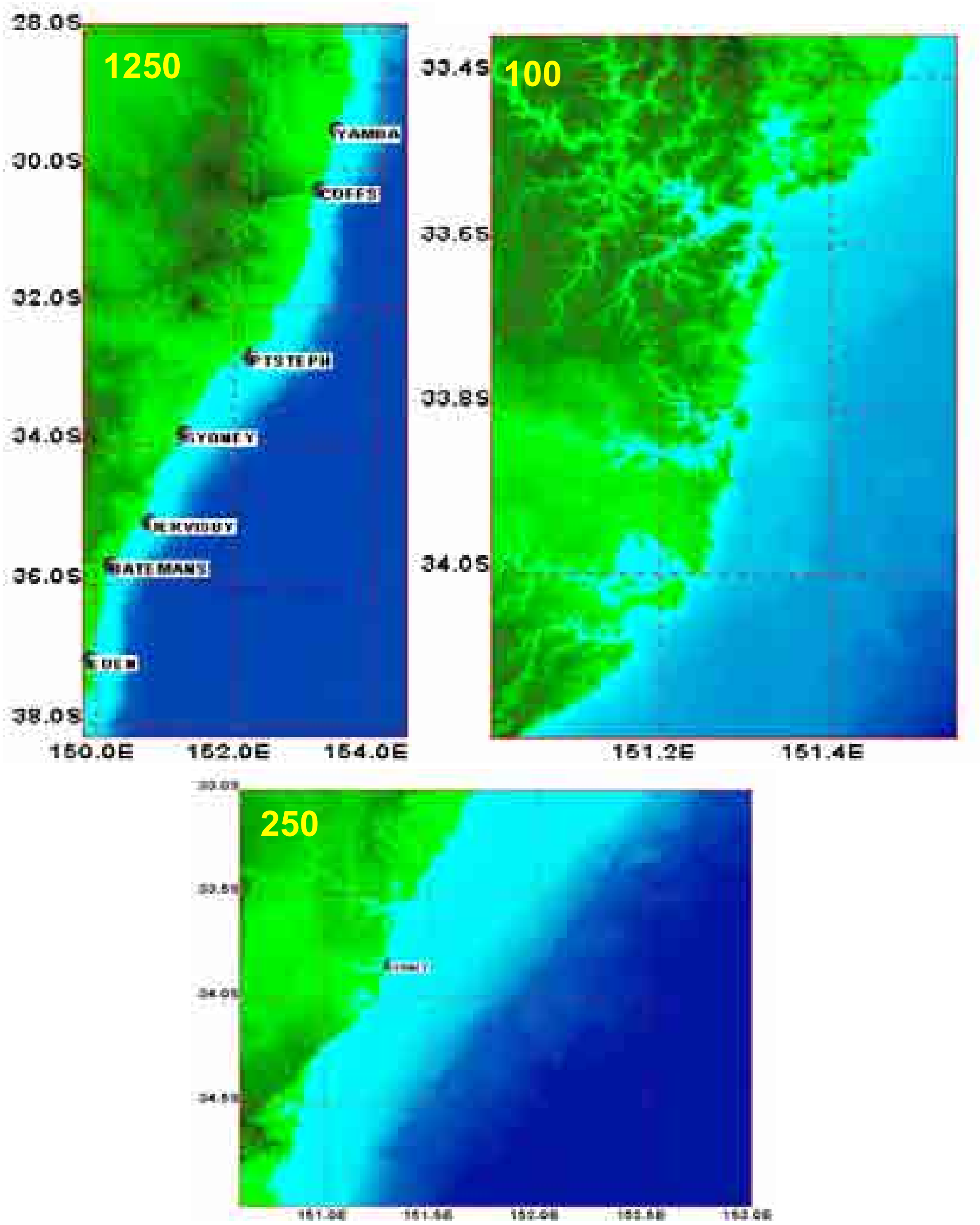


Figure 23. *The three model grids over which storm surge modelling was conducted.*

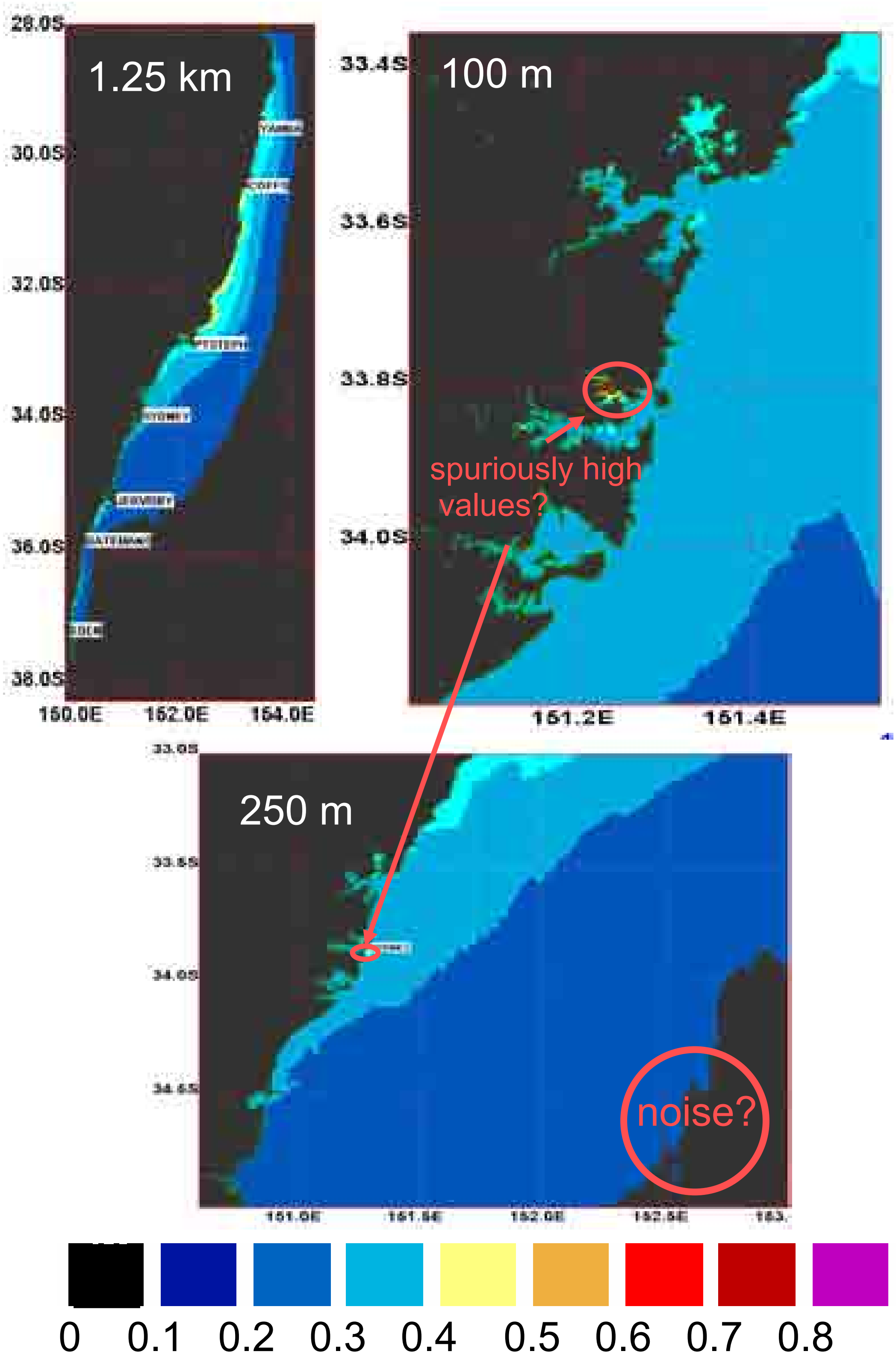


Figure 24. *The spatial pattern of storm surge along the NSW coast derived from hydrodynamic modelling. Note the areas where suspect values may be occurring.*

APPENDIX VI. STAKEHOLDER SURVEY OF PERCEIVED VULNERABILITY

"Systems Approach to Regional Climate Change Adaptation Strategies in Metropolises"

Helping the project team to get to know your council better

NB: This is a confidential survey; the information given will only be used as a bench marking exercise only.

The answers provided will help the project team to prepare to the issues workshops and will also be used to as a bench mark for which to evaluate the effectiveness and efficiency of the project

Council: ________________________________

Rate your Council's vulnerability and adaptive capacity to the following five impact areas on a scale from 1 to 9, with 1 representing low vulnerability and 9 representing high vulnerability / Adaptive Capacity.

Vulnerability Areas	*Your Councils Vulnerability rating*	*Your Councils Adaptive Capacity rating*	*Comments*
Extreme Heat Events and human health effects			
Extreme Rain Events and stormwater management			
Natural Ecosystems and assets			
Sea-level rise, storm surge and coastal Management			
Bushfire			

Are there documents, studies or other information that you are aware of that may be of use to this project?

Thank you for you participation in completing this survey, your feedback is valuable to the Project team and the project outputs.



Sydney Coastal Councils Group Inc.
www.sydneycoastalcouncils.com.au