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Risk and Uncertainty in Environmental Economics: From Theory to Policy Practice[*]

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[*] Nothing in this paper necessarily represents the policies or views of the NSW Government, the Minister for Climate Change and the Environment, or the Department of Environment, Climate Change and Water (NSW)

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Abstract

A lack of awareness and understanding of risk and uncertainty can lead to poor decision making and higher costs for policy providers, as not accounting for them may produce policy which is inflexible and with a negative effect on welfare. Further, misunderstanding of and/or failure to account for risk and uncertainty can inhibit research and development for policy to which environmental economics can contribute (for example, in developing effective measures of sustainability). The aim of this project is to develop guidelines for 'Best Practice' approaches to risk and uncertainty in environmental economics for guiding policy development and implementation, taking into account key issues such as costs, irreversibility, adaptation and dynamics. These guidelines are developed by examining the frameworks commonly used by environmental economists to account for risk and uncertainty (such as the Precautionary Principle and Cost Benefit Analysis) as well as specifically developed theories (e.g. Quiggin's Rank Dependent Utility Theory), borrowing from other disciplines (e.g. Prospect Theory) and drawing attention to lesser known ideas (e.g. Shackle's Model).

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Introduction

The aim of this project is to develop guidelines for 'Best Practice' approaches to risk and uncertainty in environmental economics. Section 1 begins by introducing the concepts of risk and uncertainty and highlights why they are important in environmental economics and policy and discusses some of the issues surrounding definitions and terminology within the literature. Understanding the distinction between risk and uncertainty is important as they are concepts which apply across many different disciplines and are often defined in different ways. Several of these disciplines, such as the physical sciences, engineering and socio-psychology, interact directly with economics in an environmental setting. Section 2 looks at existing conceptual frameworks from the literature such as Adaptive Management and the Precautionary Principle. Section 3 examines existing methodological solutions to account for risk and uncertainty in environmental economics. Section 4 devises an unique conceptual framework and a set of guidelines useful for application in the face of risk and uncertainty.

Section 1 Defining risk and uncertainty

The concepts of risk and uncertainty are defined both broadly and in terms of how they are accounted for in this paper. The definition and characterisation of risk are followed by an examination of the concept of uncertainty as it relates to environmental economics.

1.1 Defining and characterising risk

Risk relates to the probability of an event occurring and the effect or consequences of that event. This, 'scientific' or 'real' risk is relatively easy to quantify and can be accounted for in most analyses with relative ease and is sometimes known as 'statistical uncertainty'. A further definitional component of risk is to distinguish between the terms 'risk' and 'hazard'. The term 'hazard', commonly used interchangeably with risk, is often used in reference to safety standards (e.g. chemical safety, food safety and biosecurity). A hazard can be defined as "the way in which an object (substance) or a situation may cause harm" (CEFIC, 2003).[1] Exposure is the extent to which the recipient (the environment, humans or animals) is exposed to or influenced by the hazard. The risk is the likelihood that harm will occur following exposure to the hazard – that is, without the simultaneous existence of the hazard and subsequent exposure to it, there is no risk (CEFIC, 2003).

Methods to quantify risk (or statistical uncertainty) for parameters have been extensively developed, and are commonly based on the normal and the chi-squared distributions (see Figure 1.1). Statistical uncertainty is particularly important in the cases where very small data sets (e.g. rainfall records) are available. Quantifying the effect of statistical uncertainty is important for sensible use of probabilistic methods.

Risk (R) can be defined in terms of a decision rule $\alpha(x)$ which is a function of a set of possible actions that can be taken for every possible observation (x), where x is a random variable distributed over a probability density (or distribution) function (pdf), $f(x)$ with a mean, μ and a variance, σ^2. There are many different pdf's with the most well known being the standard 'normal' distribution (or bell curve), the Chi squared (X^2) distribution and the F-distribution (see Figure 1.1 below).

[1] http://www.dehp-facts.com/upload/documents/webpage/document52.pdf

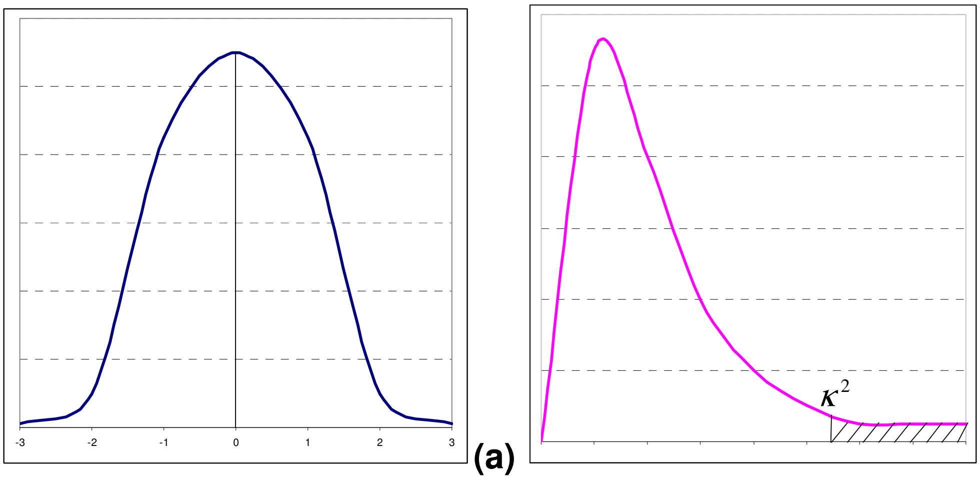

Figure 1.1 Probability Distribution Functions: (a) Normal Distribution; (b) Chi Squared Distribution [2]

There are three main methods of risk analysis, commonly used by economists, these include: the Expected Monetary Value, Expected value - Variance decision theory and a more formal risk analysis.[3]

1.1.2 Types of Risk

Although statistical definitions may be adequate for specific disciplines or scenarios, Brun (1994) (in Sjöberg et al, 2004) comments that it is important to understand that risk appears to mean different things to different people. As a result, risk can be further characterised as either objective (technical risk) or subjective risk (risk perception) and exogenous or endogenous risk. Regardless of these characterisations, all risk concepts have one common element: "a distinction between reality and possibility" (Sjöberg et al, 2004, p 7).

'Objective risk' (also known as real, technical or scientific risk) is risk that can be directly attributed with a quantifiable value. For example the risk of

[2] Most econometrics and statistics textbooks provide detailed discussions on the nature and specifications of these and other probability density functions.
[3] Details available on request.

premature death of a smoker in the US from smoking in 1990[4] was 39% (McGinnis and Foege, 1993). However, how people act and understand risk is learned by social and cultural conceptions and evaluations of the world and what it should, or should not be (Boholm, 1998).

Therefore, 'subjective risk' (or risk perception) can be defined as:

(i) How individuals perceive objective risks based on external influences such as the media, previous experiences, knowledge (related to the risk target) and internal personality traits such as their degree of risk aversion or their attitude towards risk.[5]

(ii) How individuals assess risks when they have no information (i.e. they do not have information pertaining to the objective risks). This type of subjective risk is formed nearly entirely by internal emotive or attitudinal traits.

For example, a risk averse adult who has never smoked may over-estimate the risk of premature death to others due to smoking as a result of numerous public health campaigns which highlight the dangers of smoking or because a family member died of lung cancer (personal experience, higher level of knowledge/understanding, the 'dread factor'). Alternatively a teenager's perception of premature death from smoking, for example, may be considerably lower than the objective risk because they have an attitude towards risk that makes them believe that they will not be susceptible to a premature death (risk denial, unrealistic optimism), even if others are indeed at risk.[6]

The 'dread factor' can be defined as the perceived lack of control, potential of catastrophic events, certainty of fatality, and unequal distributions of risks and benefits. People are more comfortable and less likely to over-estimate the

[4] 39 in 100 people who were smokers in the US in 1990 died at a younger than expected age from a smoking related illness.
[5] For a more 'economic' discussion of subjective risk – see Dillon, 1971.
[6] Note that this is just a convenient example and that risk denial and unrealistic optimism is not limited to younger people or those with less experience or a limited understanding of the issues.

effect of a risk they see as voluntary, controllable or natural (Slovic, 1987). This is commonly discussed in conjunction with the 'unknown factor' which is where people are more affected by and generally over-estimate the effects of a risk that they do not understand or have limited knowledge of, i.e. the risk is novel and unobservable (i.e. no objective risk exists) (Slovic, 1987). With reference to the above example, a fear of the unknown could come into play where a person does not have the knowledge of the links between smoking and cancer and may over-react if a member of their family were to contract this disease. This may be likely to occur in less developed countries e.g. in South East Asia, where there is minimal public health education related to the risks of smoking to health.

'Exogenous risk' is risk that is external to the decision maker that is it cannot, unlike 'endogenous risk', be controlled for by the subject or the system. For example, a person's risk of contracting lung cancer could be mitigated by that person choosing not to smoke, or by quitting smoking (endogenous risk), but their genetic predisposition or exposure to some external particles (e.g. asbestos) is likely to be (at least partially) outside their control (exogenous risk) and therefore their ability to protect themselves from contracting this disease may be minimal. Ability to control for external risks can exist to varying degrees dependent on the situation, for example, once on a plane the ability to control for the risk of a crash is entirely exogenous, however, a person can chose not to fly thus reducing their risk of being in a plane crash effectively to zero. Alternatively, true exogenous risks, which cannot be mitigated by choice, also exist such as the earth being hit by a comet.

1.2 Defining uncertainty

For the purposes of this paper uncertainty is defined in terms of "radical" uncertainty which is characterised by a lack of knowledge or information. Uncertainty occurs where objective (or subjective) probabilities *cannot* be assigned to outcomes and the full range of possible events *cannot* be identified (Peterson, 2006). Other terminology often used includes: Knightian uncertainty (Knight, 1921), true uncertainty, ambiguity, ignorance or interdeterminancy. Although all these terms are widely used, they shall all be referred to as 'uncertainty' unless otherwise noted for clarity or distinction.

It may be useful to examine uncertainty in similar terms used in defining risk. An uncertain event can be characterised as all future events, those where the probability of their occurrence is unknown and those events which are entirely unknown. The hazard, which may lead to harm, is also unknown probabilistically or with any certainty: the actual hazard resulting from the event is unknown and neither is the degree of harm that the hazard may bestow.

Within environmental economics, uncertainty is particularly relevant for several reasons:

1) The nature of the system/s or the problem/s to be addressed – for example, climate change –what effect may it have, what will be affected and to what degree will this occur;
2) Issues of:
    a. Irreversibility – damages or policy may be partially or totally irreversible (from Pindyck, 2006);
    b. Hysteresis – damages or policy may be reversible but on a different return path potentially changing the system;
3) And within (1) and (2) issues of imperfect information and sunk costs.

These issues will be expanded on in Sections 2 and 3.

Section 2 Accounting for risk and uncertainty

This section initially focuses on the importance of having an understanding and awareness of the existence of issues to do with risk and uncertainty. Conceptual frameworks will be addressed for risk assessment and management and for uncertainty, commonly applied to environmental problems. This will follow with a discussion of how to adapt the use of traditional/neo-classical economic theory applied to problems of risk and uncertainty on a conceptual level.

2.1 Embracing the concepts of risk and uncertainty

> *Embracing uncertainty…exposes uncertainty in an emphatic manner to simulate imaginative thinking about policy options that may be more robust or informative.*
>
> (Walters, 1986)

There are several very simple ways to account for risk and uncertainty in environmental economics and policy development. These include:

(i) Clearly defining the problem to ensure that the researcher thinks through any possible risks or issues of uncertainty and considers how they may affect the research or policy in question;

(ii) Utilising existing frameworks such as Adaptive Management and the Precautionary Principle which have been created for problems such as those in environmental economics and their resulting policy options;

(iii) Being aware of, and accounting for, the different perceptions and attitudes towards risks of different actors within the system, especially the general public.

2.1.1 Defining the problem

Avoiding ambiguity and effectively accounting for risk and uncertainty requires clearly defining the problem at hand to limit the element of surprise and allow the researcher to produce informed and relevant solutions to the problem.

The ideas below are adapted from the United States' Environmental Protection Agency (US EPA). This process has been designed to examine ecological or human health issues and does not consider the broader picture of socio-economics and the existing policy framework. As a result, the US EPA's process has been further adapted here to attempt to account for problems with a multi-disciplinary focus, particularly consideration of some political-economic issues.

- What is the nature of the biophysical problem?
  - What is the biophysical process? What form does it take?
  - Whom or what does the process affect?
  - Is the process solely an ecological issue or does it impact humans directly (i.e. their health or lifestyles)?
  - What are the hazards (risks) of concern?
  - Point versus non-point source hazards.
  - How does exposure (either human or ecological, or both) occur?
  - What is the scale of the problem?
  - Over what time frame will it occur? And is there a critical (threshold) point at which the system may change?
  - Are there possible issues of irreversibility?
  - How resilient may the system be? To what degree may the system be able to adapt (either autonomously or with active management)?
  - How resilient may those who are affected be? And to what degree may they be able to adapt?
- What are the current regulatory arrangements and how may they affect the issue?
- What social/economic framework may be best to apply for the analysis – Cost Benefit Analysis?
- What are the uncertainties that may affect any component of this problem? What might be uncertain?
  - The likelihood or magnitude of events?
  - The process in which unknown events translate into outcomes?
  - Where or when may they occur?
  - What information do we have that may help us assess the benefits and costs of these uncertainties?

- What can we learn in the future? – are there structured ways we could think about what the future holds?

(Adapted from the US EPA's Planning Phase of Risk Assessment: EPA's Guides to Human and Ecological Risk Assessment (1998)).[7]

The idea behind the US EPA's structure is to ask the right questions so as to be able to adequately characterise the risks associated with the problem, and to have an awareness of the possibility of uncertainty within the system and where it may have an impact on the research or policy work conducted. Gathering quantitative information and conducting analysis is the second stage in the US EPA's process, followed by risk characterisation which feeds directly into the final stage of risk management. Risk characterisation is a culmination of the work undertaken in the planning, information and analysis components, and attempts to provide quantitative risk estimates to help answer the preceding questions. However, as defined in this paper, uncertainties cannot be quantified and that some risks that relate to socio-economics may be very difficult to quantify due to either the nature of the risk and/or unavailability of the information.

2.1.2 Established frameworks and principles

A. The Adaptive Management Framework:

Adaptive Management (also known as Adaptive Resource Management) is defined as an iterative process of updating policy through research (Walters, 1986). Originally developed by Canadian ecologists Walters and Holling in the 1970s, it is now widely used in Australia and the US in environmental policy see figure 2.1 below, initially in fisheries management, but has been recently applied to many other areas.[8]

[7] http://www.epa.gov/riskassessment/
[8] Some Australian examples include Allan, 2008; Bennett et al, 2005; and Gilmour et al, 1999.

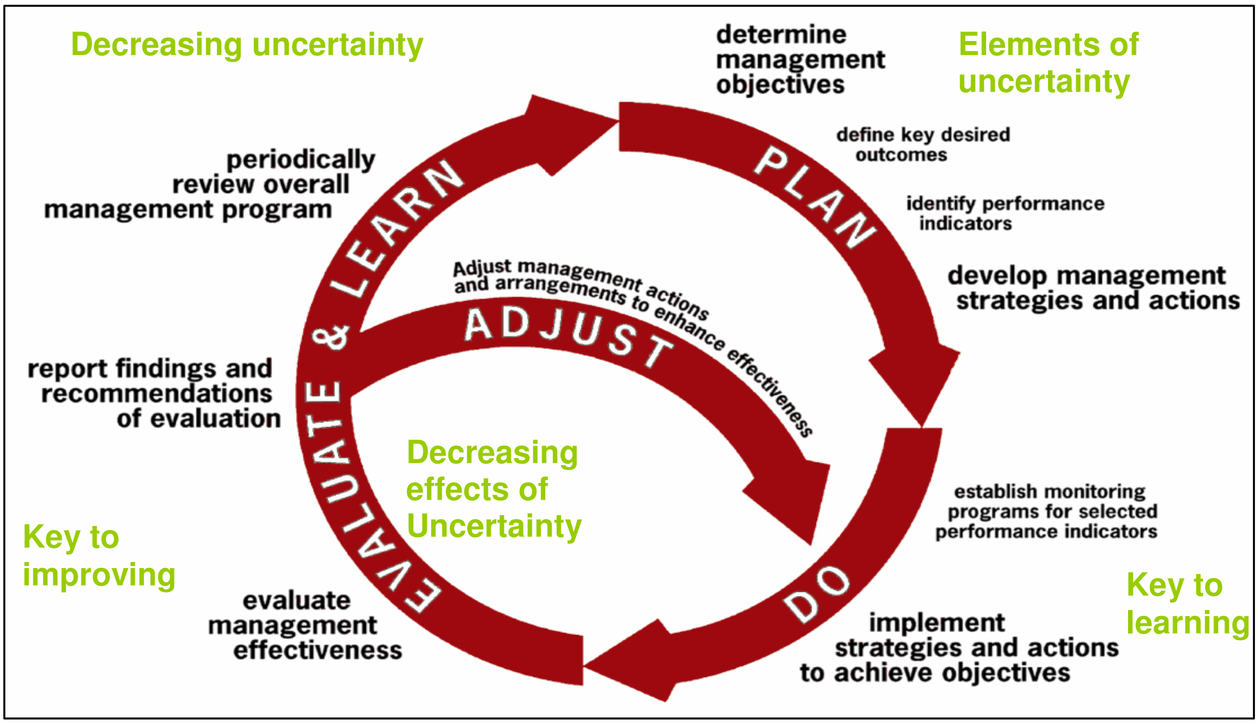

Figure 2.1 The Adaptive Management Framework
(Adapted from CSIRO Marine & Atmospheric Research, Management Strategy Evaluation).[9]

Walters (1986) focused on four main aims of Adaptive Management:

1. To bound management problems in terms of explicit and hidden objectives, practical constraints and factors in policy analysis;
2. To represent all known systems in terms of dynamic behaviour with clear assumptions and predictions to allow learning from error;
3. To represent uncertainty through time in relation to management actions using models consistent with experience to lead to improved productivity;
4. To design balanced policies that provide for continuing resource production whilst increasing understanding - e.g. use of decision tables or matrices.

[9] www.cmar.csiro.au/research/mse/

The overall objective of Adaptive Management is to reduce uncertainty over time through monitoring and evaluation. Decision making may simultaneously maximise one or more objectives and, either through research or 'doing', gain information needed to improve future management, this is represented simply in Figure 2.1 above. Ideally, an element of efficient reduction of uncertainty over time is desirable, where information is collected about initially unknown factors, whose expected costs are less than expected benefits.

There are always limitations, however, and effective Adaptive Management cycles typically require a long time horizon (Lee, 1999). Lee (1999) noted that in the late 1990s there was only one successful example of Adaptive Management working effectively – and that was the case of fisheries in northwest Australia[10] (1988) and that it took over a decade to achieve practical results in fisheries management (Lee, 1999). Adaptive Management does not work as well for problems where the outcomes are difficult to measure, when there are many policy options available, or where there are problems with extreme temporal uncertainty, such as climate change. Lee (1999) also warned against the practical problems of implementing the Adaptive Management framework such as having a clearly defined problem that can be translated into practice; an understanding of the long term and dynamic nature of the system and the interactions between the physical and human worlds (this includes interaction within the human realm e.g. stakeholder consensus or issues to do with benefit distribution); an understanding of the costs and benefits of the policy; and having effective and continuous management and leadership of the process. Without proper design and implementation Adaptive Management is no more than a 'buzz word'.

B. The Precautionary Principle:

The Precautionary Principle is taken from the German principle of *Vorsorge* or 'foresight' which was first introduced in German law in the 1970s (Gollier and

[10] This was a project by the CSIRO in 1988 designed by Keith Sainsbury. See Lee (1999) for more details.

Treich, 2003). Since then it has been applied to international conventions such as 1st International Conference on Protection of the North Sea (1984), The Maastricht Treaty (1992) and The Rio Convention (1992). It is now the most notable anticipatory principle in international law (Gollier and Treich, 2003).

Precautionary Principle is a conceptual approach which may be an appropriate foundation to base decision making under conditions of large uncertainty (Goddard, 1997) and can be defined as follows:

> Where there are threats of serious or irreversible damage, lack of full scientific understanding shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.
>
> (Principle 15, The Rio Declaration, 1992)

There are, however, many other definitions of precaution, and it may be defined as "caution in advance"; "caution practiced in the context of uncertainty"; or "informed prudence". These terms all suggest a need by decision makers to anticipate damage before it occurs. Further, it is the responsibility of the decision maker to establish that the proposed activity will not (or is very unlikely to) result in significant damage.[11] Further, if the level of damage is likely to be high there is an obligation for action to be taken to prevent or minimise such harm even when it is unknown whether the damage will be high or is even likely to occur. The need for control measures increases with both the level of possible damage and the degree of uncertainty.

The Precautionary Principle has been widely applied in areas of the environment due to the large degree of uncertainty in this field. The Precautionary Principle has been used within Australia in both a policy and

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[11] 'Significant' damage can be defined as damage that has a negative impact on social welfare or the environment.

legal approach in the environmental field. [12] Policy examples include the *NSW Protection of the Environment Administration Act, 1991*; and the *Inter-Government (COAG) Agreement on Environment, 1992*. A widely cited legal example of the Precautionary Principle in practice, Leatch v National Parks and Wildlife Service (1993) where Justice Stein noted that policy makers have a "Common sense duty to be cautious". [13]

The Precautionary Principle and policy:

There are some concerns that the Precautionary Principle may distort policy by removing focus from more perilous hazards and instead focusing on less clearly defined hazards. This may result in significant social and environmental costs (Peterson, 2006a). However, by assessing not only the importance and relevance of each element but also by considering the costs and benefits of the different policy possibilities may help to minimise these negative outcomes (See Figure 2.3 below), and further highlights the importance of the economist's role in application of the Precautionary Principle.

Figure 2.3 attempts to explain the dynamic nature of the Precautionary Principle within a simple policy process and the steps taken in designing, assessing, implementing and evaluating the policy. Note the similarities between this and Adaptive Management, described above. At the initial time period (t_0) consideration is made both of the current situations and what may happen in the future (t_1). From this point an analysis is conducted to assess the costs and benefits of the existing environmental and regulatory parameters using a Cost Benefit Analysis.

In a simple world, if benefits outweigh the costs then the policy change should be implemented, and then its performance evaluated in t_1 and adapted if

[12] For a more comprehensive discussion of the Precautionary Principle and its applications in Australia see Peterson, 2006a.
[13] This 'widely cited example' itself shows how blurred the definition and interpretation of the Precautionary Principle can be in practice. Is the Precautionary Principle merely a case of applying 'common sense' caution?

required. However, it is possible that the solution is not so clear cut, and although benefits maybe greater than costs in the short term, there may be information to suggest that this may not be the case in the long run. If this information is available then this must be taken into account when conducting the Cost Benefit Analysis. If costs outweigh the benefits then there needs to be further consideration of the future situation. If the information required to assess the situation will not be available until t_1 there may be a delay until the policy can be evaluated. If this occurs, it is important to understand that there may be losses made by waiting for t_1 and as a result attempting to determine the maximum loss made is desirable, although not fitting with the Precautionary Principle.[14] The Precautionary Principle essentially suggests that any loss as a result of waiting for further information may be crucial and the policy maker should act to ensure that there is no (further) environmental degradation; this may or may not allow time for the collation of further information in the future.

[14] Note the similarities between this concept and real options – see Section 3.2.6.

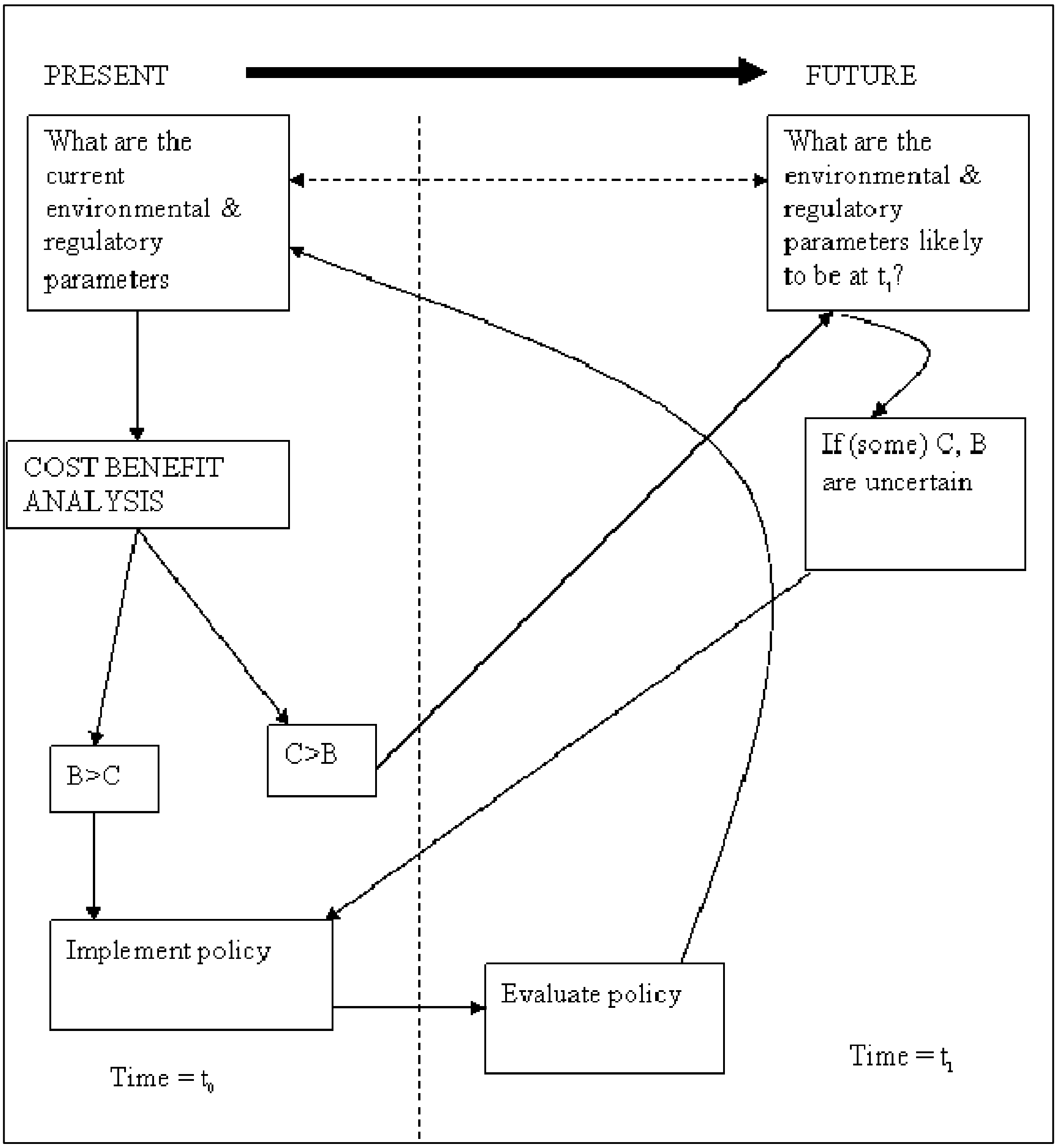

Figure 2.3 Precautionary Principle and the Policy Process

Limitations of the Precautionary Principle:

The Precautionary Principle has many limitations, both from a popular view as well as from an expert view. Generally opponents criticise the Principle on two fronts, first that the Principle undermines growth, development and business-as-usual and limits innovation (Bailey, 1999; Peterson, 2006a), i.e. it is inherently risk averse (Quiggin, no date). Second, the Principle is commonly criticised for not being clearly defined, nor having clear guidelines for policy implementation (Cussen, 2009 and Peterson, 2006b). [15]

However, the applicability and current popularity of the Precautionary Principle may be a good premise for sensible inclusion (or at least consideration) in the creation of guidelines for accounting for uncertainty.

Adaptations to the Precautionary Principle:

An alternative way of thinking of the Precautionary Principle is to focus, instead of being cautious, on flexibility and adaptation, that is, “keeping your options open”. Flexibility allows a short term decision to be made with ‘caution’ whilst further research is undertaken to enlighten the decision maker on possible, relevant alternatives or by converting the problem at hand into one that involves well-understood alternatives (Quiggin, no date). Quiggin’s ‘flexible’ approach to the Precautionary Principle means that it is a useful component of the decision making process, a constraint on the application of decision theory, not part of decision theory itself (Quiggin, no date). This idea of ‘flexibility’ links with the seminal works of Arrow and Fisher (1974) and Henry (1974) who focused on the benefit of keeping options open so as to be able to adjust policies in light of better information. This is defined as a ‘quasi-option value’ or an ‘option value’, and is an extra source of benefit to be included in any cost benefit analysis of the net benefits of policy alternatives (Ingham and Ulph, 2005). ‘Options’, however, require knowledge as to how and when the approach could be adopted, how ‘open’ the process can be and what type of methodology could be used to assess such a situation.[16]

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[15] Sandin (1999) lists 19 different meanings of the Precautionary Principle.

[16] See Section 3.2.6 for a discussion of ‘options’ which are regarded as one of the main techniques for accounting for uncertainty within an (environmental) economics framework.

2.2 Updating 'standard' economic theory

The neoclassical economic framework of maximising utility is deterministic and Expected Utility (EU) is an expansion of this with at least one random variable. EU assumes rational consumers are expected to maximise their utility subject to constraints, is one of the most widely adapted frameworks in economic theory. The EU framework is the main tool for analysis of decisions under risk with known (linear) probabilities (Von Neumann and Morgenstern, 1944). In 1954, Savage extended the EU framework to account for 'subjectivity' (i.e. unknown probabilities), this is known as the Subjective Expected Utility (SEU) model, and shows that 'rational' choices of the subjective decision maker can be derived from their expected utility. These models are widely used because their mathematical structure is applicable to both theoretical and empirical situations, and because they work well when probabilities are clear and well understood (Shaw and Woodward, 2007). The application of the EU framework in environmental economics is similar to other areas of economics, with popular methods such as Pareto Optimality and Contingent Valuation based on EU theory. [17]

However, there is evidence that conventional EU theory (linear probabilities) does not apply in the context of less clearly identifiable risks or true uncertainty these are important for the development of environmental policy because it shows that there are reasons why alternative theories should be considered over standard EU theory.

- *Allais Paradox* (1953): show an inconsistency of actual observed choices with the predictions of expected utility theory. It indicates that individual's have a tendency of individuals to react differently to high-

[17] Further detailed explanation of the traditional EU framework and some of its variants (SEU, RDEU and MMEU), is available on request.

consequence, low probability event. [18],[19] This implies that the assumption of linear probabilities is not always satisfied; in other words, decision makers are not able to assess the magnitude of risks/uncertainties objectively and tend to 'rank' risks with a high level of dread, even if they are unlikely to eventuate, as being more "important" than a less catastrophic but more likely risk.

- *Ellsberg Paradox* (1961): people demonstrate an aversion to ambiguity[20] and have a 'source dependence' (Tversky and Kahneman, 1992). Essentially, a decision maker may avoid prioritising issues where uncertainty abounds, especially if they feel ignorant of the situation, but less so when they feel they have a good understanding or knowledge of the situation.

- *Framing Effects*: Tversky and Kahneman (1986) noted that people tend to think of possible outcomes in terms of a framing effect, relative to a certain reference point (status quo) rather than to the final status. A framing effect is the manner in which a rational choice is posed, i.e. the language used and the scenario developed when presenting people with a risky situation. Essentially, people tend to conceive a risk framed in positive terms as being preferable to a risk presented in negative terms, regardless of the fact that both are identical.

- *Loss Aversion*: People also have different risk attitudes towards gains and losses and are more concerned with potential losses than potential gains (loss aversion) (Kahneman and Tversky, 1984).[21]

In order to account for these deficiencies some researchers have developed adapted EU models which relax some of the traditional assumptions and allow non-linear weights on the probabilities. Some of the best examples of this are

[18] Further details available on request.
[19] See Fundenberg and Levine, 2009 for an application to risk aversion.
[20] Ambiguity here is synonymous with Knightian uncertainty.
[21] This is the underlying premise for Prospect Theory (Kahneman and Tversky, 1994).

Quiggin's (1991) Rank Dependent Expected Utility (RDEU) which allows probabilities to enter non-linearly into an individual's objective function, avoiding the Allais Paradox;[22] and Gilboa and Schmeidler's (1989) Maxmin EU model (MMEU) assumes individuals assess probability based on their own personal experience, and which was developed to explain the Ellsberg Paradox. [23]

Section 3 Models and methods

This section looks at existing methods for accounting for risk and also proposes ways that theoretical models can be extended to account for true uncertainty.

3.1 Traditional techniques for objective risk analysis

Objective risks are relatively easily quantifiable and hence there are many standard approaches to accounting for risk in environmental economics. Table 3.1 presents a list of theoretical, empirical and qualitative techniques for accounting for objective risk (as defined in this paper) and their relevant references.

Table 3.1 Some techniques for accounting for risk in environmental economics [24]

Method	Brief description	References
	Theories	
Expected utility theory (and variations)	As discussed in Section 2.2. Accounts for people's personal preferences.	Von Neumann and Morgenstern, 1944; Savage, 1954; Machina, 1987; Gilboa and Schmeidler, 1989; Quiggin, 1993 and 2005
Cost of risk bearing	The amount of expected income a risk averse household is willing to pay in order to avoid the risk	Arrow, 1964; Fisher, 1973; Mäler and Fisher, 2005

[22] Machina (1987) has also conducted expansive research in this area.
[23] Details available on request.
[24] This list is not exhaustive and there are many other techniques that are used in the literature or in practice.

State Contingent Approach	Uncertainty is represented by a set of possible states of nature and uncertain outputs by vectors of state contingent goods. Originally designed for production uncertainty but equally applicable to choice under uncertainty.	Arrow and Debreu, 1954; Chambers and Quiggin, 1998, 2000, 2006; [25] Chavas, 2008. (Note: very little literature from Arrow and Debreu's initial study in 1954 to Chambers and Quiggin in 1998).
Ecological resilience (ER)	Irreversible shifts in state of ecosystems where each system has threshold where they become 'weak' and are not able to continue to function in the same way. When risks can be quantified ER can be explained by distance to the threshold.	Walker et al, 2007; Mäler, 2008.

Empirical Techniques		
Expected value analysis	Takes into account the size of the payout (hazard) and the probability of its occurrence (risk)	n/a
Discounting	Used within a CBA to account for the value of money over time, following the premise that benefits or costs today will not be valued the same way by future generations.[26] The value of money used is a risk that is taken in valuing environmental benefits for future generations to the detriment or advantage of current generations.	Quiggin,2006; [27] Stern, 2007; Nordhaus, 2007

[25] The definition of uncertainty in this paper is synonymous with scientific uncertainty. This differs from the defined version of uncertainty as discussed in this paper. Therefore, it was deemed more appropriate that this be represented as a technique that accounts for risk within a system.

[26] A very public debate on discount rates and climate change ensued in 2006 with the UK Stern Review on climate change, using a very different discounting approach to Nordhaus' US equivalent. This highlights the importance of discounting in CBA especially for projects with high levels of risk. See, the UK HM Treasury (2003) "Green Book", Annex 6 available at http://www.hm-treasury.gov.uk/d/Green_Book2_03.pdf
and specifically Stern (2006)'s Annex to Chapter 2 available at
http://www.hm-treasury.gov.uk/d/Chapter_2_Technical_Annex.pdf
Also, see Nordhaus (2007) and Dasgupta (2007).

[27] Quiggin's definition of uncertainty in this paper is synonymous with scientific uncertainty – i.e. "random variables with a given probability distribution" (p21). This differs from the defined version of uncertainty as discussed in this paper. Therefore, it was deemed more appropriate that this be represented as a technique that accounts for risk within a system.

Sensitivity analysis	A study of how the variation ('scientific uncertainty') in model output can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of a model (either parameters or variables). Commonly used in CBA to account for the likely variation in inputs or outcomes.	See most environmental economics textbooks or texts on Cost Benefit Analysis such as Boardman et al, 2006 for further information.
Monte Carlo simulation	Useful for modelling phenomena with significant risk in inputs (randomised sampling technique).	As above
Probability density functions and cumulative distribution functions	Distribution of a random variable is a function which describes the density of probability at each point in the sample space (discrete or continuous).	See most generic statistics textbooks for more details.
Quantitative Uncertainty Analysis (or Probabilistic Risk Assessment)	A variation on Monte Carlo analysis, where a two-stage process is applied to separate uncertainty and variability in risks.	Frey, 1992; NRC, 2009.
Value of Information Analysis	At a basic level VOI provides a set of methods for "optimizing efforts and resources to gather, to process, and to apply information to help decision makers achieve their objectives" (NRC, 2009). The process begins by determining, given statistical uncertainty, the preferred option and the net benefit associated with any information gain that may cause the decision maker to change to another option in the future. Generally perceived as a very complex procedure which is difficult to implement due to data and skills requirements.	NRC, 2009.

Qualitative Techniques		
Risk Assessment	A conceptual or practical framework designed to account for and/or consider all the risks within a system. A decision making tool.	EPA, 1998.
Expert Judgement (or Expert Elicitation)	The opinions of professionals, academics or scientists are used to fill the gaps when uncertainties are large, complex or when there is not enough information available to make a decision using the usual tools available.	Spetzler and von Holstein, 1975

3.2 Existing methods to account for true uncertainty

There are several methods that are currently used by economists to analyse policy which can either be updated to account for true uncertainty (e.g. Cost Benefit Analysis) or have been developed as techniques that are designed specifically to investigate uncertain issues (e.g. Real Options Analysis). This section examines a list of possible methods that may assist the policy analyst when faced with uncertain decisions.

3.2.1 Cost Benefit Analysis (CBA): ex ante versus ex post analyses

Cost Benefit Analysis is one of the most widely used and accepted economic approaches in the realm of environmental policy, and can be used in conjunction with many of the techniques which account for risk, as outlined above (Table 3.1), primarily discounting and sensitivity analysis. However, once true uncertainty is introduced, some of these standard techniques are not, on their own, adequate solutions to the problem. Uncertainty should not undermine the usefulness of CBA as a tool and a broader interpretation of CBA should be taken when uncertainties exist to accommodate this issue. Young (2001) suggests that CBA should be integral to all levels of the policy analysis as it is a useful technique to weigh up policy options and to organise and consolidate available information.

Further ways of accounting for uncertainty in CBA include examining the costs and benefits of a policy both prior to implementation (ex ante) and after a period of time (or at the conclusion or review of the policy) (ex post). This provides researchers with an increased understanding of the problem, including whether or not their initial CBA estimates were correct and whether or not the policy has achieved its outcome. This enables updating of current information and possible adaptation of the policy to better fit the problem. Where feasible both analyses should take place and then the differences between them should be compared and adjustments to, or recommendations about, the policy should be made.[28] However, it is often the case that neither time nor resources are available to do this in which case justification should be made as to why only an ex ante or an ex post approach has been taken.

Ex ante and ex post analyses can also be examined in the non-traditional sense of the term: i.e. opinions of the public versus opinions of experts (Cropper and Oates, 1992). Should the 'expert' decision be made to ensure the best interest of the public? Or, should consumer sovereignty be maintained? This would imply collecting further information through surveying, for example contingent valuation studies, to examine the differences between expert and lay assessments of the resource or policy options.

A further way CBA can be updated to account for uncertainty is to conduct 'scenario planning' which is essentially a qualitative form of a sensitivity analysis. Scenario planning requires comparison of a set of two to three mutually exclusive 'what if' options for the future socioeconomic and/or physical environment which should be consistent and logical and are likely to directly influence the project at hand (NSW Treasury, 2007).

[28] This updating and evaluation of information throughout the process of conducting CBAs at an ex-ante and ex-post level is similar to the ideas behind Adaptive Management (see Section 2.1.2 above).

3.2.2 The Shackle Model

A less well known, yet formally derived, model of true uncertainty is the Shackle Model of Surprise (1949).[29] The model was developed by Shackle in the 1940s and can be considered a "powerful alternative to the application of expected utility theory to cases of hard uncertainty" (Young, 2001). Shackle's theoretical ideas stem from Knight (1921) and Keynes (1921), and his formal theory is based on three main concepts:

(i) Replacement of probability as a measurement of uncertainty with a measurement termed the "degree of (potential) surprise";

(ii) Creation of a decision or action choice index (ascendancy function) which evaluates the outcomes and their degree of surprise;

(iii) Use of a gambler's preference map so that prospects can be represented as a loss or a gain.

(Young, 2001)

Essentially, Shackle's refusal to accept that probabilities can explain truly (Knightian) uncertain events makes his approach unique. Shackle's "degree of surprise" is therefore defined as a measure of the *possibility* of an event. [30], [31] Shackle's Model has been widely criticised by more mainstream economists due to its theoretical arbitrariness and 'simplicity, however, there are four advantages of Shackle's model when decisions are made under true uncertainty (Bekker and Gaunt, 2006):

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[29] See Earl, 1983 (for a behavioural economics review); Ford, 1994 (provides a general review); Vickers, 1994 and Katzner, 1995 (further developed Shackle's model); Perry, 1989; Dalmazzone, 1995 and Young, 2001 (for applications to environmental uncertainty). All cited in Young, 2001.

[30] This is the most contentious of Shackle's assumptions, and he stands, until the 1970s, the lone economist to not just critic the standard approach of using probabilities to measure uncertainty, but was also the only one who attempted to develop a formal model for explaining why they should not be used (for an interesting account of how the Shackle model fits within the history of decision theory and its relationship with modern day decision theory see Basili and Zappia, 2006).

[31] For applications of Shackle's model in environmental (and other) areas where uncertainty affects decision making see Young (2001) – highways; Bekker and Gaunt (2007) – rural electricity project; Li and Sinha (2009) – highways.

1. The notion of surprise, unlike that of probability, is applicable to unique events;
2. The surprise function is non-distributional, this implies an incomplete list of outcomes;
3. Potential surprise is non-additive and has no requirement to sum to unity;
4. Surprise and ascendancy functions are separated into desired and undesired outcomes which allow separate consideration of uncertainty aversion to gains and losses.

3.2.3 Issues of irreversibility and hysteresis

The concept of endogenous irreversibility suggests that the effects of a new policy may be hard or even impossible to reverse (Pindyck, 2006). Pindyck (2006) notes that there are two kinds of irreversibility and that they work in opposing directions:

- Sunk costs to society are usually inevitable when a policy creates environmental degradation.[32]
- Environmental damage is usually totally or partially irreversible.

Generally speaking uncertainty is the main reason that sunk costs will be incurred and damage cannot be rectified. There are several key reasons this is the case:

1. Lack of information on, or understanding of, the system(s) – e.g.:
   a. The complexity of the system(s) may mean that the system is not sufficiently understood and therefore the policy option does not adequately protect the system(s) and allows for continued or unexpected degradation (and perhaps this degradation remains undetected for a long period of time);

[32] This may be due to construction (i.e. economic development) – there will be a small loss due to capital and labour services and materials being used at a given point in time, but these are then often freed up later on; and/or the cost of the loss of ‘paradise’ which is a larger irreversibility than the costs of development.

b. The degree of interaction between the system(s) and society is not clearly defined – and therefore the true costs and benefits cannot be specified, again leading to a policy option that does not maximise welfare and has longer term negative impacts on either the environmental system(s) or society;
c. The current and/or future 'value' of the resource is unknown – e.g. a wilderness area may be protected for the benefit of future generations regardless of whether the benefit of not protecting it, and opening say a ski resort, is actually more welfare maximising in the long run.

2. The policy option may be implemented by society in a way that was unexpected (i.e. collateral damage) and may mean that levels of environmental degradation are maintained or even increased. This is especially likely to be the case if society or a key stakeholder is benefiting directly from the policy option.[33] If future policy costs and benefits are uncertain, the sunk costs create an opportunity cost of adopting the policy, rather than waiting for more information about environmental impacts and their economic consequences. A traditional cost benefit analysis will therefore be biased towards adopting this type of policy (Pindyck, 2006).

3. If damage is totally or partially irreversible then adopting a policy now rather than waiting has a sunk benefit (negative opportunity cost). This often means the adoption of more conservative policies than would be otherwise used. This implies that a standard cost benefit analysis will be biased against policy adoption (Pindyck, 2006).

For example, if a rise in sea temperatures causes irreversible damage to a reef then failure to act immediately will result in increased damage and the cost of acting now, although uncertain, is not as great as the loss of the reef if

33 An example could be the protection of native vegetation through the banning of land clearing. Society benefits from the increased availability of the native vegetation (usually indirectly) however, it is possible that specific native vegetation can become invasive causing problems for other native flora or fauna species (i.e. upsetting biodiversity) which may have a negative effect on the natural environment.

no action is taken. In other words, the level of uncertainty over the costs and benefits will greatly affect how important the irreversibilites are.

A solution to these types of problems is to implement gradual changes in policy through updating information, rather than make one single decision, to ensure that there are minimal negative effects on either the environment or to maximise net social benefits (Zhao and Kling, 2002).

3.2.4 Safe Minimum Standards

Similar to both endogenous irreversibility and the Precautionary Principle, SMS is a concept first developed in 1952 by an agricultural economist, Ciriacy-Wantrup, where Safe Minimum Standards (SMS) are defined as an objective of conservation policy, achieved by avoiding the 'critical zone', "that is, those physical conditions, brought about by human action, which would make it uneconomical to halt and reverse depletion" (Ciriacy-Wantrup, 1952), or in other words 'the threshold below which loss is catastrophic'. Crowards (1996) commented that "'large' future losses will exceed the net present benefits of development (which represent the 'cost' to society of insuring against such losses)". In other words, SMS is designed to "explicitly incorporate into the decision making process the uncertainty that surrounds irreversible impacts on the natural environment" (Crowards, 1996). Not unlike the Precautionary Principle, SMS lacks theoretical formality and clarity in its definition and application, particularly across disciplines.

An alternative definition of SMS deals with a situation where conservation is treated as the highest priority unless the benefits from the development are regarded as so great as to justify any unknown, potential and substantial losses (Bishop, 1978). Bishop (1978) formalised Ciriacy-Wantrup's concept using game theory and making use of the Wald Criteria to minimise maximum losses (minimax).[34] This approach is noted by Crowards (1996) and Hohl and

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[34] See Hohl and Tisdell (1992) for details on Bishop's game theoretic approach to SMS.

Tisdell (1992) as being 'overly conservative' due to the pessimistic nature of the minimax process.

SMS can also be viewed as a constraint (lexicographic preferences) i.e. when assessing economic efficiency of a project it must be recognised that economic efficiency is a lower priority than the SMS criterion (Perman et al., 2003). It is believed, that economics cannot truly account for 'pure' (non-statistical) uncertainty and as a result, economic tools such as CBA, expected utility theory and options theory are inadequate in addressing problems with true uncertainty and irreversibility (Bishop, 1978; 1979). For example if there is a potential extinction of a species for which there maybe no substitute, then economic efficiency should not be the priority, as the benefit of retaining that species is far greater than any economic cost that may have to be sustained in order to protect that species.

Should irreversible loss or true uncertainty exist then an SMS constraint should be implemented (Crowards, 1996). Crowards (1996) emphasised that:

> *The fundamental difference between SMS and the traditional economic approach is that rather than aim strictly to maximise expected net benefits to society, SMS acknowledges the limitations of attaching probabilities to future outcomes in the face of extreme uncertainty … It concentrates instead on identifying appropriate standards and (in the words of Ciriacy-Wantrup, 1964) "choosing premium payments and benefits in such a way that maximum possible losses are minimised".*

3.2.5 Decision Analysis

Decision analysis is broad technique for assisting with decision making in an uncertain environment and has its roots in the utility theory of von Neumann and Morgenstern (1947). Decision analysis can be defined in several ways. Keeney (1982)[35] suggests two definitions:

> *(i) A formalization (sic) of common sense for decision problems which are too complex for informal use of common sense.*
>
> *(ii) A philosophy, articulated by a set of logical axioms, and a methodology and collection of systematic procedures, based upon those axioms, for responsibly analysing the complexities inherent in decision problems.*

Decision analysis is a useful tool for all decision problems where there are several possible 'solutions' with specific and uncertain consequences, and different costs and benefits, and where only one of these 'solution' alternatives must be applied. This 'solution' is determined through a structured manner (see Figure 3.3) using the principles of EU[36] to value the preferences of each alternative to decision makers.

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[35] Keeney (1982) provides a good discussion of the finer points of decision analysis for the non-decision analyst. His paper is available at: http://teaching.pdesign.ch/2006/DADT/Keeney1982.pdf

[36] See discussion in Section 2.2.

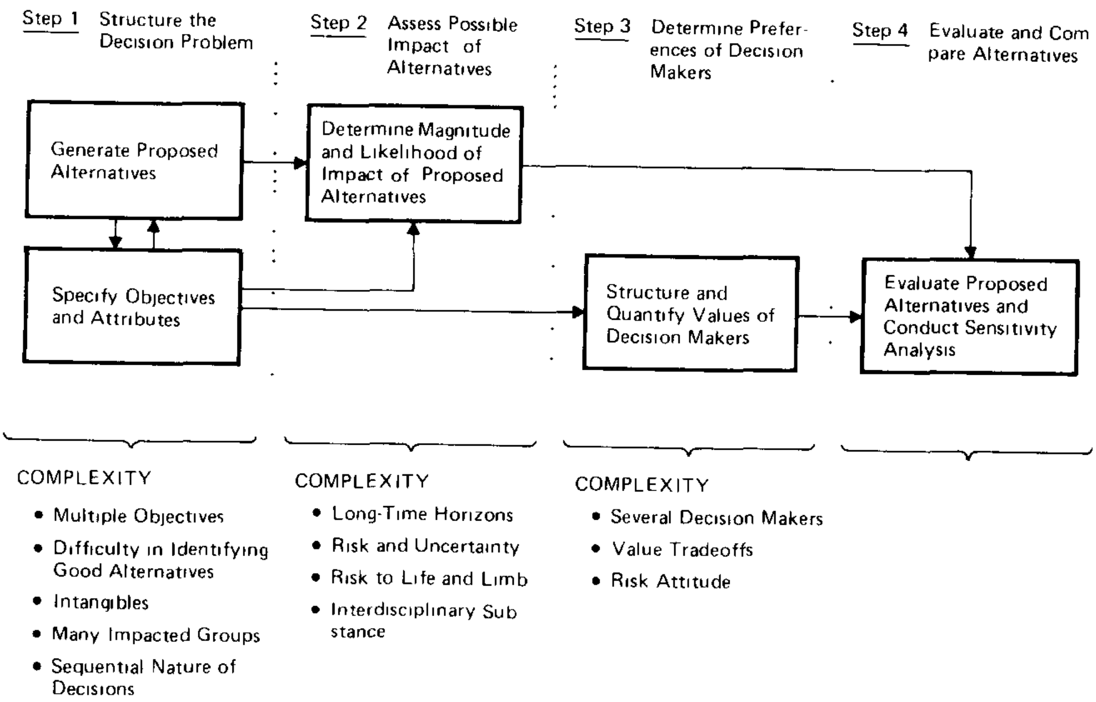

Figure 3.3 A schematic representation of the steps of decision analysis (Keeney (1982), Figure 1, p 808).

A more specific component of the broad technique of decision analysis is the use of Multi Criteria Decision Analysis (MCDA) and the formation of decision trees in an effort to quantify and account for uncertain behaviour.

MCDA aims to incorporate quantitative modelling outputs, such as risk assessments, with more qualitative research, such as CBA, (i.e. to examine many streams of dissimilar information in one framework or decision matrix) so as to "evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision making" (Kiker et al, 2005). Some of the optimisation methods used within the MCDA framework include Multi Attribute Utility (or Value) Theory, the Analytical Hierarchy Process or Outranking Models (Kiker et al, 2005).

Decision trees may also be a useful technique to employ where uncertainty is an issue, however, these trees are often highly complex and difficult to interpret often to the point of rendering them useless in a policy making environment (Quinlan, 1986). An example of the use of decision trees with true uncertainty is provided by Grant and Quiggin (2006) in their paper "Learning and Discovery" which examines uncertainties that can occur due to the individual researcher's unawareness of alternative possibilities. This 'unawareness' can be realised either through direct observation or through consultation with colleagues, as opposed to gaining more data making the use of Bayesian updating redundant when dealing with awareness of alternatives (i.e. there is a sense of ambiguity surrounding the new information) as opposed to hard or factual data which removes (some of) the uncertainty[37].

3.2.6 The Bayesian Approach

The traditional Bayesian approach treats the unknown parameters of a model as random variables. The decision maker then combines a pre-specified prior over the parameters with observations from the data to construct a predictive distribution of returns. Expected utility is then maximised with respect to the predictive distribution over the Bayesian optimal portfolios. This approach works well with respect to risk.

However, the Bayesian decision maker is assumed to have only a single prior or, equivalently, to be neutral to true or radical uncertainty. Given the difficulty in estimating points of returns and the sensitivity of portfolio weights to the choice of a particular prior, and the substantial evidence from experiments that agents are not neutral to ambiguity (Ellsberg, 1961). [38] It is important to consider investors with multiple priors who are dealing with decisions under uncertainty (Garlappi et al, 2006). [39], [40]

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[37] In Grant and Quiggin (2006), Aragones et al. (2005) notes that learning may be possible without new data, i.e. through informal nodes such as communication with a colleague. This is directly in contrast with the Bayesian case under unbounded rationality where learning can only occur as a result of new data (p. 3-4).

[38] The aversion to ambiguity is particularly strong in cases where people feel that their competence in assessing the relevant probabilities is low (Heath and Tversky, 1991) and when subjects are told that there may be other people who are more qualified to evaluate a particular risky position (Fox and Tversky, 1995).

[39] For example, Gilboa and Schmeidler (1989), Epstein and Wang (1994), and Chen and Epstein (2002), have developed models of decision making that allow for multiple priors where the decision-maker is not neutral to ambiguity.

3.2.7 Real Options Analysis

Real options are based on the idea that if, (relevant) information is available in the future that could lessen the uncertainty of the decision, then it is worth waiting for this information to become available. That is, if the policy decision is deferred now, then a 'better' decision could be made in the future. However, this delay can also come at a cost. Originating in the field of finance (Myers, 1984) the concept of real options was an expansion of options theory designed to focus on actual or real (tangible) decisions and to account for uncertainty about:

(i) The future evolution of knowledge about the parameters that determine the value of the project;
(ii) Management's ability to respond to changes in estimating these parameters.

Within economics, the seminal work by Arrow and Fisher (1974) and Henry (1974) applied the 'option value' concept to economic decision making under uncertainty. A (quasi-)[41] option value, due to arrival of new information, has five main attributes:

- Maintain the flexibility of responding to new information;
- Independent of risk attitude;
- Dynamic framework with learning.

In environmental economics, real options have been extensively applied from Arrow and Fisher's original paper (1974) to evaluating natural resource investments (Brennan and Schwartz, 1985), Pindyck's (1991) work on

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[40] It should be noted, that as with EU theory, there has been much work that attempts to account from true uncertainty within a Bayesian framework, but to date not one single method has provided a 'solution' that is widely accepted.
[41] The term 'quasi' option is sometimes applied when issues of irreversibility exist – see footnote 7 in Pindyck, 2007 for more details.

irreversibilities, pollution emissions limits (Carr and Saphores,1999) and more recently in the area of climate change (Pindyck, 2002, 2007).

From a managerial, or decision makers, perspective, the advantages of a real options analysis includes:

- Considers uncertainties and the options (flexibilities) giving two responses:
    - The value of the investment opportunity (value of the option)
    - The optimal decision rule (threshold)
- Can be viewed as an optimisation problem, maximising net present value (NPV) subject to:
    - Market uncertainties (i.e. prices)
    - Technical uncertainties (i.e. volume of stock, e.g. numbers of species etc)
    - Relevant options (flexibilities)

3.2.8 Other Dynamic Problems

Uncertainty, the more complex of the two constructs, can be accounted for in an Optimal Control Theory framework. Inter-temporal optimisation can either be done in discrete time (dynamic programming) or continuous time (optimal control theory); both can be solved analytically or numerically under certain conditions.

There are many suggestions of techniques within a dynamic programming framework that account for risk and uncertainty and these techniques are widely used in agricultural, fisheries and forestry areas as well as in environmental applications (Kennedy, 1981). Risk can be accounted for with non-linear preferences or by endogenising risk within a model.

Optimal stopping (or timing) (a subset of Optimal Control Theory) is concerned with choosing a point in time to take an action in order to maximise an expected return or minimise an expected cost. Optimal stopping problems can be found in areas of statistics, economics (Lippman and McCall, 1976) including environmental economics (see Mäler and Fisher, 2005; Pindyck, 2001 and Clarke and Reed, 1990) and mathematical finance (in relation to Options Theory).[42]

3.3 Limitations of learning and acquiring more information

In situations of pure stochasticity there are times when 'learning' will not help and when uncertainty does not change with the availability of information. Sometimes the best decision has to be made based on the condition of the environment at that specific point in time, with that being the maximum amount of information that will ever be available (Freeman and Zeitouni, 2003). This occurs when:

- The complexity of the problem or the combination of processes is such that the environment cannot be better understood than it is currently;
- The level of uncertainty today is the same as the level of uncertainty previously or what it will be tomorrow.

These issues can be overcome by either using stochastic variables in optimal stopping models (Freeman and Zeitouni, 2003), or by implementing two parallel policies that balance the need for more/better information with the need to avoid negative consequences (Manne and Richels, 1992).

Section 4 Frameworks

There are many possible solutions to addressing risk and uncertainty within an environmental economics and policy setting. Beyond increased awareness, however, it is difficult to determine which ones are 'best' and for

[42] There is a close theoretical relationship between Options Theory and Optimal Stopping (Fisher and Mäler, 2005 and Dixit and Pindyck, 1994). For further information on these theories and their relationships see Rico-Ramirez and Diwekar, 2004 and Shastri and Diwekar, 2006.

which situations and which ones are feasible both from a practical as well as a cost issue is much more difficult. This section provides a conceptual schematic which covers most of the key points outlined this paper; it also presents a decision tree type schematic of guidelines to help to think through problems and suggests specific tools that may be used throughout the thought process/analysis. This section will also discuss possibilities for a case study, Section 5, to highlight how this framework and the guidelines can be practically applied.

4.1 Framework

The aim of the framework below, Figure 4.1, is to present a big picture view of the problems surrounding, and distinguishing between, risk and uncertainty across several dimensions: time (current versus future), degree of reversibility and the expert versus public opinion debate, which is key in formulating effective policy communication. This framework also attempts to incorporate the ideas behind Adaptive Management and suggests that the Precautionary Principle be at least acknowledged in considerations concerning radical uncertainty and irreversibilities.

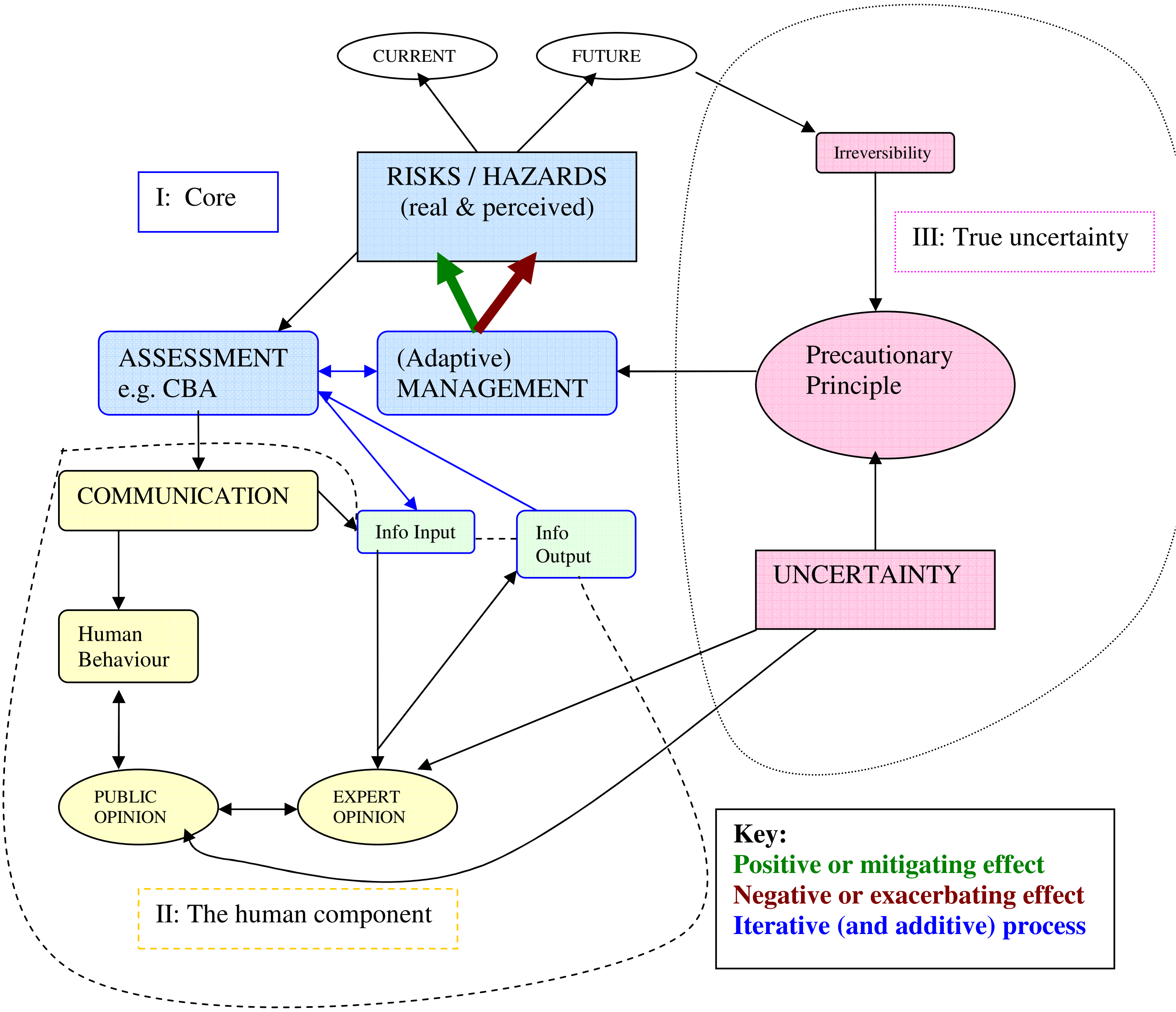


Figure 4.1 Conceptual framework

Figure 4.1 can be divided into three components:

I. *Core component* (blue): which accounts for the Adaptive Management type cycle where risks and hazards are assessed and managed. This process of evaluation allows information to flow in and out of the system and can be used to either better manage the risks or to design more effective ways of dealing with the problem. This core component may be similar to many standard risk assessment and risk management frameworks which are currently implemented in a variety of different areas. Note that this core component can be in a current or a future time frame, and assessments and management should take into account both of these states.

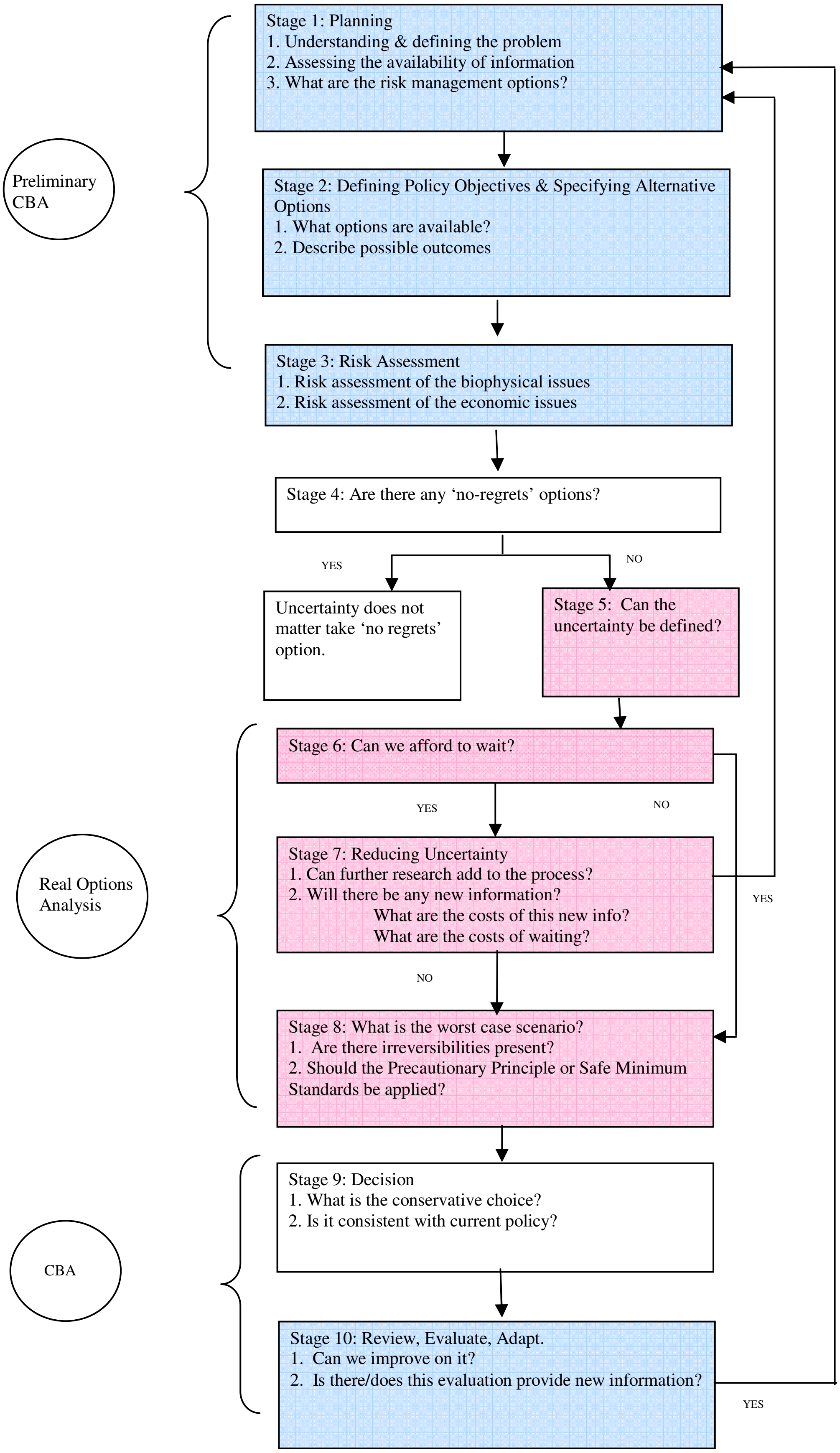
II. *The human component* (yellow – dashed line): adds a psychological dimension to the process and highlights the importance of human behaviour in deciding how to choose to assess (or perceive) and communicate risks and what they mean to different people (members of the public, policy makers, scientists/researchers).

III. *True Uncertainty* (pink – fine dotted line): ties in the issues of irreversibility and ambiguity which may be able to be accounted for in the core component through concepts such as the Precautionary Principle.

4.2 Guidelines

The following guidelines have been adapted from the VCEC Report (2009) which focuses on "Getting Environmental Regulation Right". The idea is to develop a set of guidelines (Figure 4.2 below) which arise logically from the previously discussed conceptual issues (see Figure 4.1 above). The colour coding in the below diagram suggests an interaction between figures 4.1 and 4.2, with the 'core component' (blue) and 'true uncertainty' (pink) being directly represented in both figures. The 'human component' apparent in figure 4.1 should be seen as being indirectly related to figure 4.2, in that consideration of public reaction and decision makers' individual risk attitudes should be taken throughout the process.

This figure also shows an overview of possible tools that could be used at each stage of the decision making process (represented on the left hand side of the diagram 4.2).



Preliminary CBA
Stage 1: Planning
1. Understanding & defining the problem
2. Assessing the availability of information
3. What are the risk management options?
Stage 2: Defining Policy Objectives & Specifying Alternative Options
1. What options are available?
2. Describe possible outcomes
Stage 3: Risk Assessment
1. Risk assessment of the biophysical issues
2. Risk assessment of the economic issues
Stage 4: Are there any 'no-regrets' options?
YES
NO
Uncertainty does not matter take 'no regrets' option.
Stage 5: Can the uncertainty be defined?
Real Options Analysis
Stage 6: Can we afford to wait?
YES
NO
Stage 7: Reducing Uncertainty
1. Can further research add to the process?
2. Will there be any new information?
What are the costs of this new info?
What are the costs of waiting?
YES
NO
Stage 8: What is the worst case scenario?
1. Are there irreversibilities present?
2. Should the Precautionary Principle or Safe Minimum Standards be applied?
CBA
Stage 9: Decision
1. What is the conservative choice?
2. Is it consistent with current policy?
Stage 10: Review, Evaluate, Adapt.
1. Can we improve on it?
2. Is there/does this evaluation provide new information?
YES

Figure 4.2 Example guidelines

Adapted from PWC report commissioned by Victorian Dept Treasury and Finance (2009)

Conclusion

This paper has defined the concepts of risk and uncertainty and examined the existing conceptual and practical frameworks available to account for risk and uncertainty within environmental economics. Further, a conceptual framework has been developed to account for the main issues raised in this paper and a set of 'best practice' guidelines has been has been designed to suggest a way in which to deal with risk and uncertainty in a policy framework. In summary, there does not appear to be a clear or a single 'solution' to the problem of uncertainty in a policy framework, essentially a holistic 'adaptive management' approach is needed and this should be taken ex-ante and ex-post in the policy process where possible.

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