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Climate Adaptation decision support Tool for Local Governments: CATLoG

Final Report

Stefan Trueck, Supriya Mathew, Ann Henderson-Sellers, Ros Taplin, Tim Keighley and WoonChoo Chin

CLIMATE ADAPTATION DECISION SUPPORT TOOL FOR LOCAL GOVERNMENTS: CATLOG

Developing an Excel spreadsheet tool for local governments to compare and prioritise investment in climate adaptation

Macquarie University

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES iv

ABSTRACT 1

EXECUTIVE SUMMARY 2

1 OBJECTIVES OF THE RESEARCH 5

2 RESEARCH ACTIVITIES AND METHODS 6

2.1 The Risk Management Process 6

2.1.1 Risk identification 7

2.1.2 Risk analysis 7

2.1.3 Frequency modelling 8

2.1.4 Severity modelling 9

2.1.5 Net present value, growth rates and discounting 11

2.1.6 Risk reduction 12

2.1.7 Implementation of the quantitative analysis in CATLoG 15

2.2 Multi-Criteria Analysis 16

2.2.1 Quantitative and qualitative assessment 16

2.2.2 Managing uncertainty in MCA 19

2.2.3 MCA in practice 20

2.2.4 Implementation of MCA in CATLoG 24

2.2.5 Choosing criteria 25

3 RESULTS AND OUTPUTS 27

4 DISCUSSION OF RESULTS AND OUTPUTS 28

5 GAPS AND FUTURE RESEARCH DIRECTIONS 31

REFERENCES 32

GLOSSARY 38

DISCLAIMER 39

LIST OF TABLES AND FIGURES

Table 1: Decision matrix with *n* criteria and *m* options. The scores thus create a $m \times n$ matrix. 21

Table 2: Stakeholder participation during the project 29

Figure 1: The risk management framework followed in this project. The shaded box represents the main steps of risk management, Source: Modified from (Willows & Connell, 2003; Department of the Environment and Heritage: Australia, 2006; Carter et al., 2007)....6

Figure 2: Probability density function of Normal distribution (upper panel) versus the more heavy tailed Lognormal distribution (lower panel)....7

Figure 3: Location of median and mean shown for example Lognormal distribution ... 10

Figure 4: Flowchart illustrating a 'route' for selecting appropriate tools to evaluate climate change adaptation options, Source: Hajkowicz (2006)....19

Figure 5: Relative importance of criteria according to each expert (economic, environmental, social and co-benefit). The total weights for all four criteria given by each of the experts are normalised to 1. 22

Figure 6: Expert scores (shown by black shaded, grey shaded and unshaded bars) for each option: a) scores for the environmental benefits; b) scores for the social benefits; c) scores for the co-benefits. Options along x-axis are represented by numbers 1 to 10. 23

Figure 7: Group weighted scores and ranks of options. The numbers above the aggregated benefit columns represent the ranks of the options in the order of the total benefit. 24

Figure 8: Sensitivity of ranks of options to different weights for the evaluation criteria 24

ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC), the globally-recognised reference body for climate-related research, describes warming of the climate system as ‘unequivocal’. The changing climate is likely to result in the occurrence of more frequent and intense extreme weather events. This demands preventative and preparatory actions (mitigation and adaptation) from all levels of government including local governments. No matter how robust the mitigation responses will be, adaptation actions will still be required to prepare for the already committed changes on the climate.

The study of climate extremes is particularly important because of their high impact nature. Analysis of the extreme events are challenging because of their rare occurrences resulting in very few past observations that can help in any statistical analysis or conclusions. Currently available climate projections especially for extreme events at local scales are associated with a wide range of uncertainties. Apart from that, analysis and damage assessment of the extremes over a period of time also present a lot of uncertainties related to economic analysis (e.g. discount rate, growth rate) and the unknown future.

Unfortunately, often end users do not understand the range of uncertainties surrounding the research outputs they use for extreme events. This research project was designed to develop a pilot tool to enable end users to analyse and prepare for extreme events in a less predictable, complex world. Due to the lack of historical data, the tool relies on expert judgements on the frequency and severity of such events. It is important to point out that the results of the analysis are highly dependent on the quality of these judgements such that the reliability of the results depends on finding appropriate experts in the field who can provide appropriate estimates for frequency and impact of the considered events. The Tool uses a combination of quantitative (Cost-Benefit Analysis) and qualitative (Multi-Criteria Analysis) methods to frame the decision support Tool. The current version of the Tool allows users to conduct sensitivity tests, examine the impact of uncertain parameters ranging from climate impacts to discount rates. The final product is a user-friendly decision tool in the form of an Excel add-in together with a user manual booklet that demonstrates sample worked out projects. The Tool is made flexible so that stakeholders can adopt or refine or upgrade it for their context specific applications.

Executive Summary

Climate adaptation is a challenging task due to the complex web of uncertainties surrounding the future. While most decision makers, at all levels of government and of various sectors, recognise the need to adapt, there still exists a mismatch between the decision maker requirements and available research outputs. Often, decision-makers such as local governments depend on extensive research consultations to decide on adaptation investments. This renders them ignorant about the hidden uncertainties and assumptions behind the research results. It is dangerous to take decisions based on average values that do not reflect sensitivities of the results or worst-case scenarios. It is also challenging for researchers to communicate this to end-users especially when extreme events or catastrophic risks have to be analysed and possible options need to be evaluated.

This research project has been conducted with the aim to educate stakeholders and to demonstrate the influence of various parameters on the investments they make. The project was designed to develop a tool that enables end users to analyse and prepare for catastrophic and climate impacted hazards in a less predictable, complex world. The developed 'Climate Adaptation decision support Tool for Local Governments' (CATLoG) uses a combination of quantitative methods, such as the Loss Distribution Approach and Cost-Benefit Analysis (CBA), as well as qualitative methods, such as Multi-Criteria Analysis (MCA), to enhance the decision-making process for local governments.

The theoretical framework followed for the quantitative part of the tool developed in this research is a risk management framework that includes three steps: risk identification, risk analysis and risk reduction. Risk identification includes identifying location-relevant climate extremes and exploring specific vulnerabilities of the location that are likely to be worsened if the extreme event occurs. Risk analysis and evaluation focuses on determining the frequency and potential negative consequences due to event occurrences. The tool focuses on low frequency high severity climate impacted events where historical data is scarce. Due to the lack of historical data, the tool relies on expert judgements on the frequency and severity of such events. It is important to point out that the results of the analysis are highly dependent on the quality of these judgements such that the reliability of the results depends on finding appropriate experts in the field who can provide appropriate estimates for frequency and impact of the considered events.

To quantify the impacts of the considered climate or extreme events, the co-called Loss Distribution Approach (LDA) has been implemented. LDA is a statistical approach that combines a frequency and severity distribution for generating the aggregate loss distributions. In order to derive the most appropriate parameter estimates for the frequency distribution, using a Bayesian approach, the tool allows the user to combine expert opinions with actual data on the number of events. For severity estimation, the current version of the tool estimates the parameter based on information provided by an expert. Risk reduction includes the identification of appropriate options and evaluating these options by the use of cost-benefit analysis (CBA) in order to rank the options according to their economic net benefits. These steps should lead to the appropriate choice of an adaptation option from an economic perspective. To apply this feature of the tool the user is required to use:

1) expert judgement on the frequency of the considered catastrophic event, and potentially historical data on the frequency of the considered risk type (if available).
2) expert judgement on the severity of these events.

3) expert judgement on how the considered adaptation options will impact on the frequency and severity of the considered climate impacted events (risk reduction).

The user is also required to provide estimates on the costs of the adaptation options considered as well as estimates for economic growth rates and the discount rate that should be applied in the analysis. Finally, an estimate on the increase in frequency of climate impacted events due to climatic change will be required.

The impacts of climate change are spread across easily tangible monetary damage such as infrastructure damage as well as less tangible social and environmental damage such as e.g. death of people and biodiversity loss. Therefore, a complete economic assessment of the impacts is almost impossible. The difficulty of a complete quantitative assessment places additional qualitative methods as necessary in order to assess and evaluate the impact of potential adaptation options. We decided to implement MCA, a widely preferred tool for assessing environmental management options. MCA can incorporate multi/interdisciplinary objectives, participation of various stakeholders (researchers, policy-makers, community members) and is transparent since it measures each criterion in its own units such as money expended, energy used, water consumed etc. The implemented version of MCA may involve more than one expert in order to evaluate options against multiple criteria and also allows for the incorporation of qualitative, quantitative, monetary and non-monetary data. Unlike economic tools such as CBA, MCA evaluates adaptation options against multiple objectives such as net economic benefit, improvement of environmental quality, poverty alleviation etc. The implemented MCA also allows local government stakeholders also to conduct additional sensitivity tests by e.g. varying the assigned weights for the considered criteria.

During the project, a series of workshops were conducted to test the applicability of the tool and determine future upgrading requirements. In addition to several individual tool demonstrations two main workshops were organised: i) Southern Councils group tool demo workshop and ii) Hunter & Central Coastal Councils tool demo workshop. Council officers who participated in the individual remote demonstrations and workshops were interested in using the tool with real case data for their locations. During the workshops, the tool has also been applied in a number of case studies using actual damage data and estimates for financial losses from bushfires and flooding. Unfortunately, local councils clearly pointed out that they do not want council specific data on extreme events made publicly available. Therefore, actual results obtained during the conducted workshop cannot be reported. According to involved Councils and stakeholders, the tool will be used in climate change adaptation decision making in the future. The tool was also considered as being flexible enough to incorporate both an economic analysis as well as a qualitative analysis, where Councils could choose either of it or a combination of both the tools. Stakeholders also pointed out that the tool will be very helpful for education purposes as it helps to develop a structured approach to climate adaptation decision making. The tool raises awareness of key variables that impact on potential losses from climate impacted hazards and illustrates how changes in these variables can impact on risks and losses.

Economic damage may be represented by a proxy measure such as infrastructure damage that is comparatively easier to visualise as quantifiable damage and other less tangible damage may be included in the qualitative analysis. The Councils pointed out this feature to be an important and useful function of the tool. In particular the use of Multi-Criteria Analysis was encouraged as it was easily understood by the Council personnel and provided options for both inbuilt criteria as well as user defined criteria that can be used for both screening a wide list of potential adaptation options as well as evaluation of specific adaptation options. The use of sensitivity tests was also considered an imperative part of the decision support tool, especially to understand the effect of uncertain parameters such as discount rates.

There were some challenges related to the direct use of the Tool with data in certain specific cases. For instance, analysis of floods and winds according to Council flood/storm experts did not necessarily follow the data requirements of the tool. Flood damage is usually analysed using damage curves rather than the loss distribution approach that is applied in the tool developed in this project. Thus, users might require additional guidance on translating these available data into the tool. However, information provided by damage curves can be converted into an appropriate distribution for the frequency and severity of an event. Therefore, the analysis of floods, storms or similar events are still feasibly able to be addressed with the tool.

Further it was also observed from the workshops that it was better to have a simple tool rather than making it more complex with the addition of many heavy tailed distributions for assessing the severity of the extreme events. It was essential for the Councils to consider the average damage over a period of time as well as the worst-case damage. A secondary aim of the research project was to educate Councils on the uncertainty surrounding model outputs available. Council's participated were able to understand the concept that the average damage output from the tool is not free from uncertainties, but Councils need to consider a range of values emerging from climatic (e.g. future frequency and severity variations), economic (e.g. discount or growth rates) and future uncertainties (e.g. development and growth rates).

Overall, users of the developed tool are able to enter details regarding extreme events as well as impacting variables and the tool visually show relevant charts and graphs that can improve optimal decision taking. The final product is a user-friendly decision support tool in the form of an Excel add-in together with a user manual booklet that demonstrates sample worked out projects. The tool has also been designed in a flexible way such that stakeholders can adopt, refine or upgrade it for their context specific applications.

1 OBJECTIVES OF THE RESEARCH

The Intergovernmental Panel on Climate Change (IPCC), the globally-recognised reference body for climate-related assessments states that 'warming of the climate system is unequivocal' (IPCC 2007, p.2). The Australian continent may experience more extreme events in the form of heatwaves, heavy precipitation and bushfires due to warming atmosphere (Garnaut 2008; IPCC, 2012). Currently available climate projections are also subject to a range of uncertainties due to i) socio-economic and technological uncertainties that determine future greenhouse gas emissions; ii) uncertainties associated with the Earth's response to atmospheric loading of greenhouse gases; iii) uncertainty due to spatial heterogeneity (e.g. coastal and mountainous areas), land use, land-cover change and aerosol forcing that affects regional and local-scale climate and iv) climate model input uncertainties associated with radiation schemes, parameterisation equations, initial conditions and boundary conditions applied to the models (see Randall et al., 2007; Knutti, 2008). Thus the exact details of future climate change are uncertain and hence it is also unknown how people and places will be affected by the changing climate. Garnaut 2008 calls climate change a 'diabolical policy problem' due to its uncertainties and long term insidious consequences (Garnaut 2008, p. xviii).

In spite of the uncertainties, governments at all levels are liable to take precautionary actions to reduce the potential risks. The Precautionary Principle adopted by the UN Conference on Environment and Development in 1992 and also included in Article 3 of the UN Framework Convention on Climate Change supports early action by encouraging decision-makers to protect the environment even as scientific uncertainty persists, if there is potential for serious or irreversible damage (United Nations, 1992). Government responses could be to mitigate the greenhouse emissions and/or adapt to the already committed possible impacts of climate change. In general, mitigation policies are usually agreed upon at international/national levels ultimately filtering down to local government levels for actions (Jones *et al*., 2007). While national governments and international organisations debate greenhouse emission reductions, local governments around the world face pressing demands to invest wisely in order to reduce the negative impacts of climatic change on their communities through adaptation. In this report we focus on a Tool to support local governments adapt to future climatic extremes. Adaptation here is defined as an 'adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts' (Parry *et al.,* 2007, p. 27). At present, many Australian local governments have realised the need for action and are involved in many climate adaptation activities such as conducting risk assessments and creating vulnerability maps for the extremes (e.g. Byron Shire Council, 2009; Penrith City Council, 2009). In 2009, the New South Wales Department of Environment, Climate Change and Water (DECCW) commissioned a state-wide online survey of New South Wales local governments on their knowledge of, attitudes to and organisational responses to climate change. The survey analyses showed that 12% of the respondents linked climate change actions to sustainable development, which was proposed under the Local Government Act of 1993 (Ecologically Sustainable Development or ESD).

2 Research Activities and Methods

2.1 The Risk Management Process

The theoretical framework followed for the decision support Tool developed in this research is the risk management framework (e.g. Metroeconomica, 2004; Richardson, 2010). The advantage of following the risk management framework is that it is broad enough to include a number of methods that have been used in Climate Change Impact Vulnerability and Adaptation (CCIVA) studies (Jones & Preston, 2010). There are three main steps involved in the risk management framework: i) identifying the risks; ii) evaluating the risks; and iii) determining the most appropriate adaptation option (Willows & Connell, 2003; Department of the Environment and Heritage: Australia, 2006; Carter et al., 2007; International Council for Environmental Initiatives (ICLEI), 2008).

Risk identification includes identifying location-relevant climate extremes and exploring specific vulnerabilities of the location that are likely to be worsened if the extreme event occurs. Risk analysis and evaluation focuses on determining the frequency and potential negative consequences due to event occurrences. Risk reduction includes the evaluating of the identified options in order to rank them in terms of their benefits. These steps lead to the appropriate choice of an adaptation option.

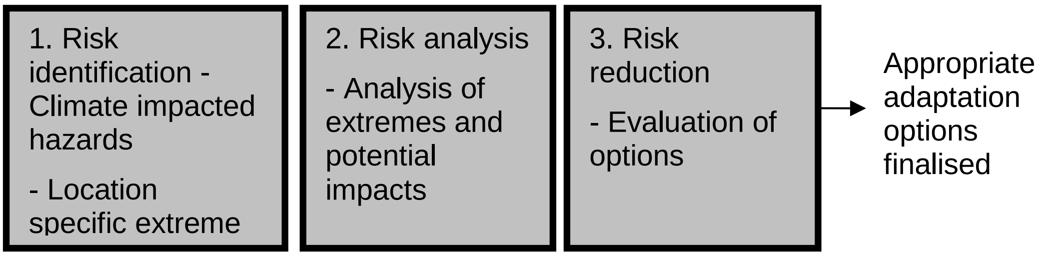

Figure 1: The risk management framework followed in this project. The shaded box represents the main steps of risk management, Source: Modified from (Willows & Connell, 2003; Department of the Environment and Heritage: Australia, 2006; Carter et al., 2007)

The remainder of this chapter is structured the following way: for the quantitative analysis, Sections 4.1.1 – 4.1.6 describe the theoretical foundations and underlying ideas provided in the literature, while Section 4.1.7 explains the approach that has been implemented in CATLoG to conduct the quantitative evaluation and cost-benefit analysis. For the qualitative examination and multi-criteria analysis, theoretical foundations, frameworks and references referring to practical approaches are provided in Section 4.2.1 – 4.2.3. Finally, Section 4.2.4 explains the multi-step procedure for conducting multi-criteria analysis that has been implemented in the tool.

It is also important to note that there is not necessarily a recommended order for the application of the quantitative and qualitative analysis. Situations may arise where conducting MCA in a first step is the better option. For example, MCA can be used to identify only those adaptation options that will meet qualitative but important criteria before subsequently undertaking quantitative CBA only for these options. Clearly, a quantitative analysis requires significant additional effort and work such as e.g. sourcing experts and data, quantifying impacts of the considered adaptation options, before the analysis can be conducted. On the other hand, situations may arise where the cost-benefit analysis may be conducted in a first step and the results for the economic and financial analysis can then be entered in a subsequently conducted MCA that also includes social or environmental impacts.

2.1.1 Risk identification

The first step of the risk management process requires active consultation of local Council officers, local academic and non-academic experts and review of existing literature to obtain details of the location. During risk identification location relevant extreme events and vulnerability of the location to the particular extreme event are identified. Climate projections relevant for the location are also collected for sensitivity tests to be conducted during the steps of risk analysis and risk reduction. Non-extreme related vulnerabilities such as presence of ageing population and socio-economically disadvantaged communities, coastal proximity of locations, potential growths or developments likely to affect the location are also noted.

2.1.2 Risk analysis

In general, an extreme climatic event is considered as one that is rare at a particular place and time of year (IPCC, 2007a). The definitions of extremes in the literature vary widely and may be based on i) extreme values of a meteorological parameter such as temperature or rainfall; ii) consequential impacts such as heatwaves or flooding or iii) impacts to social, environmental and/or economic systems (Alexander & Tebaldi, 2012; IPCC, 2012). The definition of an extreme event is also dependent on the characteristics of the extreme event relevant for the location considered. The focus of the Tool and this research is on extreme events where the data for frequency of the events or damage due to the events are not sufficient enough for statistical derivation of appropriate distributions.

In general, frequency of extreme events is modelled using a Poisson distribution and damage/loss/severity is modelled using a Lognormal distribution or other extreme value distributions (Shevchenko & Wüthrich, 2006). Extreme event damage data are usually not symmetric but rather skewed and are often represented using heavy tailed distributions. **Figure 2** illustrates the difference between a symmetric Normal distribution (upper panel) and the more heavy tailed Lognormal distribution (lower panel). As shown in the figure, the Lognormal distribution is only defined on the positive half line, is asymmetric and, unlike the Normal distribution, allocates some probability to extreme outcomes such as e.g. high losses from climate impacted events.

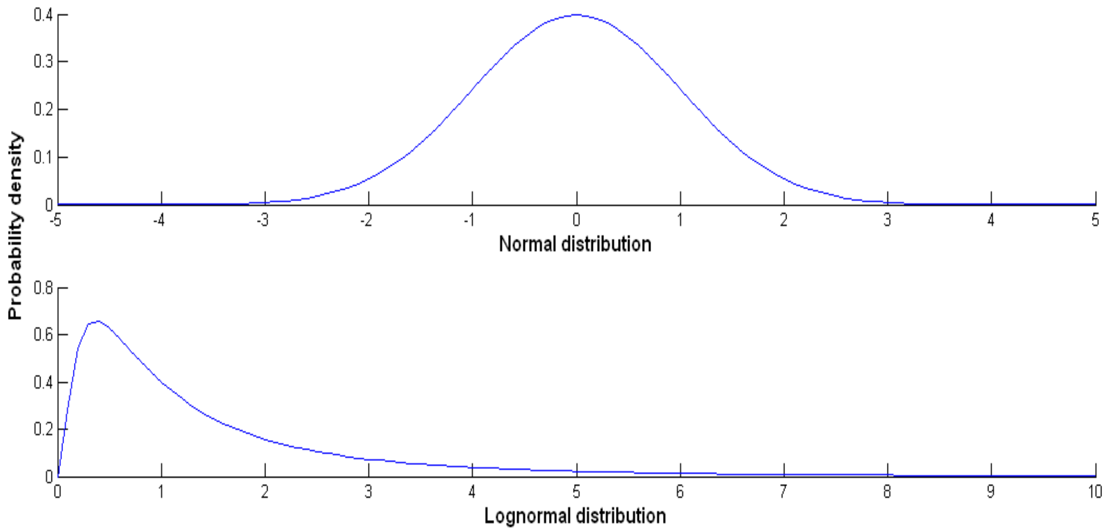

Figure 2: Probability density function of Normal distribution (upper panel) versus the more heavy tailed Lognormal distribution (lower panel).

2.1.3 Frequency modelling

Frequency of extreme events is modelled using a Poisson distribution that is a single parameter (λ) distribution. Consider $\mathbf{N} = (N_1, N_2, ..., N_n)$ as independent random variables drawn from a Poisson distribution with parameter λ, then the probability density is given by

$$f(N \mid \lambda) = e^{-\lambda} \frac{\lambda^N}{N!}, \lambda \geq 0 \tag{4.1}$$

In the first step of the Bayesian process, a prior distribution (Gamma distribution) is derived from local experts to obtain an estimate for the parameter λ. The actual event occurrences are then used to obtain the likelihood of data $f(\mathbf{N} \mid \lambda)$ $f(\mathbf{X}|\theta)$. In the second step, a posterior distribution $\hat{\pi}(\lambda \mid \mathbf{N})$ is derived by combining the prior distribution with the likelihood and is given by

$$\hat{\pi}(\lambda \mid \mathbf{N}) = f(\mathbf{N} \mid \lambda) \frac{\pi(\lambda)}{f(\mathbf{N})} \tag{4.2}$$

Let us assume that the initial parameter value suggested by experts $\lambda = 0.1$ (i.e. bushfires every 1 in 10 years). The expert estimate for frequency of the extreme event was given as a range such that there was 66% probability that the frequency of the extreme (every 10 years) lay between every 7 years and every 15 years. Also assume that there were two extreme event occurrences in 2002 and 2004 during the period 2000-2009. This information is used to update the expert information (prior distribution) and obtain an updated value for the parameter λ.

The detailed steps followed in obtaining the updated parameter value of λ are described below:

Step 1 The prior Gamma distribution

The prior distribution is given by

$$\pi(\lambda \mid \alpha, \beta) = \frac{\left(\lambda/\beta\right)^{\alpha-1}}{\Gamma(\alpha)\beta} \exp\left(-\lambda/\beta\right), \quad \lambda > 0, \beta > 0, \alpha > 0 \tag{4.3}$$

the Gamma distribution, $Gamma(\alpha, \beta)$ with parameters α and β.

In most cases, experts prefer to provide an intelligent guess of the estimate as lying within an interval [*a*, *b*] with probability $\Pr[a \leq \lambda \leq b] = p$. The values of α and β are then calculated using

$$\Pr[a \leq \lambda \leq b] = p = F_{\alpha,\beta}^{(G)}[b] - F_{\alpha,\beta}^{(G)}[a] \tag{4.4}$$

where $F_{\alpha,\beta}^{(G)}[b]$ and $F_{\alpha,\beta}^{(G)}[a]$ are the cumulative Gamma distributions at *b* and *a* respectively. As mentioned previously expert suggestions are the following: *p*=0.66; *b*=1/7 and *a*=1/15.

The value of the Poisson parameter based on the prior distribution is thus calculated to be

$$\lambda_o = \alpha \times \beta; \; \lambda_0 = 0.1 \tag{4.5}$$

Step 2a The likelihood function

The likelihood function conditional on a given value of λ is given by

$$f(\mathbf{N} \mid \lambda) = \prod_{i=1}^{n} \exp(-\lambda) \frac{\lambda^{N_i}}{N_i!} \tag{4.6}$$

Let the past extreme event observations be N = [0, 0, 1, 0, 1, 0, 0, 0, 0, 0], such that there were 2 reported events in the past 10 years.

Step 2b The posterior Gamma distribution

Using Equation (4.6) the posterior distribution is given by

$$\hat{\pi}(\lambda \mid \mathbf{N}) \propto \frac{\left(\lambda/\beta\right)^{\alpha-1}}{\Gamma(\alpha)\beta} \exp\left(-\lambda/\beta\right) \prod_{i=1}^{n} \exp(-\lambda) \frac{\lambda^{N_i}}{N_i!} \propto \lambda^{\hat{\alpha}-1} \exp\left(-\lambda/\hat{\beta}\right) \tag{4.7}$$

i.e. a Gamma distribution, with updated parameters $\hat{\alpha}$ and $\hat{\beta}$ given by

$$\alpha \to \hat{\alpha} = \alpha + \sum_{i=1}^{n} N_i \text{ and } \beta \to \hat{\beta} = \beta / (1 + \beta \times n) \tag{4.8}$$

The updated values obtained for $\hat{\alpha}$ and $\hat{\beta}$ are calculated to be 8.4836 and 0.0132 respectively.

Step 3 The predictive distribution

The updated parameter of the Poisson distribution is now determined from the updated parameters of the Gamma distribution, written as

$$\hat{\lambda} = \hat{\alpha} \times \hat{\beta} \tag{4.9}$$

After the *k*th year, $Gamma\left(\hat{\alpha}, \hat{\beta}\right)$, the predictive distribution could be obtained using the updated parameters as indicated below

$$\hat{\alpha}_k = \hat{\alpha}_{k-1} + X_k \text{ and } \hat{\beta}_k = \hat{\beta}_{k-1} / \left(1 + \hat{\beta}_{k-1}\right) \tag{4.10}$$

In our example, the value of the updated parameter is $\hat{\lambda} = 0.113$. If we assume that for the past 15 years there were only 2 events, then the updated frequency would be 0.1064. These updated opinions could be further updated as more recent observations become available.

2.1.4 Severity modelling

So called heavy-tailed distributions or distributions allowing for extreme outcomes, such as the Gumbel, Burr or Pareto distributions, are widely used to fit damage data and are suitable to better represent the tails of the distribution (Coles, 2001; Naveau et al., 2005; Alexander & Tebaldi, 2012; Dorland *et al.,* 1999; Brabson & Palutikof, 2000; Jagger *et al.,* 2008). As mentioned before, here we focus on specific contexts where data available may not be sufficient even to determine which extreme value distribution may be used for modelling the damage. Thus, data available may be very scarce or almost none such that it is difficult to derive parameter values of frequency and severity distributions based on observations. Expert opinions and Bayesian estimation can be applied in such circumstances to determine the parameter values. In the Bayesian method, expert opinions are solicited to obtain values of the distribution parameters, which are further updated with available data (see Shevchenko & Wüthrich, 2006; Shevchenko, 2011). Parameters of the damage distributions (usually two parameter distributions) may be derived if information on any two quantiles, or information on the tail of the distribution and measures of central tendency such as mean, median or mode are available. Although the mean is more widely used and popular among key stakeholders, when it comes to the mean and median of a distribution stakeholders are likely to misunderstand the two terms when the distributions are skewed. The positions of median and mean are hence shown graphically to key stakeholders to make sure appropriate opinions are collected, see **Figure 3** for an example plot.

One major problem with finding solutions using the mean and the 95th percentile of heavy tailed distributions (e.g. Lognormal distribution) is that often several parameter combinations for the same distribution will satisfy the given constraints and will yield the same mean and 95th percentile. Then the user would have to decide which of the possible parameter specifications is optimal. On the other hand, collection of more information, e.g. three or four percentiles or location parameters, can make it difficult to derive parameter values that satisfy all the constraints and may result in more confusion. Therefore, it was decided to collect information on the median of a distribution and the 95th percentile (worst-case scenario). These conditions will be satisfied by exactly one combination of parameters for the available distributions in the tool. The chosen approach allows for three different heavy tailed distributions for severity modelling whose distribution parameters are obtained by solving values for the median and the worst-case damage of the distributions.

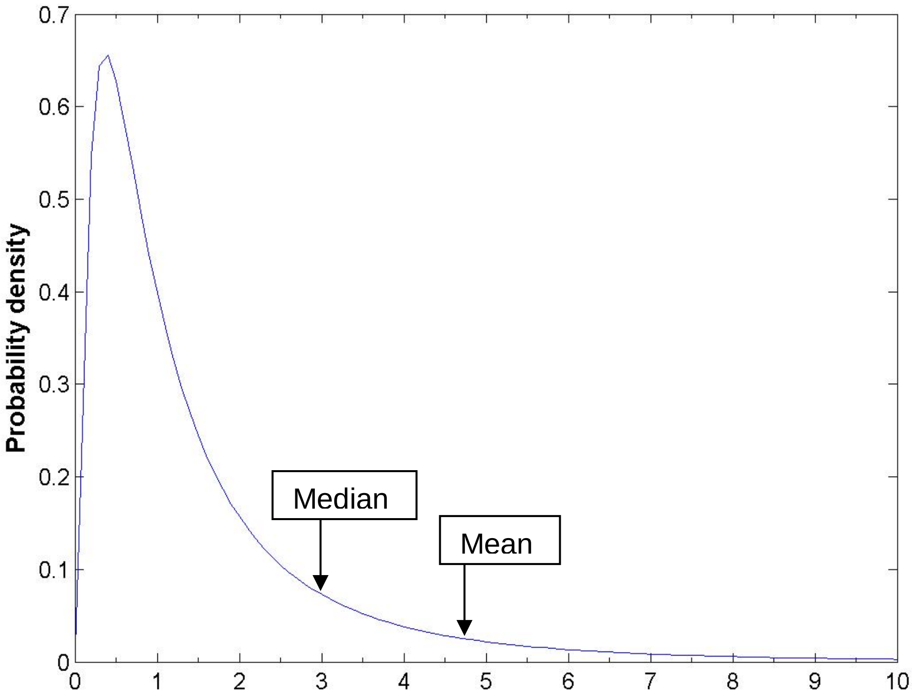

Figure 3: Location of median and mean shown for example Lognormal distribution

1) The cumulative distribution function of the Lognormal distribution is given by $F(x;\mu,\sigma) = \Phi\left(\frac{\ln x - \mu}{\sigma}\right)$, where Φ is the cumulative distribution function of the

standard normal distribution and μ and σ are parameters of the Lognormal distribution. The median (50th percentile) is given by $m = \exp(\mu)$ and the worst-case damage (95th percentile) is given by $w = \exp(\mu + 1.645\sigma)$.

2) The cumulative distribution function of the Weibull distribution is given by $F(x; g, h) = 1 - e^{-\left(x/g\right)^h}$, where *g* and *h* are parameters of the Weibull distribution. The median (50th percentile) is given by $m = -g\ln(0.5)^{\frac{1}{h}}$ and the worst-case damage (95th percentile) is given by $w = -g\ln(0.05)^{\frac{1}{h}}$.
3) The cumulative distribution function of the Burr distribution is given by $F(x; c, k) = 1 - (1 + x^c)^{-k}$, where *c* and *k* are the parameters of the distribution. The median (50th percentile) is given by $m = (2^{1/k} - 1)^{1/c}$ and the worst-case damage (95th percentile) is given by $w = (20^{1/k} - 1)^{1/c}$.

It was also observed during the programming phase of the Tool that when the worst-case value was very large compared to the median, the solutions for the distribution parameters were not derived properly based on the Visual Basic for Applications (VBA) optimization routine implemented in Excel. Therefore, a scaling approach was implemented where the median and worst-case were both divided by the median (new median $m^{'} = 1$ and new worst-case damage $w^{'} = \frac{w}{m}$) to get the correct solutions.

Finally the frequency and severity parameters derived as discussed before, the Loss Distribution Approach (LDA), a statistical approach, may be used to combine the two distributions for generating the aggregate loss distributions (Lewis, 2004; Taplin et al., 2009; Trück et al., 2010): The following steps are performed to obtain the aggregate loss L_t for year *t*:

1) Random numbers are drawn from the derived frequency and damage distributions;
2) The number of events and the individual damage are simulated, then the corresponding aggregate annual loss is calculated, and
3) A further 10,000 Monte Carlo simulations are run to obtain the empirical aggregate annual loss.

2.1.5 Net present value, growth rates and discounting

In the previous section, it was merely illustrated how the annual aggregate loss L_t can be calculated. If the total loss over a number of years, say 20 years, has to be calculated, discounting will be necessary to convert the future monetary units into present monetary amounts so that a valid comparison can be made with all the costs incurred in present monetary terms.

Based on the methodology suggested in Section 4.1.4, the discounted present value of the cumulative loss (*DPVL)* over the considered time horizon *T* can then be calculated using the simulated annual aggregate loss L_t, the applied growth rate *g*, and the discount rate *d*, using the following formula:

$$DPVL = \sum_{t=0}^{T} \frac{L_t (1+g)^t}{(1+d)^t} \quad (4.11)$$

The growth rate *g* represents economic growth, i.e. rising costs for replacement of e.g. infrastructure, but also increase in exposure to risk or increase in economic damage due to the extremes along the time horizon considered. For instance, suppose an expert estimates a damage of 100 houses today in a bushfire risk zone which is likely to increase to 110 houses ten years later due to more development in the bushfire risk zone. Under such circumstances a growth rate of approximately 1% may be used to represent this increase in exposure to risk in the conducted analysis.

There is a lot of debate in the climate change literature regarding the 'correct value' of a discount rate (Nordhaus, 2008; Quiggin, 2008; Tol & Yohe, 2009; Halsnæs et al., 2007; Garnaut, 2008). One reason for the discount rate controversy is that the value of a discount rate can be derived either in a financial sense, where the discount rate reflects a private investor's point of view on the cost of capital or the cost of acquiring funds (e.g. Nordhaus, 2008), or in an economic sense, where the discount rate considers the importance of present consumption against future consumption (e.g. Stern, 2006). While the reports by Stern (2006) and Garnaut (2008) recommend the use of rather low social discount rates, their arguments have been criticised by various authors (e.g. Dasgupta, 2007; Weitzman, 2007; Nordhaus, 2008). In this research the aim is to choose among a number of adaptation options, the most appropriate one which may involve the use of resources in the present and by future generations (Trück et al., 2010). At the same time, in a practical world strict budgets can limit free choice of discount rate values, and the economic vs. financial discount rate debate remains beyond the local government climate adaptation challenge.

Nordhaus (2008) uses a discount rate of approximately 3%, while Ng (2011) argues for a low discount rate (0.1%) presenting climate change as a problem of catastrophe prevention. Van den Bergh, (2010) suggests interest rates of risk-free savings or bonds, while Markandya & Halsnaes (2001) support discount rate values that at least partly reflect the opportunity costs of capital. Time varying (declining) discount rates are also being used to give more weight to future impacts (e.g. HM Treasury, 2003; Pearce et al., 2003).

The values of discount rates are important in every economic analysis as a higher discount rate results in smaller future damage than a lower discount rate (Nordhaus, 2008). Discounting is also crucial for analysing options that are expected to be long-term investments (Hepburn, 2007). Ng (2011) explains this importance using a simple example: the NPV (Net Present Value) of a million US dollars 200 years from now discounted at 1.4% (used by Stern) has a PV (Present Value) of US$59,618, but has a PV of only US$35 if discounted at 5% (market rate) i.e. a difference of a factor of 1,700 between the two calculations. The choice of an appropriate discount rate is thus important as the results of economic analyses may be sensitive to the value chosen. In case there is not a clear agreement on the choice of the discount rate in the analysis, sensitivity tests, including the variation of the discount rate, may help to understand its effect on the final damage calculated.

2.1.6 Risk reduction

In this section, the process followed for the selection of adaptation options and methods that may be used to evaluate the benefits of adaptation options are discussed. Adaptation options for each extreme may be selected by involving Council officers, Community representatives and local experts. Ku-ring-gai Council in Sydney, Australia chose its adaptation options by conducting a series of workshops, first with Council officers alone and then with academic experts, local experts and interested community representatives where each of the groups where asked to order a list of options and add any options that were not included before (Ku-ring-gai Council, 2010). In general, a careful selection of options could also help to manage uncertainty. For instance, reversible and flexible options such as demountable or movable housing in flood prone areas, safety margins for new high investment structures such as dykes, soft adaptation options (e.g. awareness on how to prepare for extreme events or water conservation education in preparation to droughts) with longer-term perspectives and short-term options to benefit from newly available information, are all ways to incorporate uncertainty (e.g. Hajkowicz, 2006; Gersonius *et al.*, 2012; Nassopoulos *et al.*, 2012). Soft options such as institutional policy responses are also likely to be more flexible than high investment adaptation infrastructures. The choice of flexible adaptation options promotes adaptive management and supports option review as more information becomes available (see Dessai & van der Sluijs, 2007).

The economic tools most commonly used for option appraisal include CBA (Cost-Benefit Analysis), CEA (Cost-Effectiveness Analysis) and CUA (Cost-Utility Analysis) (see Hoagland *et al.*, 1995; Hajkowicz, 2006). CBA calculates the costs and benefits of a number of alternative adaptation options and is an important decision-making tool (Metroeconomica, 2004). In this research project, a CBA is followed to calculate the net benefits of adaptation options. Note that we recommend focussing on financial costs and benefits in the quantitative analysis. Additional economic values such as community values, environmental or political costs and benefits can most likely be examined more appropriately using MCA, since it will be very difficult for consulted experts to appropriately quantify these values and costs in the supplied framework. The financial benefit of each option is calculated by consulting experts in respective fields. The potential risk reduction if an option is implemented is expressed as a percent reduction in economic damage caused by the extreme event under consideration. Thus an updated loss distribution is derived based on the expert information. Benefits of the options are further calculated by subtracting the initial damage (damage without any new option in place) from the updated damage (damage with a new option in place). The net benefit is then the difference between the cost of the options and its benefit. The net benefit over a period of time will have to be calculated with the discounted costs and benefits. The net benefits in monetary units determine the economic, or rather financial, viability of options as well as identify the most preferred option. McInerney et al. (2012) discuss the importance of considering both the expected utility as well as the utility cost of the worst-case. Thus while presenting the total loss, it is essential to mention both the average loss as well as the worst-case loss. Therefore, decisions should consider both the average as well as the worst-case. Thus sensitivity tests with respect to the average and worst-case are to be conducted while calculating the benefits and net benefits.

In this project we focus on the use of CBA, but other economic tools such as CUA can be used when the costs are already available in monetary units and the benefits expressed only in non-monetary attributes such as improvement of quality of life (Tapsuwan *et al.*, 2009). Financial objectives of most institutional arrangements tend to be towards minimising costs and maximising benefits. The focus thus is on cost per unit benefit, which can be monetary or non-monetary and hence least cost options, providing desired outcomes (e.g. environmental objectives) are preferred (Ackerman & Stanton, 2011). The method of CEA is useful in such cases and can be used to compare two or more options that deliver similar benefits (Tapsuwan *et al.*, 2009). In CEA, the focus is more on the cost side of the options than the benefit side unlike CBA (Metroeconomica, 2004). The disadvantage of the CEA method is that efforts to reduce costs may compromise the reliability and quality of the response.

To calculate the discounted present value of the total cost of an adaptation project, let T be the time horizon, C_0 the initial capital cost, M_t the annual maintenance cost, g the applied growth rate, and d the discount rate. Then the discounted present value of the costs (*DPVC*) of the costs of the adaptation project can be calculated as

$$DPVC = C_o + \sum_{t=0}^{T} \frac{M_t (1+g)^t}{(1+d)^t} \tag{4.12}$$

On the other hand, it can be assumed that annual aggregated losses (L_t for year t) from the considered extreme event will be reduced due to the adaptation project.

One way to model the reduced risk is by adjusting the calculated parameters of the frequency and severity distribution based on the suggested reduction of the risk according to an expert. Further details on how the risk reduction is implemented in CATLoG are provided in Section 4.1.7. Let's assume that the (reduced) annual aggregated losses after implementation of the adaptation option are L^*_t for year t such that the discounted present value of the aggregated annual losses can be expressed by:

$$DPVL^* = \sum_{t=0}^{T} \frac{L^*_t (1+g)^t}{(1+d)^t} \tag{4.13}$$

Then cost-benefit analysis requires you to compare the present value of the discounted annual aggregate losses under a no-action scenario, i.e. DPVL in equation (4.11), with the discounted present value of the costs for the adaptation option (DPVC) plus the discounted present value of the reduced annual losses ($DPVL^*$) after implementation of the adaptation option.

Overall, the implementation of an adaptation project will be beneficial if the discounted costs for implementation of the option plus the discounted present value of the (reduced) annual losses will be smaller than the discounted present value of the annual losses under a no-action scenario, i.e.:

$$DPVC + DPVL^* < DPVL \tag{4.14}$$

On the other hand, the option will not be viable from a financial or economic viewpoint if

$$DPVC + DPVL^* > DPVL \tag{4.15}$$

Therefore, the net present value of an implemented project can be expressed as:

$$NPV_{project} = DPVL - (DPVC + DPVL^*) \tag{4.16}$$

The main advantage of using quantitative assessments is that the results are in commensurate units and, furthermore that, the uncertain input parameters can be varied to study their effect on the final outputs. As pointed out previously, one of the main challenges in conducting an economic analysis is the appropriate choice of a discount rate. Despite the uncertainties associated with economic evaluations, the main supporting argument towards efforts to monetise non market entities is that monetary equivalents of the entities are more welcome and justifiable in most institutional settings, including local governments. Even after complex economic modelling efforts, there is a possibility of the economic results being placed out of context (e.g. without discount rates mentioned), making them less meaningful. The results can also be altered to meet specific vested interests if the assumptions and uncertainties are not conveyed properly (Spash *et al.,* 2005).

2.1.7 Implementation of the quantitative analysis in CATLoG

The implemented version of the quantitative analysis in CATLoG is a multi-stage procedure that can be summarised as follows:

1) In a first step, the frequency distribution for the considered climate impacted hazard is estimated. The applied distribution is the Poisson distribution and the frequency parameter is estimated based on information provided by an expert and, if available, historical data on the number of events. To do this, an expert provides an estimate for the frequency parameter as well as a range for this parameter. If available this estimate can be combined with the number of previous events for the hazard considered during a specified time period. If no historical data is available, the estimate provided by the expert is used for the subsequent analysis and simulation. Otherwise the expert estimate and the historical number of events are combined to determine the best possible estimate using Bayesian inference (see Section 4.1.3).

2) The parameters of the severity distribution are determined based on expert judgments on the median and the 95th percentile of the loss distribution. In this step the expert can also specify which of the three distributions should be applied. The 'default' option in CATLoG is to use the Lognormal distribution, however, for potentially more severe events, the choice of the Burr distribution may be more recommendable. On the other hand, for less severe events the choice of a Weibull distribution may be more appropriate. See Section 4.1.4 for more details on this step.

3) In the next step, the user will provide the considered time horizon (up to 100 years) for the simulation as well as the applied discount rate and the growth rate for the analysis. See Section 4.1.5 for more details on the discussion about an appropriate choice of a discount and growth rate.

4) Based on the estimated parameters for the frequency and severity distribution as well as the supplied values for the time horizon, growth rate and discount rate then the discounted present value of the aggregated annual losses over the entire time horizon (DPVL) are simulated. CATLoG does provide a distribution of the simulated DPVLs as well as the mean, median, standard deviation and the 90th, 95th and 99th percentile of the simulated DPVL distribution. The 90th, 95th and 99th percentiles can be considered as worst-case scenarios the user may also want to consider.

5) In a next step the user can apply sensitivity analysis in order to investigate how the choice of different parameters impacts the distribution of the DPVL.

   In particular, the impact of the following inputs as well as the sensitivity of the results with respect to the following input parameters can be examined:

   - the time frame, i.e. the number of years that should be considered
   - the discount rate
   - the growth rate
   - the frequency parameter
   - the median of the severity of losses
   - the 95th percentile of the severity of losses
   - the shape of the applied distribution.

   The user can also examine the potential impacts of climatic change that may result in an increase of the frequency and/or severity of the considered events.

   In this step, the user will be able to get an idea how sensitive the results are to the choice of the provided figures. The user can also examine the potential impacts of climatic change that may result in an increase of the frequency and/or severity of the considered events.

CATLoG then offers the option to calculate the impacts of implementing an adaptation project by conducting cost-benefit analysis:

6) For the cost-benefit analysis, in a first step a name for the adaptation option is entered by the user as well as the initial investment costs and the annual maintenance costs for the project. The user can also specify a time horizon, i.e. the lifetime of the project, as well as an applied discount rate. The suggested default values for the time horizon considered and the applied discount rate are the same as for the simulation of the DPVL in order to keep the results comparable. Altering these parameters, especially the time horizon, may make comparison of the results difficult and is not recommended. However, it is included if you have a need for it.

7) Then, in a next step the user will specify the impacts (or benefits) of the adaptation option on the frequency and severity distribution of the losses. Since it is possible that an adaptation project will only have an impact on the severity, but not on the frequency of the events (or vice versa), both frequency and severity parameters are adjusted separately. The reduction for frequency and/or median and 95^{th} percentile of the severity distribution are measured in percent. For example, assume that the median of the severity distribution for damage to infrastructure of a catastrophic event was $2,000,000, a reduction by 10% would reduce this value to $1,800,000. It is assumed that adaptation options will not increase the frequency or severity of the losses.

8) After the specification of the costs and benefits of the adaptation option, a simulation is conducted in order to calculate *DPVC* and $DPVL^*$. Then, the simulated distribution of discounted present values for ($DPVC + DPVL^*$) are provided and compared to a no-action scenario (*DPVL)*. CATLoG also provides the mean of the net benefits of the implemented adaptation option as well as the net benefits at the 95^{th} percentile of the distribution.

9) In a final step, the user also has the option to conduct sensitivity analysis for the implemented adaptation option – similar to Step 5). Such analysis will enable the user to evaluate under what conditions a specific adaptation investment is beneficial or, under which conditions it may not be viable anymore.

Further details about the implementation are provided in the CATLoG Handbook.

2.2 Multi-Criteria Analysis

2.2.1 Quantitative and qualitative assessment

The impacts of climate change are spread across easily tangible monetary damage such as infrastructure damage as well as less tangible social and environmental damage such as death of people and biodiversity loss. A complete economic assessment of the impacts is thus almost impossible. The difficulty of a complete quantitative assessment places qualitative methods also integral to impact assessments and evaluation of potential response options.

Multi-Criteria Analysis (MCA) is a qualitative method that can be used to assess and address social and environmental issues (Hajkowicz & Higgins, 2008b). It is a suitable evaluation technique when there are multiple objectives to consider that are not just limited to economic returns but also extend to social and environmental issues (Mardle & Pascoe, 1999; Herath & Prato, 2006). This is essentially the case when adaptation options are evaluated against the triple bottom line (TBL) measuring financial, social and environmental impacts. In MCA, each option is evaluated against a set of criteria.

A qualitative ordinal scale or quantitative units such as dollars can be used for scoring the options (Hajkowicz, 2006). MCA has become a widely preferred tool for assessing environmental management options as it can incorporate multi/interdisciplinary objectives, participation of various stakeholders (researchers, policy-makers, community members) and is transparent since it measures each criterion in its own units such as money expended, energy used, water consumed, etc. (Munda, 2004). MCA may involve more than one expert to evaluate options against multiple criteria and can be conducted in single/multiple rounds. It can also incorporate qualitative, quantitative, monetary and non-monetary data. Unlike the economic tools such as Cost-Benefit Analysis discussed before, where economic efficiency is the key objective, MCA evaluates adaptation options against multiple objectives such as net economic benefit, improvement of environmental quality, poverty alleviation, etc. (Wegner & Pascual, 2011).

Hajkowicz (2006) separates the contexts in which CBA, CUA, CEA and MCA tools become applicable using a flowchart (**Figure 4**). This tool selection 'route diagram' indicates that CBA is applicable when costs and benefits are available in monetary units or, in other words, costs and benefits can be derived from observable market prices. If costs are in monetary units but benefits not derivable from market prices, then an effort may be made to evaluate benefits using non-market evaluation techniques described in Section 4.2.3. If the benefits can be expressed in monetary units, with the help of non-market evaluation methods, then CBA is again applicable. If benefits are measured against a single objective, then CEA can be used to compare a number of available options to derive the option that delivers the same benefit with the least cost. CUA is used if the benefits can be expressed only in qualitative measures (e.g. environmental quality). MCA may be used when the options are to be assessed against multiple objectives and when the units of measurement are different. In both CBA and MCA, sensitivity tests may be required, e.g. in CBA varying values of discount rate and for MCA varying weights of the criteria (Hajkowicz, 2008). Apart from these sensitivity tests, there are also methods/approaches that help deal with climate or economic uncertainty. These are discussed in the next section.

An alternative to MCA could also be the application of the Delphi method, where convergence of opinions among participating anonymous respondents is reached through a number of iterative rounds. After each round, a facilitator provides an anonymous summary of the experts' evaluations and outlines the reasons the experts provided for their judgments. Thus, using the Delphi method experts are encouraged to revise their earlier answers based additional information and judgements provided by other members of their panel. Clearly, MCA and the Delphi method can both be used as tools for ranking adaptation options. The main difference between the two methods is that for MCA neither consensus of opinion nor anonymity of respondents are essential (Linstone & Turoff, 2002; Hajkowicz, 2008). The Delphi method may be preferred over MCA when there are i) respondents having different personality, positions and reputation, which at times is likely to affect the free expression of opinions if identity is disclosed and ii) wide differences in opinions among participating respondents. The obvious disadvantages of both the tools are that they are prone to the subjective nature of expert opinions and also dependent on the choice of the experts involved and the skills of the facilitator.

MCA is currently being used for identifying and evaluating adaptation options by local governments. For instance, the climate change action pack developed by the Local Government and Shires Associations of New South Wales (LGSA) uses MCA (see LGSA Plus, 2010 climate change action pack). This Microsoft Excel-based tool has criteria that assist Australian local governments decide on response options to risks imposed by climate change. The criteria include i) immediacy criteria, determining how quickly the action can be implemented; ii) financial viability criteria, determining how financially viable the action is for a council; iii) community acceptance criteria (popular, indifferent, controversial), describing how the action may be perceived by the community; iv) flexibility criteria (non-responsive, moderately flexible and adaptive), examining if the option can be altered in the future; v) concurrent effects criteria (potential negative effects, neutral and positive effects), examining other effects the options would have on the council and vi) political feasibility criteria (leader, collaborator and influencer), determining how the council would be positioned in implementing the action. A risk effectiveness score is also mentioned, representing the risk reduction by each option. MCA has also been adopted by the UK local governments, where a manual explaining the tool has also been published (Department of Communities and Local Government: London, 2009). MCA has also been used to identify climate risks and opportunities posed to people's lives and livelihoods in India with special focus on poverty reduction programs (Tanner *et al.*, 2007). MCA4climate, a United Nations Environment Programme (UNEP) initiative specifically designed to assist decision-makers in developing countries devising solutions to adaptation and mitigation, also supports the use of MCA. The criteria used for evaluation consider public financing needs, policy implementation barriers, climate-related risk and economic, social, political and institutional aspects of development (see UNEP, 2011). Under the MCA4climate project, MCA was used to evaluate climate adaptation policy options to increase infrastructure resilience in Mumbai, India (see Hallegatte, 2011).

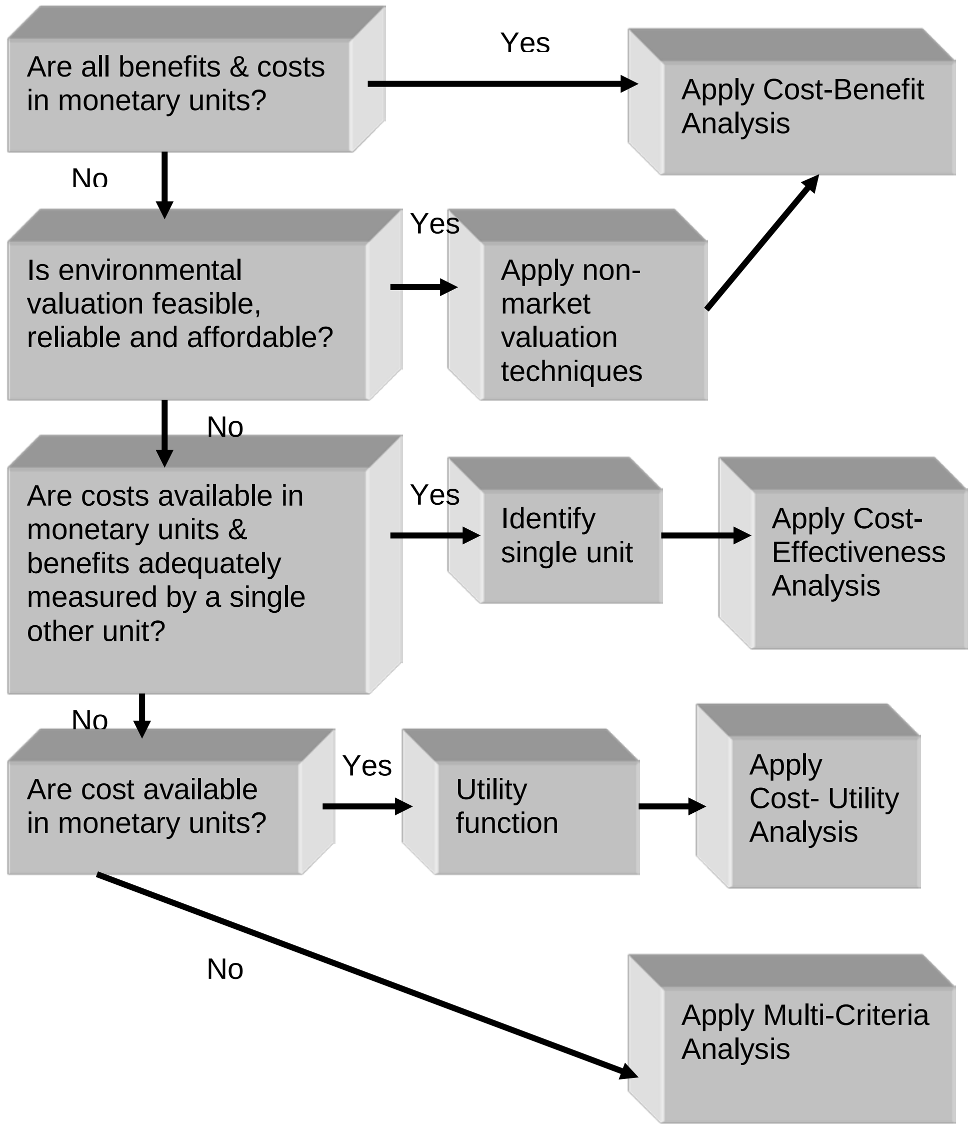

Figure 4: Flowchart illustrating a ‘route’ for selecting appropriate tools to evaluate climate change adaptation options, Source: Hajkowicz (2006)

2.2.2 Managing uncertainty in MCA

It has been discussed previously that a way to deal with insufficient data or future uncertainty is by soliciting expert/stakeholder opinions or including expert intuition in the analysis (e.g. Hanson *et al.*, 2006; K. de Bruin *et al.*, 2009). This method draws opinions from individuals who have expertise in the specific fields or across fields or who have local knowledge (e.g. Cohen *et al.*, 2006; Kundzewicz *et al.*, 2008). Tools such as the Delphi method, MCA and Bayesian inference exploit expert judgements by drawing information from the expertise and intuition about future scenarios (e.g. Hajkowicz, 2006; Shevchenko & Wüthrich, 2006). Expert judgements may be used for collecting all relevant information before starting research and to augment data when there is less time for a comprehensive study or when the information available is insufficient. The disadvantage of this method, as mentioned in previous sections, is that the opinions are subjective and dependent on the choice of the experts. There are also challenges associated with developing questionnaires to ask the right questions to experts, interpreting the expert opinions and aggregating the opinions from a group of experts (Stratus Consulting, 1999).

In particular, uncertainty may be managed in MCA by appropriately choosing criteria as well as conducting sensitivity tests:

1) Choice of criteria
   a) Local constraints/context specific criteria
   b) Options no regret (Flexible, adaptable)
2) Sensitivity Test
   a) Variation of weights of the chosen criteria (economic, social etc.)
   b) Variation of weights allocated to experts

Uncertainty can be managed by assessing adaptation options against appropriate criteria that help to select ‘low regrets’ options. In the low regrets method (previously termed as no regrets method), options are justified under different plausible future scenarios including the absence of anthropogenic climate change (Eales *et al.*, 2006). The choice of adaptation options may also be dependent on its benefits, technical, social and institutional complexities, time horizons over which outcomes of options are observable and also how urgent the options are required (K. de Bruin *et al.*, 2009). Some studies assess adaptation options against co-benefits that do not have direct relevance to climate adaptation, or against mitigation benefits (K. de Bruin *et al.*, 2009; Hallegatte, 2009).

Marinoni *et al.* (2009) developed a MCA software tool that could identify a number of options that return maximum benefit aggregated across a set of criteria under a constrained budget. Such an analysis is also important for local governments since the available funds are often limited, restricting options with high capital cost. In their case study, the choice of options obtained from the local experts had been filtered to account for the local budget constraints (i.e. whether the options were affordable or else a possible source of funding was targeted).

At local government levels, the main advantage of the MCA function of CATLoG is that it is simple and easily transferable to stakeholders and requires less quantitative inputs than economic modelling methods such as CBA (Cost-Benefit Analysis), CEA (Cost-Effectiveness Analysis) and CUA (Cost-Utility Analysis). Moreover, a qualitative analysis may be better suited to create dialogues between local authorities, experts and community members for risk assessments and evaluation of options. MCA evaluates options against a set of criteria to measure the objectives to improve the welfare of the community. The criterion scales that can be in different units, are converted into commensurate units. Each criterion may be assigned different weights and so appropriate mathematical algorithms are used to combine the weighted scores of each criterion and finally options are ranked in the order of their weights (e.g. Hajkowicz, 2006, 2008). Sensitivity tests also accompany MCA and are conducted by changing the weights given to the criteria or to the expert opinions.

2.2.3 MCA in practice

The criteria identified for MCA should satisfy certain attributes as will further be discussed below (Department of Communities and Local Government of London, 2009; Haque *et al.*, 2010). The objectives of each criterion should be well represented and complete. The performance of each alternative should be measured against each criterion either quantitatively (e.g. costs in dollars) or qualitatively (e.g. qualitative descriptions or user defined scales such as 1-10). One of the cautionary measures to be taken in selecting the criteria is to avoid duplication such that each criterion has clear objectives with no overlaps between criteria. Preferential independence (meaning that preference scores assigned to all options on one criterion should be unaffected by the preference scores for other criteria) should be attained and this is a mandatory requirement for aggregation of the weighted scores. In this particular case, selected criteria should be understandable not only to the experts but to the stakeholders also. Criteria to suit contexts should also be chosen as criteria used in a developing country are highly likely to differ from criteria used for evaluation in a developed country. Thus the chosen criteria should reflect local conditions and requirements.

The main steps to be followed in MCA (see Hajkowicz, 2006, 2008; Hajkowicz & Higgins, 2008) are:

1. Developing the decision matrix

After the criteria and options for evaluation are defined, the next step is to create the decision matrix. Let the decision matrix $X_{i,j}$ be a $m \times n$ matrix with m options represented by $(O_1, O_2, ..., O_m)$ and n criteria represented by $(C_1, C_2, ..., C_n)$ as shown in **Table 1**. Each option is valued against each of the criterion and given individual performance scores represented by $X_{m,n}$. Thus a $m \times n$ decision matrix as shown in **Table 1** is developed.

2. Weights assignment (user defined or obtained through various rounds)

After the decision matrix is developed, experts or scorers assign weights to the criteria used for the evaluation. The weights $(W_1, W_2, ..., W_n)$ are indicative of the relative importance of each criterion. Often it is also suggested to normalize the weights such that $(W_1, W_2, ..., W_n)$ are defined subject to the following constraints:

$$\sum_{j=1}^{n} W_j = 1 \text{ and } 0 < W_j \leq 1. \quad (4.17)$$

Note that for CATLoG, the weights for the criteria can also be allocated by the stakeholders, e.g. local governments directly. They may also be allocated in a consultation process with a group of experts.

Further, since it is likely that not all experts will have the same expertise across all of the considered criteria (e.g. economic, environmental, or social benefits), weights may also be given by experts to rate their expertise or confidence level for each criterion. Such expertise ratings for each criterion may be between e.g. 0-10 or 0-100. It is unlikely that local governments will be able to find experts who will have the same expertise in the areas of economic, environmental and social benefits.

For example, an expert who rates her expertise for social benefits to be only 50 out of 100 will only get half the weight in this area in comparison to another expert who rates her expertise to be 100 out of 100 for the social benefits criterion. For further details on this approach see the handbook.

Table 1: Decision matrix with *n* criteria and *m* options. The scores thus create a $m \times n$ matrix.

Alternatives	Criteria, j=1, C_1	Criteria j=2, C_2	…	Criteria j=n, C_n
Option, i=1, O_1	$X_{1,1}$	$X_{1,2}$	…	$X_{1,n}$
Option, i=2, O_2	$X_{2,1}$	$X_{2,2}$	…	$X_{2,n}$
…	…	…	…	…

Option, i=m, O_m	$X_{m,1}$	$X_{m,2}$	$\cdots$	$X_{m,n}$

3. Prioritisation of the alternatives based on their performance against the criteria

A simple way of aggregating the scores is applying the method of linear weighted summation. This method is easier for stakeholders to understand and, moreover, it does not require complicated computational procedures (Howard, 1991). The use of this method is further supported by the fact that, though the results vary with type of MCA algorithms used for aggregation, the variations are typically minor (Hajkowicz, 2006). If the scores against each criterion measure different units such as dollars or metres, then the scores need to be standardized. The performance scores (in different units) have to be transformed into common units for combination. In short, in weighted summation, all criteria are transformed onto a common scale, then multiplied by weights and finally summed to attain overall utility (e.g. Hajkowicz & Higgins, 2008). Finally, the options are ranked based on their aggregate scores.

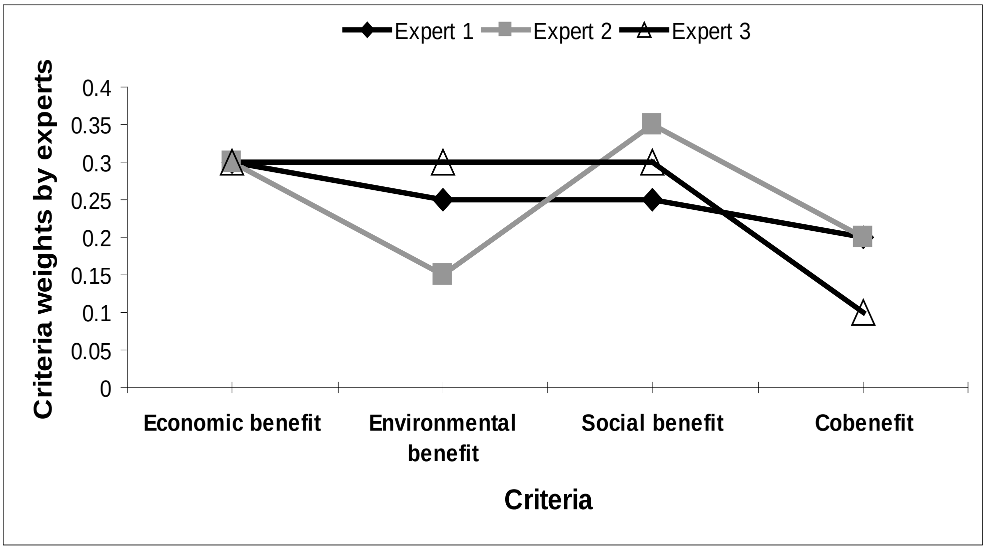

Figure 5: Relative importance of criteria according to each expert (economic, environmental, social and co-benefit). The total weights for all four criteria given by each of the experts are normalised to 1.

For example, in a pilot study for this project, Ku-ring-gai Council sustainability officers conducted a MCA to obtain a list of options for all location specific extreme events with feedback from local experts and Council residents (Ku-ring-gai Council, 2010). A result from this pilot study is that MCA is also well-suited for the selection of options based on a wide range of criteria relevant to the local government. However, the final evaluation should be specific to the benefits of the options. Thus, a 2 tier MCA could be implemented: i) to derive a portfolio of options considering all the location specific characteristics and constraints (e.g. Ku-ring-gai Council, 2010) and then, ii) to derive the total benefits of the options. The second MCA is useful in understanding the benefits specific to the extreme event under study as well as any other additional benefits. Therefore, in the second MCA, criteria may be broadly classified as criteria relevant to that analysis of benefits to mitigate the impacts of extreme events and criteria relevant to address other benefits. The focus of the study being extremes, here the sub-criteria for benefits to extremes may be divided into economic benefits, environmental benefits and social benefits. Additional social, environmental and economic benefits can be categorized under one criterion, termed co-benefits. The co-benefit criterion is also important to account for the uncertainty related to the future occurrences of the extremes and obtain low regret options.

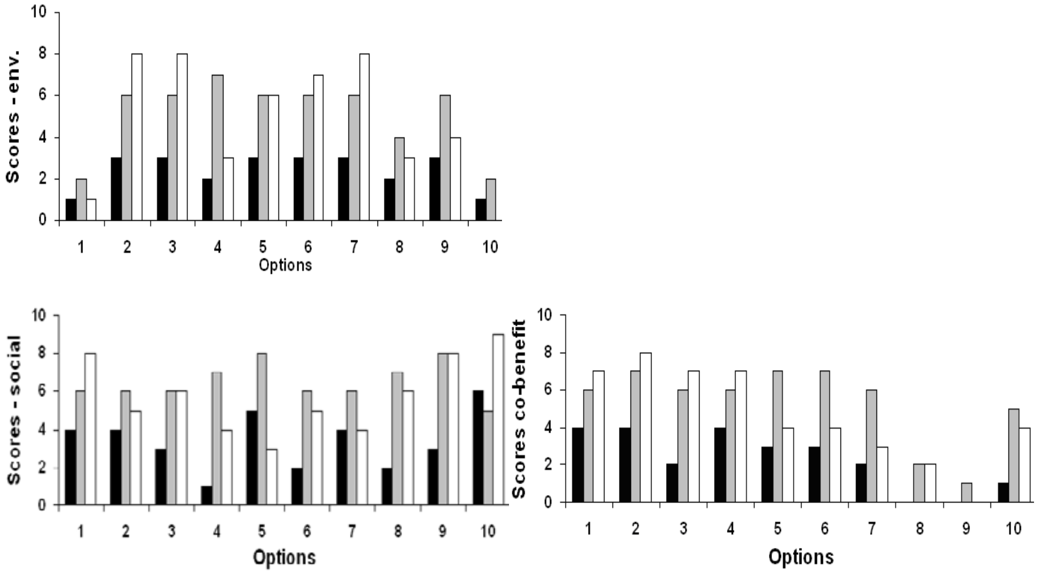

Figure 6: Expert scores (shown by black shaded, grey shaded and unshaded bars) for each option: a) scores for the environmental benefits; b) scores for the social benefits; c) scores for the co-benefits. Options along x-axis are represented by numbers 1 to 10.

Let us assume that in the second tier criteria analysis, three of a Council's sustainability team members assessed the relative importance of the economic, environmental, social and co-benefit criteria as given in **Figure 5**. Further, for each of the ten options scores between 0 and 10 were assigned, see **Figure 6**.

In the next stage the scores across the four criteria need to be aggregated. The most common approach in MCA is to simply apply the method of linear weighted summation, i.e. for each criterion, the score allocated to an option is multiplied by the weight of the criterion in order to obtain the total score for an option.

Note that instead of aggregating the scores by simply applying the method of linear weighted summation, weights could also be determined using the Social Judgment Scheme (SJS) (see Tsiporkova & Boeva, 2006). In the SJS model, each expert's score is compared to the dominant score and thus weights depending on how close or how distant they are to the central dominant score are derived.

The weights of the expert opinions could also be derived based on the consistency of the individual expert scores in a multi-level ranking or scoring analysis (e.g. Beroggi, 2000; Tsiporkova & Boeva, 2006). The principle behind such a strategy is that the weight of an expert's opinion depends on how consistent the scores are between rounds for each option. If an expert changes his/her score drastically between rounds, a lower weight will be assigned to that particular expert compared to others as he/she is considered less reliable. An expert opinion can also be rejected based on such behaviour.

In a similar way, the scores given by the experts for the adaptation options against each criterion could be transformed into consensus scores to obtain the group scores. The group scores can then be multiplied by group weights to obtain final scores for each option. The final scores including their corresponding ranks are shown in **Figure 7**. It becomes clear that for the stylized example, option 3 would be ranked highest, while also option 2 and option 6 are ranked among the top three.

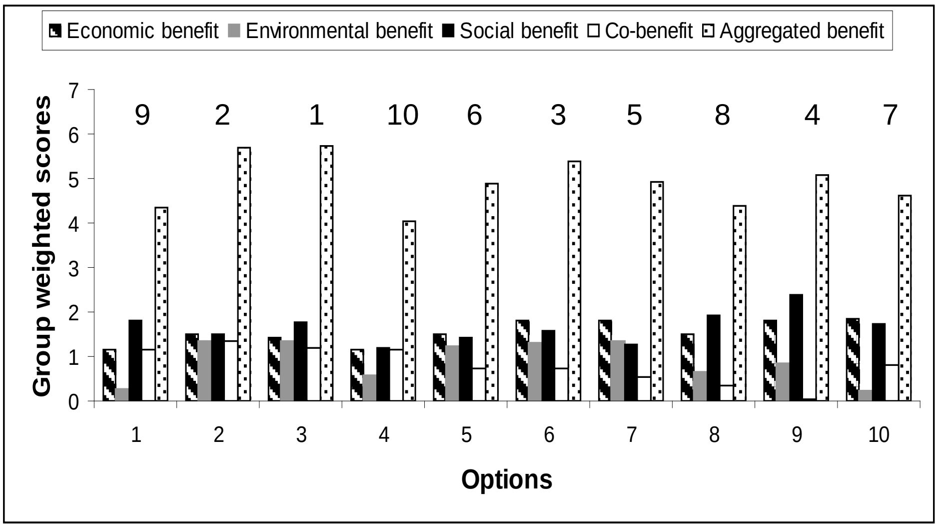

Figure 7: Group weighted scores and ranks of options. The numbers above the aggregated benefit columns represent the ranks of the options in the order of the total benefit.

It is important to note that the level of knowledge in local governments might not be complete and could be quite limited even amongst its experts and may be evident when the experts are asked to clearly separate the extreme event benefits from the co-benefits and adaptation benefits from mitigation benefits. It is thus important that the MCA scores are supported by additional qualitative statements and sensitivity tests. Such sensitivity tests may mainly be based on varying the weights for the different criteria. **Figure 8** shows results for conducted sensitivity tests when applying different weights to the considered four criteria, for example allocating equal weights to all criteria. The sensitivity analysis indicates that also with different weights being allocated to the considered criteria, options 2, 3 and 6 are the most preferred options.

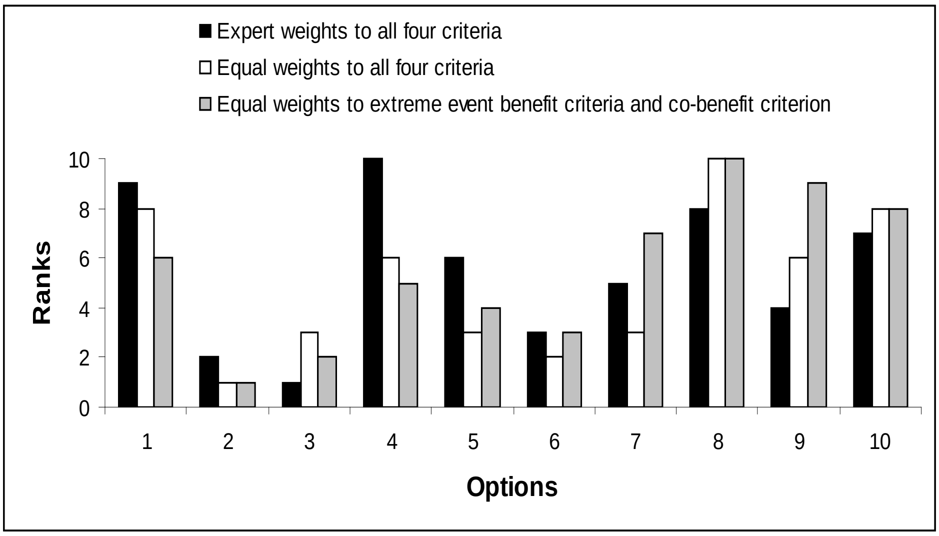

Figure 8: Sensitivity of ranks of options to different weights for the evaluation criteria

2.2.4 Implementation of MCA in CATLoG

Note that in the version of MCA that has been implemented in CATLoG, the weighting of the criteria is a multi-stage procedure including the steps described below. Note that the number and type of criteria is not pre-specified for this tool, but can be decided by the user. Not all applications will require the same number and type of criteria for the analysis. For example, some council might prefer a triple bottom-line analysis, while others will base their decision on e.g. quadruple bottom-line analysis adding an additional dimension. The tool offers the user the flexibility to choose the number of criteria to be considered.

1) In a first step, local governments should evaluate the importance of each criterion (e.g. economic, environmental, social and co-benefits). This can be done in consultation with experts and other stakeholders, but may also be decided by the council before the experts are asked for their evaluation of the options. According to the agreed importance of the individual criteria for the decision making process, weights are then allocated to each criterion.
2) Experts provide a 'credibility weight' for each criterion, i.e. they rate their expertise or confidence level for each criterion. The weights for each criterion are between 0 and 100 and determine the weight of the experts' score of each option for a particular criterion. These 'credibility weights' may also be adjusted by the council, in case an expert significantly over- or understates her expertise for a given criterion.
3) For each adaptation option, the score for a particular criterion is then calculated based on the method of linear weighted summation. Thus, for each expert, the scores for an option are multiplied by a normalized credibility weight to determine the score of an option for each criterion separately.
4) In a final step, the total score of an option is then calculated again by linear weighted summation, i.e. for all criteria, the option's score is multiplied by the weight of the criterion as determined in 1).
5) Finally, a sensitivity analysis can be conducted by the council through varying the weights of the criteria. The credibility weights of the experts could also be adjusted. Note however that the latter should only happen if there is a significant reason for such an adjustment, for example doubts about the appropriateness of the credibility weights suggested by an expert.

Further details on the implementation of MCA in CATLoG are provided in the Handbook. Overall, multi-criteria analysis is an important additional approach for measuring less tangible social and environmental impacts of climate impacted hazards. MCA plays an important role for complementing cost-benefit analysis in the decision making process, especially since complete economic assessment of all impacts is almost impossible. Therefore MCA should also be considered as an integral tool to impact assessments and evaluation of potential response options.

2.2.5 Choosing criteria

MCA in CATLoG allows up to 6 experts to score up to 10 adaptation options on up to 25 criteria. As pointed out above, not all applications will require the same number and type of criteria for the analysis. The tool offers the user the flexibility to choose the number of criteria to be considered.

By default CATLoG suggests 4 criteria: Economic, Environmental, Social and Co-Benefit. These can easily be removed, changed or added to.

Not all applications will require the same number and type of criteria for the analysis. For example, some councils might prefer a triple bottom-line analysis, while others will base their decision on e.g. quadruple bottom-line analysis adding an additional dimension. We do not believe that there is a ‘best’ choice of number and type of criteria and would like to leave such decision up to the user.

3 RESULTS AND OUTPUTS

Results and outputs of the project include the items listed below:

1) An Excel spread sheet tool for local governments to compare and prioritise investment in climate adaptation

The developed tool 'Climate Adaptation decision support Tool for Local Governments' (CATLoG) allows local government and other stakeholders to compare and prioritise investment in climate adaptation. It also allows the user to conduct sensitivity tests, examining the impact of uncertain parameters ranging from possible climate impacts on the catastrophic risks to economic factors such as growth or discount rates.

While the tool has been developed with focus on catastrophic and climate impacted events, the tool is flexible enough to also suit decision making under uncertainty for sectors such as human health, agriculture, tourism or insurance. The tool can also be further adopted or refined by stakeholders for their application.

The tool is publicly available through the NCCARF website (www.nccarf.edu.au) as well as through Macquarie University's research centres:

'Climate Futures' (www.climatefutures.mq.edu.au/) and the 'Centre for Financial Risk' (http://www.businessandeconomics.mq.edu.au/research/financial_risk).

2) A handbook and user manual for the tool containing exemplary case studies for potential users

The project team has also developed a user handbook for the Excel tool explaining key functionalities of CATLoG. The handbook also contains exemplary case studies to illustrate the application of the tool, sensitivity analysis and other functions. The handbook is publicly available through the NCCARF website (www.nccarf.edu.au).

3) Research Articles / Publications

Further information about the research project will be available through four journal articles. A copy of these articles will be made available through NCCARF.

4) Workshops with local government and other stakeholders

Several workshops with local governments and other stakeholders have been organised (see also **Table 2** in Section 6) in order to showcase, promote and further improve the tool. The tool was well-received by participants of these workshops and several suggestions for further collaboration have been made. These suggestions include, among others: joint grant applications with local councils to government and other funding bodies, additional training workshops and local council case studies involving the tool, potential collaboration with environmental consulting companies in order to commercialise the tool.

5) Presentations at workshops/conferences to promote the project and the tool

The project and tool have also been presented at a number of workshops (see **Table 2** in Section 6 of this report) and at the 2013 NCCARF conference in June 2013

6) Applications for additional research funding

Planned applications include an ARC Linkage with partners from several local governments as well as other major grant applications (e.g. the Bushfire and Natural Hazard Cooperative Research Centre and other funding organisations).

4 DISCUSSION OF RESULTS AND OUTPUTS

The need for local action on climate change is being recognised among local Councils within Australia as most of the Councils are prone to extreme event risks such as heatwaves, bushfires and sea level rise. There is a requirement for Councils to effectively consider and plan for the projected impacts of the extreme events. The developed tool aims to provide councils with a consistent and transparent decision support tool for determining appropriate adaptation options. The CATLoG Tool provides both an assessment of the damage due to climate-impacted extreme events as well as an assessment of potential adaptation responses to these events.

A series of workshops were conducted to test the applicability of the tool and determine future upgrading requirements. In addition to several individual tool demonstrations, two main workshops were organised: i) Southern Councils group tool demo workshop and ii) Hunter & Central Coastal Councils tool demo workshop (see **Table 2** for details). Council officers who participated in the individual remote demonstrations and workshops were interested in using the tool with real case data for their locations. During the workshops, the tool has also been applied in a number of case studies using actual damage data and estimates for financial losses from bushfires and flooding. Unfortunately, local councils clearly pointed out that they do not want council specific data on extreme events made publicly available. Therefore, we are not able to report actual results obtained during the conducted workshop in the report and Handbook but can only provide stylized examples in the documents. According to involved Councils and stakeholders, the tool is flexible enough to incorporate both an economic analysis as well as a qualitative analysis, where Councils could choose either of it or a combination of both the tools.

Economic (or financial) damage may be represented by a proxy measure such as infrastructure damage, what is comparatively easier to visualise as quantifiable damage and other less tangible damage may be included in the qualitative analysis. The Councils pointed out this feature to be an important and useful function of the tool. In particular the use of Multi-Criteria Analysis was encouraged as it was easily understood by the Council personnel and provided options for both inbuilt criteria as well as user defined criteria that can be used for both screening a wide list of potential adaptation options as well as evaluation of specific adaptation options. The use of sensitivity tests especially to understand the effect of uncertain parameters such as discount rates was also considered an imperative part of the decision support tool. One of the key issues that became apparent during conducted workshops was the significant influence of applied discount and growth rates (in comparison to the impact of other parameters) with respect to the viability of possible adaptation options.

There were some challenges related to the direct use of the Tool with data in certain specific cases. For instance, analysis of floods and winds according to Council flood/storm experts did not necessarily follow the data requirements of the tool. Flood damage is usually analysed using damage curves rather than the loss distribution approach that is implemented for the tool developed in this project. Thus the damage data available cannot be readily entered into CATLoG and Councils would need guidance on translating these available data into the tool. Further it was also observed from the workshops that it was better to have a simple tool rather than making it more complex with the addition of many heavy tailed distributions for assessing the severity of the extreme events. It was essential for the Councils to consider the average damage over a period of time as well as the worst-case damage.

A secondary aim of the research project was to educate Councils on the uncertainty surrounding model outputs available. Stakeholders pointed out that the tool will be very helpful for education purposes as it helps to develop a structured approach to climate adaptation decision making. The tool raises awareness of key variables that impact on potential losses from climate impacted hazards and illustrates how changes in these variables can impact on risks and losses.

Table 2: Stakeholder participation during the project

Meetings/Workshops	Participants	Feedback and action
NCCARF Emergency Management, Principal Investigators' Meeting	Other NCCARF EM CIs, Stakeholders from government, Red Cross, etc.	Approach is fairly complex, tool requires comprehensive but understandable implementation
NCCARF showcase seminar	Local governments within NSW	Local government contacts
Tool demo to Ku-ring-gai Council	Ku-ring-gai Council officers	Tool refinement
Meeting with Ryde Council, Consultants Complexitas and Lead Environment Consultants	Officers from Ryde Council, Complexitas and Lead Environment Consultants	Tool commercialisation and future support of the Tool
Willoughby Council breakfast meet & Tool demo	Climate commission speakers, Community and Council officers of Willoughby Council area	Handbook and Tool availability NCCARF website
Gosford Council initial demo	Gosford Council officers	Tool refinement
Southern Councils group tool demo	Southern rivers Catchment Management Authority, Department of primary industries, Office if Environment and Heritage, NSW, Kiama Council, Shoalhaven Council	Handbook refinement and special cases Shoalhaven Council interested in getting Macquarie University Masters students to perform case studies using CATLoG –Follow up through Macquarie University
Hunter & Central Coastal Councils Tool demo workshop	Gosford City Council, Wyong Shire Council, Lake Macquarie City, Hunter & Central Coast Regional Environmental Management Strategy	Tool to receive recommendation from state or Office of Environment & Heritage, NSW for formal support; Future consultation with real data from the Councils Follow up through NCCARF; Collaboration with Councils for future funding
Ryde City Council	Ryde City Council	Tool applicable for various projects, Ryde council interested in further testing tool for case studies, Potential development of ARC Linkage application in 2013 with Ryde City and other councils
Clarence City Council, Tasmania Remote login demo using LogMeIn (https://secure.logmein.com/AU/)	Clarence City Council officers	Access and future support for the Tool In liaison with a Software development group to take over support of the tool

Council and stakeholder participants were able to understand the concept that the average damage output from the tool is not free from uncertainties, but Councils need to consider a range of values emerging from climatic (e.g. future frequency and severity variations), economic (e.g. discount or growth rates) and future uncertainties (e.g. development and growth rates).

A list of presentations about the research conducted in this project, tool demonstrations and conducted workshops can be found in **Table 2**.

5 GAPS AND FUTURE RESEARCH DIRECTIONS

The current CATLoG Tool is a pilot effort to assist local governments in adaptation decision-making. Currently, the Tool provides local governments with general support for adaptation decision-making in relation to extremes. A number of context specific features and Tool function extensions were identified during the stakeholder workshops conducted during the project period. These are not incorporated in the current version due to time limits, but we are looking to upgrade the Tool with the help of a consultancy or by obtaining additional research funds in 2013.

The current version does not support combining empirically observed data with expert opinions for severity modelling. The Tool derives the distribution for severity based on the estimates given by the expert only. In most cases this seems to be the most suitable approach, because severity data are difficult to obtain. However, in an extended version of the tool we intend to include this feature.

Further, the Tool Workshops suggested that in conducting sensitivity tests there may be situations where the change in parameter values are not linear but exponential as in the case of increase in days with fire danger. Thus an addition of more options such as exponential increase for frequency of events or an exponentially declining discount rate needs to be introduced. Further addition of positive and negative values for discount rates would also be useful as some Councils suggested the use of a negative discount rate for valuing culturally significant assets.

This Tool does not directly incorporate assessment against maladaptation or inclusion of negative impacts due to adaptation options. Assessment of more than one option at a time as well as addition of new options on top existing options was also a requirement for some of the councils. At present, the Tool can help to conduct these assessments, but Councils will be able to do it only with some external help.

During our meetings with Gosford and Ryde Councils we have observed that in particular for managing the risks of floods, the severity of events is usually measured using ‘damage curves’ (1 in 10 year events, 1 in 100 years events, etc.) and not the ‘loss distribution approach’ (that requires specifying a distribution for the severity of an event) proposed in our project. While it would be possible to provide users with a possibility to use either of these approaches when entering their estimates and data – damage curves can be transformed into a severity distribution – given the current time frame of the project, we did not have the time to implement such an option. However we consider this as a very useful additional functionality for our tool in the future.

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GLOSSARY

Term	Definition
CATLoG	Climate Adaptation decision support Tool for Local Governments
CBA	Cost-benefit analysis. This is applicable when costs and benefits are measurable in monetary units.
CEA	Cost-effectiveness analysis. This is applicable when you comparing several options that deliver the same benefit with different costs.
CUA	Cost-utility analysis. This is applicable when benefits can only be expressed in qualitative measures (e.g. environmental quality).
Damage curves	An alternative way of specifying the frequency and severity of events. Instead of giving a distribution that covers all events, individual events are assigned to a class, e.g. 1 in 10 year event, 1 in 100 years event, etc.
Discount rate	The rate that is used to convert the value of a dollar in future years to the value of a dollar in present time. See Section 4.1.5 for more discussion of discount rates.
DPVC	Discounted present value of the costs. The aggregated costs over the time horizon taking into account the discount and growth rates.
DPVL	Discounted present value of the cumulative loss. The aggregated loss over the time horizon taking into account the discount and growth rates.
Growth rate	This can be an increase in the cost of replacement over time, i.e. inflation, or an increase in exposure to risk over time.
LDA	Loss distribution approach. The frequency and severity of events are specified using distributions. The aggregate loss is calculated by combining the 2 distributions.
MCA	Multi-criteria analysis. A way to compare adaptation options using qualitative criteria. Multiple experts can score each option for each criteria and an overall ranking of the options is produced.
NPV	Net present value. The difference between the loss under a no-action scenario and the loss plus costs of an adaptation option.
Sensitivity analysis	This allows the user to investigate how the choice of different parameters impacts the distribution of the losses in CBA or the rankings in MCA.
Time horizon	The number of years to consider for the analysis. This could be the council's planning horizon or the limit for which reasonable estimates of damage can be produced.

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Specifically, the program relies on input from the user. The quality and accuracy of the estimates provided by the user is paramount to the reasonableness of the output. It is up to the user to select appropriate experts who can provide such estimates.

We would appreciate acknowledgement if the software is used.

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