ENVIRONMENTAL DECISION MAKING FOR GROUNDWATER SYSTEMS

Janet C Gough

Lincoln Environmental/Centre for Resource Management
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ABSTRACT

All decisions that impact on the environment have technical, economic, social and cultural implications. To achieve our national goal of sustainable management, there is a need to develop and test environmental decision-making processes that incorporate these factors, and that take account of the inherent risk and uncertainty associated with environmental management. Three risk-based methods have been reviewed as decision-aiding tools for environmental management. These methods were evaluated against the characteristics of a typical groundwater decision problem to determine the preferred methods for each of four identified levels of decision making.
1 INTRODUCTION

1.1 Uncertainty and Ignorance

Decisions affecting the natural and social environment are characterised by both scientific uncertainty and ignorance, or lack of knowledge. Scientific uncertainty is associated with random processes, measurement uncertainty (sometimes called statistical uncertainty), and the interpretation of measurements. Wider uncertainties, including problem identification and whether or not appropriate models and parameters have been used, relate to ignorance (Wynne and Mayer, 1993).

All types of uncertainty can be reduced by the provision of appropriate information. However, in the case of ignorance this is more difficult as the lack of knowledge may be unknown. Where environmental problems are concerned, there are often significant social, cultural and economic implications. Lack of adequate information in these areas, and limited means of incorporating it into decision-making processes, increase the problems caused by uncertainty.

1.2 Environmental Decision Making

The objective of decision making processes is to make ‘good’ decisions. Typical decision processes use feedback from previous decisions to improve decision making. The difficulty with environmental decision making is that the outcomes of decisions are often not realised for a very long time after the decision is implemented, and deducting from cause to effect is not always possible. The decision maker may not receive any feedback and therefore must rely on judgement. When a ‘bad’ outcome is recognised, it is often difficult to go back (in time or space) to where the decision was made to assess how it could have been improved. Improving decision making therefore requires looking for ways of improving the quality of the judgement of the decision maker (Fischhoff, 1990).

Basic criteria for ‘good’ decision making are efficiency, effectiveness and equity. A further criterion specific to environmental decision making is flexibility (the ability to respond or to learn). In the context of environmental decision making, efficiency can be interpreted as good process (rather than economic efficiency), and effectiveness as good outcomes (Gough and Ward, 1994, 1996). The long lead time before the outcomes of environmental decisions can be evaluated means that good environmental decision making depends more on the criterion of procedural efficiency than effectiveness. Ideally, if outcomes can be predicted with reasonable certainty (i.e. there is minimal uncertainty) then good process should lead to good outcomes. The chances of good process leading to good outcomes are enhanced if there is an appropriate amount of high quality information available. The timing of information is important also. If we are planning a lunch-time picnic but cannot get a weather forecast until midday, then this information is useless. A further consideration revolves around the ‘cost’ of making the decision, and the ‘value’ of the outcome to the person making the decision. These costs and values may be measured quantitatively or qualitatively. A quantitative example concerns an anxious concert promoter who may be prepared to spend a large sum of money to get a high quality weather forecast for a major outdoor event.

In real world decision making, the concept of a ‘good’ decision depends on a combination of good process and good outcomes, and according to the circumstances different weights may be given to different aspects. In the context of environmental decision making, where it may be a long time before the outcomes can be assessed, it may be desirable to weigh the process more heavily.
Apart from uncertainty and long lead times, there are a number of other typical factors that complicate environmental decision making. These include:

- sparse or poor quality data;
- the need for social, cultural, ecological, economic and technical aspects to be considered;
- complications arising from multiple objectives;
- the large numbers of decision makers and stakeholders commonly involved in environmental decision making.

Decisions are seldom made in isolation from consideration of benefits, and environmental decision making often involves the balancing of short term gain against long term uncertain loss (Fischhoff, 1990). The precautionary approach, in contrast, values possible long-term gain over short-term loss (Simpson, 1995). A further issue concerns the global implications and hence international constraints associated with some environmental decisions (e.g. GATT).

1.3 The Nature of Risk

Risk exists when there is the possibility of loss or adverse outcomes, and when the probability and some measure of the magnitude of these outcomes can be estimated either quantitatively or qualitatively. It does not exist of itself: risk is associated with the adoption of an action or a decision. If all the possible outcomes of an action are known and it is possible to define (either quantitatively or qualitatively) the probability and magnitude of these outcomes then the risk of an action can be calculated quite precisely. If it is suspected that some of the outcomes may not be known, or if the probabilities and magnitude cannot be calculated, then there is uncertainty. Risk is thus a subset of uncertainty and both are inherent to environmental decision making.

Environmental risk is not simply risk to the natural environment. New Zealand’s far reaching Resource Management Act (New Zealand Government, 1991) defines ‘environment’ as including people and their social and cultural beliefs, as well as the natural environment. Environmental risk, therefore, includes ecological risk, human health risk, social, and cultural risk. This is consistent with the approach taken by the USEPA with their comparative risk assessment prioritisation of environmental problems (USEPA, 1987, 1993). Comparing these different types of risk is not straightforward, and combining the different aspects into a comprehensive risk management framework relates to the difficulty in comparing different types of risk, measured in different units, and with different utilities (weights).

1.4 Managing Environmental Risk

Risks cannot be controlled, but they can be managed (Crouch and Wilson, 1982). The preventative and precautionary approaches to environmental decision making denote a shift towards attempts to manage risks to the environment. Managing risk means finding ways of reducing (proactive), mitigating (reactive), or simply learning to live with risks. How this is done depends often on the acceptability of the risk. There are some risks that the public considers unacceptable. Society chooses whether it is prepared to pay a high cost to avoid some of these types of risk. Other risks are considered less important or more acceptable. Some of the main factors affecting people’s willingness to accept risk are the degree to which they believe they are personally exposed or involved, the judged unpleasantness of the adverse effect and the extent to which the risk is voluntary (Fischhoff et al., 1985).
The preventative approach concentrates on eliminating waste and pollution by prevention at source. The precautionary approach to risk assessment, based on the Precautionary Principle (O'Riordan, 1993) is more demanding and requires the adoption of control measures before harm is proven.

The Precautionary Principle has been adopted by the Economic Union and the United Kingdom as guiding principle of environmental policy. It is used when information suggests cause and effect but can't prove it (e.g. Montreal Protocol regarding ozone depleting substances). Justification for use of the precautionary approach is thus on grounds of either complexity (inability to unambiguously identify all cause-effect relationships) or uncertainty (where there is no previous knowledge on which to base the prediction of impacts) (Tait and Levidow, 1992). It is also used when the possible undesirable consequences are so great that a “business as usual” approach cannot be chanced (Simpson, 1995). Practicality would suggest that it is desirable for policy makers to have accurate forecasts of the effects of a technology before it is highly developed. Many scientists have concerns about the adoption of the precautionary approach on the grounds that it effectively requires ‘proof of safety’. There are also significant practical difficulties related to applying the Precautionary Principle. As Wynne and Mayer (1993) note, “where the environment is at risk there is no clear-cut boundary between science and policy”.

1.5 Risk Assessment and Risk Management

Risk assessment and risk management are closely related processes. Risk assessment is an analytic technique that is used to provide decision makers with the information required to make a decision. It comprises three steps: risk identification, risk estimation and risk evaluation (Rowe, 1980). Risk identification attempts to identify all the possible outcomes that may eventuate from a particular action. Risk estimation uses analytical methods to estimate the probability of occurrence and the magnitude of the risks. The basis of risk estimation, which should enable the analyst to compare the alternative actions available, is historical statistical information. Risk evaluation (which involves the decision maker) takes this technical information and evaluates it, including any additional appropriate decision criteria, to select a preferred option. Risk evaluation is concerned with judging the significance and acceptability of risks (Boshier, 1990). Risk determination therefore tends to be viewed as a scientific process based on technical information, whereas risk evaluation allows for consideration of social, cultural, and other issues.

The objective of risk management is to ‘treat’ or manage (i.e. avoid, eliminate, reduce and mitigate) risks, whereas the objective of risk assessment is simply to ‘measure’ risk. Jasanoff (1993) refers to risk management as “what we wish to do about risk” and risk assessment as “what we know about risk”. In this context, risk management takes the information generated by the risk assessment process and uses it to manage or treat the risk.

The USEPA approach to comparative risk assessment (CRA) views risk assessment and risk management as two separable processes (USEPA, Science Advisory Board, 1990). Massman (1990) considers that the advantages of this separation are that:

- the expertise of scientists and engineers can be compiled without forcing them to become involved in emotional and ethical judgements;
- a separated risk assessment is more amenable to scientific peer review and more easily modified.

Risk assessment is seen as a scientific, objective process, whereas risk management is seen as a judgmental, subjective process. The main argument against this separation is that scientists and engineers make value judgements from the moment they select a method or model and choose the data to be used. Risk assessment can never be a purely objective process.
The alternative view is that risk management is the whole process of risk assessment and risk treatment. Separating risk assessment and risk management also limits the utility of risk management since it does not allow for the necessary feedback between assessment and evaluation. In this paper the latter view of risk management as a composite process is adopted.

1.6 Groundwater Management in New Zealand

Sustainable resource management is the basis of much of New Zealand's environmental legislation and the Resource Management Act. The meaning of sustainable management for groundwater resources needs to be examined since at the present time their management is an ad hoc process. Up until recently most regional authorities with responsibility for management have granted allocations of groundwater for irrigation and other uses with few restrictions (Beanland et al, 1994). As more pressure is put on the resource, and as fears of potential contamination and depletion grow, more systematic approaches to managing groundwater systems are needed. For example, increased recognition of the requirements of the Treaty of Waitangi and the need to take account of bicultural attitudes has led to a growing demand for land disposal of effluent in New Zealand. In turn, this poses substantial additional risks of contamination of groundwater sources already facing stress from other land use practices.

Groundwater contamination occurs through point source and diffuse source contamination. The problem that is particular to groundwater systems is that there is considerable uncertainty related to limited understanding of the way contaminants move in groundwater. Uncertainty as to the structure of aquifer systems, and interactions between users, further complicate the issue. Technical risk assessment methods need to be expanded to take account of the social and cultural concerns that relate to groundwater.

1.7 Levels of Decision Making

In New Zealand decisions affecting groundwater are made at four levels. Regional and district councils have direct responsibility for granting resource consents (for water extraction and recharge, and land use), for preparing management plans, and for preparing policy statements. Longer term planning is a joint responsibility of regional councils and central government agencies including the Ministry for the Environment. Table 1 summarises the four levels, the types of decision, and the time frame involved.

Table 1: Levels of decision making for groundwater

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Primary Responsibility of</th>
<th>Time frame of decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>activity or operational level - linked to granting of resource consents</td>
<td>regional &amp; district councils</td>
<td>within year</td>
</tr>
<tr>
<td>3</td>
<td>tactical or management level - linked to preparation of 'management plans'</td>
<td>regional &amp; district councils</td>
<td>1-5 years</td>
</tr>
<tr>
<td>2</td>
<td>policy level - linked to preparation of policy statements</td>
<td>regional councils with public input</td>
<td>5-10 years</td>
</tr>
<tr>
<td>1</td>
<td>strategic level - beyond current planning horizon, linked to sustainability, standards, and national policy statements</td>
<td>central government with public input</td>
<td>10-30 years</td>
</tr>
</tbody>
</table>

1 The Treaty of Waitangi was signed in 1840 between Maori Chiefs and the Crown. It is recognised in New Zealand law, and specific legislation, such as the Resource Management Act, explicitly requires that it be taken into account.
All resource use issues require consideration of risk to the environment. The application of classical risk formulations to environmental risk and in particular to issues such as quantity and quality of groundwater has two limitations: probabilities are not appropriate where there is no frequency basis, and it is likely that there will be considerable uncertainty present in other variables (Bogardi et al., 1989). Alternative approaches that emphasise the management of the overall risk, including social, cultural and economic criteria, are likely to provide more sustainable solutions in the context of environmental decision making in New Zealand (Baines et al., 1988).

Risk assessment has been used internationally for a number of years as a tool for assessing the risks associated with different activities that impinge on the environment (Anderson et al., 1990). It has, however, not been used in this context in New Zealand. In most cases this form of environmental risk assessment has been limited to one type of risk and a restricted geographical area. Typically, groundwater risk assessments are used to identify possible migration routes, exposure pathways and receptors for exposure to groundwater contamination. The common approach follows the process of hazard identification, dose-response assessment, exposure assessment and risk characterisation to determine threshold levels for adverse impact on the population. The first two steps may be general, however, the second two will be specific to the particular case. This process requires complex modelling processes that are difficult to verify. In addition, such models do not address the wider social issues that are involved in the management of groundwater.

Risk management has a broader perspective than risk assessment and allows for the inclusion of additional information from different risk assessments as well as other assessment processes such as environmental impact assessment, social assessment and technical assessment. It provides the umbrella under which information from many different sources can be combined so that the ‘decision’ can be implemented on a comprehensive basis. Risk management can be applied at different levels: to managing the activities at a single site or within an organisation, and at policy level, providing a basis for guidelines for activities or for prioritising areas for action to be taken. It is an ongoing process, not a one-off exercise to be undertaken and filed.

Three different risk-based approaches were selected to assess their effectiveness as tools for managing groundwater. They were selected as representative of different risk assessment/risk management approaches.

### 2.1 Technical Risk Assessment

The first approach selected, is referred to as ‘technical’ risk assessment. It is based on traditional risk assessment principles and comprises identifying all the possible sources of risk, estimating probabilities and magnitudes for all the possible outcomes that might result from the alternative actions (options) and evaluating this information. This evaluation includes consideration of additional information such as social and cultural assessments, environmental impact assessment and economic analyses. Although social, cultural and environmental (ecological) impacts can be taken account of in the process described here they are included as an optional ‘add-on’, and in many cases are not addressed in a systematic or rigorous manner. They are not treated as risks. Decisions are likely to be made either by an individual, or a small group. Risk communication can be used to provide input from a wider group.

Technical risk assessment requires defining the problem and the options available. These options become the basis for the decision. Once the options have been defined then the risks associated with these options must be identified in terms of the outcomes and the probabilities of the outcomes. These
probabilities and magnitudes are then estimated either quantitatively or qualitatively, depending on data availability and the required precision, and combined in some way to provide an estimate of the risk. This risk estimate may be in the form of a probability, an expected value or a risk index. The final step is the selection of a preferred option. This may be done by simply applying a decision rule such as minimisation of the expected value or direct ranking of risk indices, or other criteria may be included and trade-offs made.

‘Technical’ risk assessment can provide considerable information about the system being studied. If adequate high quality data is available it can be used to calculate the probability and magnitude of particular risks associated with certain options. If the units are commensurate then decision rules can be used to make choices between options which might involve a number of different risk outcomes. Varying decision rules can be used that reflect risk-prone, risk-neutral or risk-averse attitudes. However, if high probability/low consequence and low probability/high consequence risks are compared within the same expected value type calculation then the results will be meaningless. Comparison of dissimilar risks, for example risks incurred in the workplace and risks incurred through recreation, is also meaningless. Although technical risk assessment is often purported to be value free, this is not accurate since value judgements enter the analysis from the very beginning with the selection of the model and choice of data collection.

In short, technical risk assessment is appropriate:

- when the outcomes of the alternative actions can be clearly identified;
- when there is sufficient data/information to allow for good quantitative or qualitative estimates of the probability and magnitude of the outcomes;
- risks are of similar ‘order’ and type;
- for assessing and comparing risks resulting from different actions or activities;
- for determining the risk of a specific activity.

Technical risk assessment is not appropriate or should not be used:

- to calculate the risk of a single action;
- to directly compare different types of risk (voluntary versus involuntary);
- when there is significant scientific uncertainty and ignorance;
- to compare high probability, low consequence with low probability, high consequence risks;
- when there considerable variability in the quality of data for different risks being considered.

Technical risk assessment is best suited for assessing the impact of well defined activities at specific sites, when processes are well understood, and when there is high quality and consistent data available.

2.2 The Decision Analytic Approach

The second method was based on the decision-analytic approach to risk assessment. With this approach, risk is not “regarded as an objective property of an object or situation but as a subjective mental construction based on personal beliefs about the occurrence of specific outcomes of an event or action” (Otway and Peltu, 1985). Subjective evaluations are explicitly included along with statistical estimates. Different attributes or types of risk such as social and cultural risks can be included directly in the analysis, rather than considered separately at the end. The main limitation with this approach is that analysts are required to interpret decision makers’ preferences in a quantitative manner so as to assign weights to the attributes or risks being assessed. Variations of the decision-analytic approach have been used in a number of environmental risk assessment applications where there is limited quantitative data available.
The decision analytic approach derives from classical decision analysis and has been developed to allow the values and judgements of the decision makers to be represented. It begins in a similar fashion to technical risk assessment by defining the problem and the options available. The decision maker or decision makers are then asked to state preferences for these options based on the attributes or characteristics of the options. These attributes will include risks, but there will also be other characteristics that do not necessarily have risk features. Once these preferences have been established then the decision makers assign weights based on their own decision objectives, and these are used to order the options. Cost-benefit analysis can be viewed as a special case of the decision analytic approach where all the attributes are measured in the same units.

The decision analytic method extracts the decision makers preferences directly. The approach can cope with a large number of attributes or criteria. It allows consensus building across disciplines and special interest groups, and incorporates values. The decision analytic method uses whatever data is available, but is more overtly value and judgement driven than technical risk assessment.

The decision-analytic approach is appropriate:

- when there are large numbers of stakeholders and decision makers;
- where there is a large number of attributes (or ‘risks’) that need to be taken account of when making a decision (choice);
- when there are significant social costs involved;
- when explicit recognition of values is required.

The decision analytic approach is not appropriate:

- when quantitative or semi-quantitative estimates of the risk are required for comparisons (possibly with other situations);
- The decision analytic approach is best suited to situations when there are a number of different risks to be considered with variable quality data, where there may be significant social costs and when relative relationships between risks are more important than a precise estimate of a single risk.

### 2.3 Comparative Risk Assessment

The third approach was based on the United States Environmental Protection Agency (USEPA) comparative risk assessment and risk reduction approach (CRA/RR). The CRA/RR approach is a means of directly reconciling the technical with the judgmental. The USEPA is currently using this methodology to set priorities for action on environmental problems areas (USEPA, 1993). Risks to human health, ecosystems, and welfare are identified and ranked within risk type using risk assessment methods. In this way technical, financial, environmental and social impacts are incorporated as risks. Risk rankings for all different types of risk are combined using risk reduction criteria, and additional criteria as deemed appropriate. The original ‘within risk’ ranking, referred to as ‘risk assessment’ is undertaken by groups of experts in the individual areas, while the second stage of including risk reduction criteria and attempting to reconcile the rankings over risk types is often the task of community based groups (Minard, 1991). This stage is referred to as ‘risk management’. There is a tendency to consider the risk assessment as an ‘objective’ process as opposed to the ‘subjective’ risk management. Because the ranking process is viewed as a relative process, and no absolute measures of risk are calculated, the CRA/RR approach precludes the need to measure all risks in the same units and allows for all types of risk to be given equal weight in decision making.
The first step in comparative risk assessment is to identify the problem areas or issues of concern. A set of risks is then selected that will typically include ecological risk, human health risk and some measure of social risk. Groups of experts then use a coarse risk assessment process (estimation and ranking) to rank the problem areas or issues within each risk type. A group of decision makers or stakeholders then takes these individual risk rankings and re-evaluates them taking other factors into account, including risk reduction and risk-benefit analyses. Part of the re-evaluation may include creating a composite ranking of the problem areas/issues over all risk types. Finally, priorities for action are set. It should be noted that the ranking processes used are generally quite approximate and that problem areas tend to be grouped into about five different categories rather than being given absolute rankings.

The comparative risk assessment approach deals with risks and 'other' attributes separately. It also allows consensus building across disciplines and special interest groups and incorporates values. It is suitable for situations where it is desirable to involve the community directly in decision making and can provide a forum for debating the issues. It is primarily a regulatory tool. In the form applied in the United States it considers residual risks, or risks remaining under current controls and allows managers to set priorities. It does not, however, evaluate options or alternative actions.

The comparative risk assessment approach is appropriate:

- when there are large numbers of stakeholders and decision makers;
- when there are several disparate risks types of risks to be considered;
- when the quality of information for different risk types is highly variable;
- for comparing different risk types and making comparative judgements as to the greatest severity (prioritising risk areas);
- for situations where explicit recognition of values and value judgements is required.

The comparative risk assessment approach is not appropriate:

- when quantitative or semi-quantitative estimates of the risk are required;
- when scientific and value judgements are considered not able to be separated;
- when the risk of a specific activity is required.

The comparative risk assessment approach is best suited for large scale risk management problems where 'problems' are defined in general terms, where the risks involved are varied and the data variable in quality, and when grouping of priority areas rather than specific ranking of risks is adequate. It requires the commitment of a considerable number of resources.

2.4 Summary

The aims of the three approaches vary, but are not inconsistent. 'Technical' risk assessment aims to compare options using risk criteria and to select a preferred option (that is, make a decision based on technical risk alone). The decision analytic approach aims to order the options according to the 'problem owners' objectives and the expected outcome is an ordered range of options (one of which will be selected). The difference between the two is that 'technical' risk assessment uses a 'scientific basis' for the ordering process whereas the decision analytic approach bases the decision explicitly on value judgements (which will take account of scientific results). The comparative risk assessment approach aims to identify significant problem areas or issues, to rank these, and to set priorities for taking preventative or ameliorating action. Its outcome is an ordered list of problem areas. All three approaches are concerned with minimising or reducing overall risk.
Although the three approaches are described here as though they are discrete, this is not necessarily the case, and in practice there are overlaps and similarities. Table 2 outlines the characteristics of the approaches.

**Table 2: Comparison of methodologies**

<table>
<thead>
<tr>
<th></th>
<th>‘Technical’ Risk Assessment</th>
<th>Decision Analytic</th>
<th>Comparative Risk Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Approach</strong></td>
<td>Define problem and options (decisions)</td>
<td>Define problem and options (decisions)</td>
<td>Define problem and identify areas or issues</td>
</tr>
<tr>
<td></td>
<td>• identify risks</td>
<td>• extract preferences (based on attributes)</td>
<td>• select risks</td>
</tr>
<tr>
<td></td>
<td>• estimate probabilities and magnitudes</td>
<td>• assign weights</td>
<td>• rank within risk types (expert consensus)</td>
</tr>
<tr>
<td></td>
<td>• evaluate overall risk and choose a preferred option</td>
<td>• order outcomes</td>
<td>• re-evaluate ranking</td>
</tr>
<tr>
<td><strong>Aim</strong></td>
<td>to compare options using risk criteria</td>
<td>to order options according to decision makers objectives</td>
<td>to prioritise problems or issues</td>
</tr>
<tr>
<td><strong>Expected Outcome</strong></td>
<td>a ‘measurement’ of risk for each option</td>
<td>an ordered range of options</td>
<td>an ordered list of problem areas</td>
</tr>
<tr>
<td><strong>Basis</strong></td>
<td>scientific</td>
<td>value judgements</td>
<td>scientific + value judgements</td>
</tr>
<tr>
<td><strong>Decision criteria</strong></td>
<td>minimisation of loss</td>
<td>maximisation of decision-makers subjective expected utility</td>
<td>combination of min. of loss and maximisation of expected utility</td>
</tr>
<tr>
<td><strong>Relationship to risk management</strong></td>
<td>component of risk management</td>
<td>component of risk management</td>
<td>• risk assessment and risk management separated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• risk management defined differently</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• RA and RM are components of CRA</td>
</tr>
<tr>
<td><strong>Use as a decision-making tool</strong></td>
<td>used to choose a preferred option</td>
<td>used to choose a preferred option</td>
<td>used to set priorities for action</td>
</tr>
<tr>
<td><strong>Mixed units of measurement</strong></td>
<td>not able to include mixed units - requires separate analyses</td>
<td>includes mixed units by weighting attributes (value judgements)</td>
<td>includes mixed units by subjective weighting</td>
</tr>
<tr>
<td><strong>Data Quality</strong></td>
<td>data needs to be of similar quality</td>
<td>can use mixed quality data</td>
<td>data quality can vary widely</td>
</tr>
<tr>
<td><strong>Way of dealing with uncertainty of outcomes</strong></td>
<td>sensitivity analysis</td>
<td>sensitivity analysis of critical uncertain variables (plus value of information analysis)</td>
<td>sensitivity analysis and value judgements</td>
</tr>
</tbody>
</table>
3 A CASE STUDY COMPARISON

The three risk-based decision-making methods described were assessed in the context of a typical groundwater system using a two step process. The first step consisted of comparing the approaches against a set of criteria for good decision making. These criteria were not used to either rank or eliminate any of the three approaches, but rather to investigate their validity as decision-making tools. The second step consisted of matching the characteristics of each approach against the characteristics of a typical groundwater management problem. The overall objective was to select an approach to risk management that allowed for the incorporation of social, cultural, economic, technical, and ecological information and was consistent with the goal of sustainable management of the resource.

3.1 Groundwater Systems

Groundwater systems are complex and are characterised by a number of uncertainties. These relate to the structure and boundaries, transport mechanisms, and interactions between different sectors. Historically, considerable effort has been put into constructing and testing models that can provide information about different aspects of groundwater. Friedman et al. (1984) give examples of the types of issues tackled by groundwater models. These include available supply, conjunctive use, drinking water quality, agricultural pollution, movement of pollutants, and salt-water intrusion.

Activities that affect groundwater systems include:

- general farming practices
- land based effluent disposal
- the siting of underground storage tanks
- the use of septic tanks
- landfills
- commercial activities such as timber treatment plants
- forestry areas
- extraction and recharge

Point source and non-point source pollution may occur. Contamination may result from short term ‘incidents’ or spills, from larger scale or longer term contamination that may be able to be tracked, such as major chemical spills to groundwater or rupturing of underground tanks, or from cumulative smaller-scale activities over a long period. Over extraction may lead to depletion of groundwater resources, with results such as reduced stream flows, surface water (swamp) depletion, land subsidence and structural damage to the aquifer, and salt water intrusion.

Groundwater systems are sensitive to climate change and fluctuations in rainfall. Measuring the effect of these changes is difficult. The impact of decisions relating to groundwater may not be known for a long time, and may be irreversible.

For this project a generalised scenario was postulated to give context to the evaluation of the three risk management approaches. This scenario comprised a description of the physical, social, and institutional bounds of a ‘typical’ New Zealand groundwater system with a mixture of confined and unconfined aquifers. The scenario was constructed in very general terms so that all of the four levels of decision making would be relevant. Therefore, the physical boundaries were set for a major catchment area containing several significant rivers, flowing across farmland areas with small towns interspersed to the sea.
The physical bounds were associated with the inputs and outputs. Inputs are from rainfall and rivers (related to rainfall higher in the catchment area). Land use in the upper part of the catchment includes farming and forestry. Water is extracted for irrigation and stockwater, rural community water supply (scattered and difficult to control) and town water supply (fixed, established wells, tested regularly). A mixture of shallow and deep bores exist. Industrial sites are situated on the outskirts of towns.

Groundwater is a renewable source. However, the time delay between rain in the upper catchment and replenishment of the resource is seldom known with great accuracy. It will depend on the pattern of rainfall over an extended period of time. It is assumed that there is a reasonable understanding of the geology of the groundwater resource and that reasonable estimates of the characteristic response time of the system are available through monitoring of well levels and pressures.

Society recognises a number of values and spiritual features related to groundwater. In New Zealand there is a strong belief in the purity of groundwater and any contamination, however minor, is judged as unacceptable.

Regional councils grant resource consents for extraction of groundwater, and permits for effluent disposal, based on Regional Management Plans. Decisions affecting groundwater are made at four levels as described previously (Table 1). Stakeholders, including farmers and managers of industrial sites undertake activities that may affect groundwater and which may also affect others’ ability to use the resource.

Activities impinging on groundwater pose risks associated with both the quantity and quality of groundwater. Risks associated with groundwater contamination include economic risk (cost of cleanup or obtaining water from a different source), political (linked to the social, cultural and spiritual characteristics), risks to human health, risks to aquatic life, and risks to wildlife and domestic livestock. There are also social, cultural, economic, ecological and technical risks associated with activities affecting water quantity.

3.2 Uncertainty

Uncertainty is an inherent part of groundwater management. All risk management methods are able to explicitly consider uncertainty although this may not occur in practice. A common way of addressing the impact of uncertainty is through sensitivity analysis of the probabilities of particular events occurring. This is effective as long as some estimate of the possible variation is available. Other levels of uncertainty, including ignorance, can be addressed by developing scenarios or by adoption of the precautionary approach. Because risk management is an on-going process, areas of uncertainty (or potential concern) can be noted and monitoring can be instituted. All uncertainty is reduced by additional information, however, unless the existence of uncertainty or lack of knowledge is recognised it will not be obvious that further information is required.

3.3 Evaluation of the Three Approaches

Basic criteria for 'good' decision making were defined as efficiency, effectiveness and equity. Since it is difficult to measure outcomes, and good process is most likely to lead to good outcomes, criteria for assessing decision making concentrate on the procedural. Fischhoff et al. (1981) developed a set of criteria for evaluating approaches to determining acceptable risk. Merkhofer (1986) adapted these criteria and used them within a framework for comparing decision-making approaches, given a set of risk-problem characteristics. He demonstrated how this framework could be used to compare different decision-making approaches: cost-benefit analysis, decision analysis and social choice analysis.
A set of criteria, based on those described by Fischhoff and Merkhofer and taking account of the specific requirements of environmental decision making, was used to evaluate the three selected approaches to risk management. The criteria were:

- correctness (accuracy)
- completeness
- consistency
- openness
- an appropriate level of detail
- balance
- political acceptability
- flexibility

These criteria are not necessarily complete. Cost and economic efficiency have not been included at this stage because they will be specific to the particular application.

The three approaches were assessed against a set of characteristics of groundwater management problems:

- outcome uncertainty with long lead times and the possibility of irreversibility
- probability uncertainty
- structural (problem) uncertainty
- multiple stakeholders and decision makers
- mixed objectives (quantity and quality)
- complexity (interactions)
- cumulative effects
- high environmental sensitivity

Each approach was assessed against the criteria using a tabular form. Each problem characteristic was considered separately and a score given according to the approach's ability to meet each of the criteria for a situation or problem with that characteristic. A score of '+1' indicated that the approach was able to adequately address a problem with the characteristic being assessed. A score of '-1' indicated that the approach was not able to adequately address it. A '0' indicated either that the test was not appropriate, or that no definitive judgement could be made.

For example, 'technical' risk assessment scored '-1' on the criterion 'correctness' for the characteristic 'outcome uncertainty', on the grounds that if outcomes are unknown then the results of a 'technical' risk assessment are likely to be inaccurate.

The highest possible score was 64 (eight criteria times eight characteristics). No attempt was made at this stage to apply weights to either the criteria or the characteristics, or to use this method to choose a preferred approach. All three approaches scored significantly above zero, and none was consistently preferable to the others in all cases. Although the scoring process was somewhat coarse and subjective, it provided a useful demonstration of the general adequacy of all three methods, and also for clarifying areas of strengths and weaknesses.

This 'first pass' assessment of approaches to environmental risk decision making concentrated on ensuring the adequacy of the decision-making process. Flexibility is also related to outcome since the process is required to be able to adapt to feedback.
Having established that all three risk management approaches were adequate decision-making tools and that none of them scored significantly higher than the others over all categories, a ‘second pass’ was made to directly compare them and to select a preferred approach.

3.4 Management Options

As described earlier there are four levels of decision making for groundwater:

- the granting of ‘resource consents’ or permits for activities that may affect groundwater (activity level);
- the establishment of rules for this purpose within management plans (management level);
- the preparation of policy statements (policy level); and
- long term strategic planning (strategic level).

The groundwater resource fluctuates over time according to rainfall, and resource consents need to include mechanisms to take this into account. Long term climate change also requires flexibility. Contamination may arise from planned (permitted) activities as a risk outcome, but also from unplanned activities. Management for short term outcomes such as spills requires the establishment of emergency systems for cleanup before contaminants can enter the groundwater. Where contaminants have already entered the groundwater it may be necessary to have procedures for tracking contaminant plumes. Long term chronic contamination, such as may result from land use practices, is likely to be extremely costly to remediate, therefore precautionary approaches are more appropriate.

The summary of the characteristics of the three risk management approaches identified that:

- technical risk assessment (TA) is best suited for assessing the impact of well defined activities at specific sites, or for specific activities, when processes are well understood, and when there is high quality consistent data available
- the decision analytic (DA) approach is best suited to situations when there are a number of different risks to be considered with variable quality data, where there may be significant social costs and when relative relationships between risks are more important than a precise estimate of a single risk
- the comparative risk assessment (CRA) approach is best suited for large scale risk management problems where ‘problems’ are defined in general terms, where the risks involved are varied and the data variable in quality, and when grouping of priority areas rather than specific ranking of risks is adequate; it requires the commitment of considerable resources

In addition to the general characteristics of groundwater management problems (defined earlier), at each level of decision making there are particular features that will determine which of the three risk-based decision-making approaches will be most appropriate. The emphasis required for the general characteristics also varies according to the time frame being considered. The hierarchy of decisions inherent in the definition of the four levels means that decisions made at ‘lower’ levels are dependent on decisions made at ‘higher’ levels. At the same time, information received from impacts noted at the ‘lower’ levels is fed back into the decision-making process at the higher levels.

At the strategic level (level I), decisions have long term implications and consequences associated with considerable uncertainty (outcome uncertainty, probability uncertainty and structural uncertainty). The implications of ignorance are greatest at this level.
Decisions:

- may lead to irreversible outcomes
- involve many decision makers and stakeholders (including future generations)
- need to address cumulative issues
- have high environmental sensitivity
- have significant potential social costs
- show great variability in the quantity and quality of data available to the decision makers

Decisions made at the strategic level provide the context, and set the boundaries for each of the 'lower' levels. Precise estimates of risk are not required.

**Policy level decisions (level 2)** must be consistent with strategic level decisions, and have similar characteristics. The main difference between the two levels is spatial, and is reflected in the national nature of strategic level decision making and the regional aspect of policy level decision making.

**At the management level (level 3)**, decisions are based on principles established at the strategic and policy levels. Information received from the outcomes of decisions made at level 4 allows for adjustments to be made to management plans. Where possible estimates of risks (either qualitative or quantitative) should be used.

**Activity level decisions (level 4)** are based on rules established at the management level. Decisions are generally localised and well defined. Although they tend to be incremental by nature, the cumulative impact of the risks needs to be addressed. Although there is uncertainty in all three areas, the narrow nature of the definition of the 'problem' means the impacts of decisions at this level are more easily measured and addressed. The number of decision makers and stakeholders is limited and hence there is less likelihood of mixed objectives. Estimates of risks are required.

To determine preferred approaches for each level the requirements for decision making at the four different levels were matched against the characteristics of each approach, and the approaches were ordered at each level. The process followed is summarised and illustrated for two of the four levels in Tables 3 and 4. In these tables, the notation 'a', 'b', and 'x' indicates the degree to which the particular approach includes provision for addressing the issues or problems associated with the characteristics of groundwater management decisions. An 'a' indicates that the approach is judged to be very good in this area, 'b' indicates that the approach is adequate, and 'x' indicates the approach cannot adequately address the issue, in terms of ensuring efficiency or good process. Where two or more approaches score the same, but it is recognised that one approach is preferred, then a '+' qualifier is used.

Two further important considerations must be taken into account; the precision required, and the resources required and available.
Table 3: Selecting a preferred approach for strategic level decision making

<table>
<thead>
<tr>
<th>Strategic Level (Level 1)</th>
<th>Risk Management Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision characteristics</td>
<td>TA  DA  CRA</td>
</tr>
<tr>
<td>Long lead times and uncertain potentially irreversible outcomes (uncertainty includes magnitude of effect and timing and both quantity and quality)</td>
<td>x  b  b+</td>
</tr>
<tr>
<td>Probability uncertainty including statistical uncertainty and inability of experts to agree</td>
<td>b  b  b+</td>
</tr>
<tr>
<td>Uncertainty as to which issues require to be addressed</td>
<td>x  b  b</td>
</tr>
<tr>
<td>Significant ignorance or lack of knowledge about technical and social implications</td>
<td>x  x  x</td>
</tr>
<tr>
<td>A potentially large group of decision makers and stakeholders to be considered (political aspects indirectly risk related require consideration)</td>
<td>x  a  a+</td>
</tr>
<tr>
<td>Mixed or multiple objectives (different types of risk, measured differently to be reconciled) - not well specified or able to be uniquely defined</td>
<td>x  b  b</td>
</tr>
<tr>
<td>Potentially significant cumulative effects about which little is known (value judgements required)</td>
<td>x  b  b</td>
</tr>
<tr>
<td>Complexity (interactions)</td>
<td>x  b  b</td>
</tr>
<tr>
<td>High environmental sensitivity</td>
<td>b  b  b</td>
</tr>
<tr>
<td>Significant potential social costs</td>
<td>x  b  b</td>
</tr>
</tbody>
</table>

Table 3 matches the characteristics of groundwater management decisions and the characteristics of the three approaches in terms of strategic level decision making and management. From this table it can be seen that the decision analytic and comparative risk assessment approaches are both suitable for decision making for groundwater management at this level, and that they are both significantly preferable to the ‘technical’ risk assessment approach. The additional considerations of degree of precision of estimates and availability resources do not affect the selection at this level; precise measurements of specific risks are not able to be made (mixed quality of data), and the potential benefits of good decision making are likely to ensure the availability of adequate resources for whichever method is selected.

The main differences between the two approaches, as shown previously in Table 2, are the outcomes of the process, the way in which different aspects (attributes or risks) are incorporated, how decision makers and stakeholders are included, and the degree of separation between the ‘objective’ assessment and ‘subjective’ management. The decision-analytic approach is concerned with options and hence the outcomes are actions. The CRA approach ranks problem areas and sets priorities for action. Although risk reduction (or the ability to reduce risk) is taken into account in the ranking process the CRA approach does not assess options or actions.

In practice, both approaches separate the technical processing of data (or risk assessment) from the value judgements of decision makers and stakeholders. The decision analytic approach considers all attributes (or risks) together. The CRA approach develops separate rankings within risk types then
considers composite rankings as a separate step. The latter approach is simpler to implement, but may produce distortions during the process of combining rankings because it does not take explicit account of interactions between risk types. In many cases, in practice, rankings are not combined, however, at times this makes it more difficult to use the results.

Groundwater management and decision making at the strategic level has two basic requirements or desired outcomes associated with the linkages between the decision making levels. The first requirement is to establish a framework or set of guidelines that can be used to aid effective and efficient decision making at the policy, management and activity levels. The second is for a procedure for incorporating feedback from lower level decisions to modify this framework. Flexibility has been identified as an important criterion for good environmental decision making. Comparative risk assessment relies on prioritising ‘risks’ according to existing conditions, and in this sense it can be described as primarily a reactionary approach. This is an important aspect of establishing a framework and guidelines, since existing problems must be addressed.

For these reasons it is difficult to choose between the comparative risk assessment and decision analytic approaches at the strategic level. Ultimately, the comparative risk assessment approach was selected as preferable because of its ability to incorporate multiple stakeholders and decision makers at different levels ranging from the lay public to politicians, as a result of the two-level structure.

Table 4: Selecting a preferred approach for activity level decision making

<table>
<thead>
<tr>
<th>Activity Level (Level 4)</th>
<th>Risk Management Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision characteristics</td>
<td>TA</td>
</tr>
<tr>
<td>Outcome uncertainty but reasonable estimates for required time frame able to be made</td>
<td>a</td>
</tr>
<tr>
<td>Probability uncertainty exists but bounds able to be placed on estimates</td>
<td>a</td>
</tr>
<tr>
<td>Problem known and well specified</td>
<td>a</td>
</tr>
<tr>
<td>Lack of knowledge, but generally what is unknown can be identified</td>
<td>a</td>
</tr>
<tr>
<td>A limited defined group of decision makers and stakeholders</td>
<td>a</td>
</tr>
<tr>
<td>Small number of types of risk (often 1-2)</td>
<td>b</td>
</tr>
<tr>
<td>Cumulative effects able to be measured incrementally</td>
<td>b</td>
</tr>
<tr>
<td>Complexity (interactions)</td>
<td>b</td>
</tr>
<tr>
<td>Limited and assessable environmental sensitivity</td>
<td>b</td>
</tr>
<tr>
<td>Limited potential social costs</td>
<td>b</td>
</tr>
</tbody>
</table>

Table 4 implies that the three approaches are effectively equivalent at the activity level. In this instance, two other factors must be considered. At the activity level, estimates or ‘measurements’ of risks are required where possible, and therefore the technical risk assessment approach is preferred. At this level also, the resources available are most limited, hence the decision analytic approach is ranked second.
Similar processes were undertaken for the policy and management levels of decision making. At the policy level, the arguments are similar to those mounted for the strategic level. However, the DA approach was selected as preferred, as the decision makers and stakeholders are more homogeneous and identifiable. Management level decision making is more closely linked to activity level, and the assessment process resulted in the decision analytic approach being the most preferred, followed by technical risk assessment.

Table 5 summarises the ranked approaches for each level of decision making.

Table 5: Ranking of preferred risk-based decision-making approaches for four levels of decision making

<table>
<thead>
<tr>
<th>Level 1</th>
<th>CRA</th>
<th>DA</th>
<th>TA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2</td>
<td>DA</td>
<td>CRA</td>
<td>TA</td>
</tr>
<tr>
<td>Level 3</td>
<td>DA</td>
<td>TA</td>
<td>CRA</td>
</tr>
<tr>
<td>Level 4</td>
<td>TA</td>
<td>DA</td>
<td>CRA</td>
</tr>
</tbody>
</table>
4 CONCLUSIONS

Recent changes in institutional structures and environmental legislation in New Zealand have meant that there is a need to develop improved tools for environmental decision making that allow for the management of adverse effect on the environment. Rule-based decision-making tools previously used are reactionary and inflexible. Risk-based approaches are more flexible, cost effective and directed towards the prevention of adverse effects.

Three risk management approaches have been examined in the context of a particular environmental decision-making problem, the management of groundwater resources. The analysis was undertaken in two steps. The first step consisted of comparing each approach against a set of criteria for good decision making. Secondly, the advantages and disadvantages of the three approaches were determined and assessed in terms of the characteristics of groundwater systems. Four levels of management and decision making were addressed:

- the activity level of day-to-day decision making;
- the management level which relates to the establishment and maintenance of regional management plans;
- the policy level linked to the preparation of regional policy statements;
- the strategic level where national guidelines for long term planning are established.

An important aspect of the matching process was the ability of the approach to incorporate a variety of factors or risks including technical, economic, social and cultural aspects.

The basic premise is that risk management is a useful tool for environmental decision making. This arises because making environmental decisions inevitably involves risk, and usually considerable uncertainty. Risk management provides a way of explicitly incorporating uncertainty in the analysis and decision making. It is, however, simply one tool, and should be used in conjunction with other tools such as environmental impact assessment, technical assessments, and social impact assessments. Information from these different sources can be combined either in series or in parallel before decisions are taken. The former approach requires establishing a priority list, for example, technical assessment, financial assessment, environmental impact assessment etc., then using each of these as a filter to eliminate possibilities. If the most restrictive assessment is applied first then options can be quickly reduced. Risk management procedures can be used to assess impacts in parallel. This approach is preferable because of the complex interactions between areas such as ecological environment and social environment that cannot be addressed by the filtering process. Risk management provides a consistent framework for the analysis of all potential adverse effects, and this allows different aspects of activities to be compared on a common basis. The incorporation of different types of risk allows various types of information to be included, such as social, cultural, economic and so on.

At the activity level, risk management based on technical risk assessment is an effective way of assessing applications because it can provide a consistent way of comparing potential risks with existing risks; risks are addressed at the margin. At the management level, the decision analytic approach is preferred to technical risk assessment because it is better able to incorporate value judgements. At the policy and strategic levels, technical risk assessment is less useful because it relies on being able to make assessments of individual risks, and is not able to address the increasing complexity, cumulative impacts, and potentially large groups of decision makers and stakeholders. The decision analytic approach and comparative risk assessment approaches are preferred for the policy and strategic levels respectively.
To test the validity of these rankings, the first two risk-based decision-making approaches selected for each level are being applied to a particular ‘real’ groundwater system. This process has been started at the activity level (level 4), where both technical risk assessment and the decision analytic approach are currently being applied to real groundwater decisions in the Canterbury area. Criteria based on the characteristics of good decision making (used in the first pass of this process) and the requirements for decision making at the particular level, including precision of estimates and requirements for, and availability of resources will be used to test the validity of the ordering.
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