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Risk Assessment and the Environment

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Introduction

This paper reviews the use of risk assessment techniques in the field of environment protection. I will argue that in some important instances the development of environment policy has been a source of fruitful development of a risk based methodologies. In other cases the importation of risk assessment techniques has proved much more problematic.

As the scope of environmental regulation increases so does the possibility of inconsistent and arbitrary solutions to problems. The need for a more systematic approach to the development of environmental regulation has never been stronger, so it is important to understand the reasons for the mixed success of risk assessment. This applies equally to those nations with long traditions of the regulation of private sector industry and those just beginning on this course. The way ahead may be to extend our ideas of how to express risk and uncertainty. Some of the recent cause celebres of environment policy show this challenge very clearly. As an example, this paper will look at the problem of assessing the risk of man-made climate change.

Defining "Environment"

It is not surprising that environmental regulation severely tests many of the well tried decision making approaches, because it embraces such a wide field of activity. Einstein is reputed to have defined the environment as "everything that is not me". This certainly reflects the breadth of the problem – can any single decision making methodology hope to embrace the whole of environment policy? However this definition misses a further important ingredient – that the resolution of environment policy is an intensely social and political process. One distinguished commentator has paraphrased the Einstein definition as "the environment is everything that is not my fault". Tongue in cheek or not, this definition reflects that people may have very different views as to damage and risk of damage, dependent on their relationship to the environmental issue. This will emerge as I look at some examples.

Classes of Regulator Issues

It is convenient, when analysing the success and limitations of risk assessment in the environment, to break down the regulatory problem into sub-categories. Four possible categories of regulatory context suggest themselves:

- **process safety** e.g. regulation of the *process* of safe disposal of waste to land
- **incidental exposure** e.g. controls on marketing and use of chemicals to limit *general* exposure of the environment to dangerous chemicals
- **once off events** e.g. assessment of the impact of a civil engineering project on a natural habitat

– **"continuous accidents"** e.g. permitted discharges to rivers

I will look at risk assessment in each of these categories in turn. I will follow the convention on terminology

hazard to mean the property of a substance or process that has the capability to do harm;

hazard analysis to mean the identification and quantification of those hazards;

consequence analysis to mean the identification of the consequence of the harm being realised;

risk analysis to mean the identification of the probabilities of such consequences occurring, and

risk assessment to cover the whole assessment process.

The natural place to begin is the risk assessment of environmental process safety since this is the origin of risk assessment methodology.

Use of risk assessment techniques — Process Safety

An industrial accident can lead not only to harm to people but also damage to the environment. The Seveso, Sandoz and Chernobyl accidents led to widespread environmental contamination. However it is only recently that environmental as well as human health and safety considerations have been widely factored into the regulation of hazardous installations. Before this recent development the main issue of process safety to merit the special concern of the environment regulator has been the process of disposing of waste.

Under most regulatory systems of waste disposal, the process is intended to be safe. Damage occurs when an unintended event, such as the failure of a lining or other method of containment occurs. By far the most developed process risk assessment in waste disposal policy is the assessment of the disposal of radioactive waste.

The development of risk assessment techniques for radioactive waste disposal undoubtedly owes much of its origin to close proximity in the public eye to the highly developed assessment techniques used elsewhere in regulating the nuclear industry.(1) As typical studies show(2) assessing radioactive waste disposal does represent its own problems in risk assessment.

One of the most challenging aspects is the long timescale over which the risk is to be borne by society, perhaps 100,000 years. Thus while a typical industrial risk analysis might reflect a relatively high risk over a short period to an individual, the regulator of radioactive waste disposal has to assess exposure not only to society, but to many future generations. What is more, different engineering solutions to radioactive waste disposal may give the same time average risk but distribute it quite unevenly in time. Despite this difficulty some choice has to be made. Even if no more nuclear power stations were to be built, the world has still to find a home for the spent fuel and radioactive waste generated by the operation of some 400 installations, once the potential for the recovery of further nuclear fuel from radioactive waste is exhausted. The hazard is realised and the regulator has to find the approach which will reduce levels as low as reasonably achievable, economic and social factors being taken into account.

A similar impetus applies for toxic wastes. Once a toxic waste is produced a process has to be found for disposal. Assessment techniques are less developed in this field. This difference in part reflects the very high value added of radioactive waste disposal which can justify extraordinary efforts to assess geological and other factors at a site. Studies of this nature are seldom feasible for more ordinary waste disposal processes. However hazard assessment of classes of waste is a common regulatory approach which is used to control the final waste stream to which a waste may be directed.

Unlike radioactive wastes, most toxic wastes are by their nature reactive and transformed by the disposal process. A well engineered site is effectively a slow bio-reactor. The greatest risks are then either through improper disposal, or from the products of the transformation for example atmospheric micro-pollutants from incinerator stacks or toxic leachates from landfills. Many of the current problems of land contamination now emerging as a particular difficulty in Central and Eastern Europe, are a direct result of failure to identify and deal with the risks of toxic waste disposal. Waste regulation has become an increasingly scientific and tightly controlled enterprise since the 1970's in much of the developed world. As it develops further there will be a need for more structured hazard and risk assessment methodologies.

Some materials may however be particularly difficult in the waste disposal process, and the regulatory response may choose to prohibit the manufacture of the chemical in the first place. Recent examples are PCB's and asbestos. This leads naturally to my second class of regulatory function, the control of entry into the market place of substances that could be hazardous through incidental exposure to the environment.

Use of Risk Assessment — Incidental Exposure

There are supposedly some 100,000 man-made chemicals on the European market. New chemicals arriving on the market are required to be notified to the competent authority, and have associated with them a number of tests which indicate their possible impact on the environment. Notification is not strictly a control procedure. It simply establishes the prima facie case for the hazard assessment.

In judging whether further controls are necessary regulators employ a number of different approaches. For some substances there is a clear dose response relationship, with an identifiable threshold concentration at which effects occur in the indicator tests. The regulator might then employ a safety factor to judge the significance of the chemical. This can provide a rough and ready means of comparing the scale of realised hazard. For example, the Royal Commission on Environmental Pollution, in making its recommendation on the withdrawal of lead from the environment, noted that the safety factor between realised blood lead levels and those producing frank symptoms of lead poisoning was smaller than for many other chemicals.(3)

It is also not uncommon to use an analysis of the possible pathways by which a chemical once released into the environment could reach its target. Environmental lead to which I have already referred, can reach the bloodstream through contamination of water, contamination of food or inhalation. Dioxins can reach a human target by many different routes.(4) The total dose will be the sum of the contributions from these different pathways.

Pathway analysis is therefore very important for the control of persistent chemicals which can accumulate in the environment. A top predator such as a bird can accumulate dangerous chemicals accumulated by its prey across its whole habitat. In some ways a pathway analysis is analogous to the fault-tree analysis in traditional risk assessment. Since we are considering continual dosing of the environment, "failure rates" are now replaced by expected average dose rates. The main common element between fault-tree analysis and pathway analysis is the need for a rigorous investigation of the possibilities that could constitute pathways.

A special case of the control of the environmental effects of chemicals is the regulation of pesticides. By definition pesticides are both actively distributed into the natural environment, and are designed to be harmful to at least one living creature. A commercially successful pesticide can be exposed to the environment in very large quantities and over many years. Persistence in the environment, and accumulation in the food web are therefore real hazards. For this reason consideration of environmental safety has been added to the existing regulation of pesticide use for food safety.

It is clear that risk assessment of chemicals has a firm grounding in hazard identification and analysis. In principle it could include a greater element of probabilistic analysis in its risk analysis of the consequences. However reducing the average consequence is not always the thrust of the relevant legislation. Thus is might be possible to calculate the probability that a fisherman liked to fish in a river that was contaminated with mercury, that he was successful with his catch, that he was married, that his wife was pregnant, and that she shared his enthusiasm for a fish diet. However legislation more frequently focuses on the protection of a sometimes hypothetical "target" (or critical group in the case of radiological terminology) thus short circuiting, for good or ill, much of the meat of a risk analysis. It is in effect the allocation of a right to the target group concerned. In my example to pregnant fisherman's wives.

Releasing a new chemical also poses a different type of hazard. The regulatory test procedures may simply have not anticipated something. It is often remarked how difficult it would have been to have anticipated the effects of CFC's on the stratospheric ozone layer at the time that they were engineered. Of course it is possible to look at the performance of the regulatory regime retrospectively, and fortunately, as we would expect, the likelihood of error is decreasing.

A novel form of hazard assessment is associated with the regulation of the deliberate release of genetically modified organisms.(5) Since by definition the phenotype, or outward expression, of a transgenic organism is not finally characterised until the organism is released, the regulatory system has to judge the appropriate step by step approach by which to manage any risk. This risk can have a probabilistic content, for example, a containment process might fail. However, much of the difficulty lies in judging the uncertainty in the full implications of the release. Incidental contamination of the gene pool through horizontal transfer of genetically material might occur. As with introductions of alien species, freak competitive advantage may enable the organism to spread rapidly to the disadvantage of natural competitors. Various proposals have been made to address hazard assessment in this context.(6) This technology is likely to become a major part of world traded products, and it is therefore essential that international agreement is reached on the general approach to biotechnology safety.

The difficulty facing risk assessment of chemicals is a very diffuse understanding at the time of placing a substance on the market of its likely fate in the environment. This limits the use of quantitative risk analysis. For a new chemical there would simply be no data on which to quantify the risk it posed let loose in the world. However the overall risk of the release can be reduced by monitoring the subsequent changes in concentration in the environment. It has often been through monitoring (for example of DDT in species in parts of the world remote from its use) that has led to a reassessment of a chemical. Risk management therefore complements risk assessment, and in part reduces the problem of determining the mechanisms and pathways of the chemical. This is especially true for the major reassessment of existing chemicals now underway in the OECD.

Risk management with continuous monitoring and response, is seldom likely to be an option for a one-off impact on the environment, say through the construction of a dam or a new motorway, yet there are difficulties at least as great in assessing the secondary and tertiary impacts on an ecosystem of such projects.

Use of Risk Assessment — Once Off Events

Many States now require a full environmental impact of major projects. These impact assessments can include the possibility of accidental damage, such as a tanker accident on a motorway. This would be handled very much in the way that I described in my first category of assessment. If risk management plays a part it would be in determining the accident response strategy, as for example with marine oil spills. The environmental impact assessment could also include the impact of continuous emissions, although this is usually assessed in the context of local pollution control systems. I will deal with these in the next category. However, the impact assessment can involve assessing the wide impact of a project through its disruption of the local natural environment. Possibly the most common problem is to have to assess the long term impact on an ecosystem of the loss of some proportion of the habitat.

Using our traditional risk assessment terminology hazard analysis is straightforward, in the sense that the assessment is on the basis that the hazard — say the loss of 25% of a nature reserve — is realised. It is the consequence analysis that is the major challenge. First there is seldom enough data. Most models of an ecosystem require not only large quantities of cross-sectional data, but also significant longitudinal time series data. Nevertheless since many of the theoretical ecosystem models of the 1970's were probabilistic in structure, it might have been thought that there was a good prospect of representing data gaps as sampling errors and so lead to a quantitative risk assessment. However while text book models derived for heuristic purposes have simple structural relationships, nature contrives to make real world cases much more complex. Real world efforts to model ecosystems thus have problems of structural uncertainty as well as scaling errors.

A particularly interesting recent development in theoretical ecology which has yet to make its mark in risk assessment generally has been the introduction of models based on chaotic sequences rather than probability distributions. Some of the best known chaotic sequences are those that produce the pseudo random numbers in computer languages. Each next step is determined by previous steps, but over time the change in values take on random-like qualities. The ecological population growth equation can be cast in just such a chaotic form.

Chaotic models of the natural environment are not that much less hungry for data than stochastic models, but they do offer the prospect of better qualitative descriptions of the total effect of a project on an ecosystem. Chaos related models could have more prospect of determining the answer to questions such as "will the species survive?" and thus becoming a tool of a hazard analysis approach. In contrast probabilistic models tend to provide an over differentiated output of probabilities and population densities which may not be so useful as a basis for decision.

Use of Risk Assessment — "Continuous Accidents"

The bread and butter of environmental pollution policy is the control of polluting processes. There is no question in this case of a hazard analysis. The hazard, if it exists, is being realised continuously. Once again the focus of attention is on the consequence analysis, and once again it proves to be uncertainty in the consequence analysis itself which introduces the possibility of unwanted outcomes.

The classic textbook model of a pollutant is a substance with a very short lifetime in the environment and a threshold concentration below which no harm occurs, and above which harm gradually increases. With a short environmental lifetime, realised concentrations are immediately proportional to rates of emission. The aim of policy would be to get emissions low enough to keep the concentrations below the harm threshold. The aim may be too expensive to achieve at first and a trade-off between abatement cost and emissions has to be settled in the form of a regulatory requirement on the abatement technology to be employed. This is a problem which is now being addressed in an acute form in several Central and East European Countries.

Even this simple world view offers substantial difficulties for consequence analysis. It would seem a reasonable pollution control policy to locate polluting plant as far as possible from environments with low thresholds of harm. However to be sure that no harm is taking place requires detailed analysis of the transport properties of pollutants. The cause celebre of transport models has been those modelling the transport of acid oxides. It is not only the transport of the pollutant that is important, but its transformation either to strong acid oxides or secondary pollutants while it is transit. Models to incorporate all the known science are very complex and difficult to validate in their entirety. Models of this form seldom contain stochastic analysis of their internal errors. In Europe confidence in the output is expressed by comparing the outcome of models of the same process by different modelling centres.

The natural risk management strategy is to monitor the environment at the remote location and at the first sight of damage abate emissions. However recent patterns of environmental damage suggest that this approach may be inadequate as a risk management strategy. An environment may be initially resistant to acid rain damage because as the acidity of the environment is raised, alkaline compounds present in the soil begin to dissolve into surface waters restoring the neutrality. The alkaline compounds "buffer" the acidity and obscure its effect. When the rate of deposition exceeds the rate at which the buffer is replenished by natural processes, the buffer becomes depleted. When the buffer is exhausted the environmental chemistry changes suddenly. Even if the deposition was to stop altogether recovery would not be immediate, but determined by the rate at which the natural buffer was replenished. This can be very slow. One of the most dramatic examples of chemical buffer depletion has been the depletion of autumn Antarctic stratospheric ozone. Although the depletion was first observed in 1988, and although world emissions are dropping rapidly, it is not expected that the ozone hole will be repaired until at least 2000.

If consequence analysis can be difficult to validate, and effects monitoring may be misled by buffering effects and unanticipated accumulation, a risk management strategy has to give some bias towards prevention of damage ahead of direct evidence when the hazard shows some particular properties. These add dynamic elements to the assessment. First the hazard has to show the property of being irreversible, or quasi-irreversible. This includes the property of bio-accumulation, long environmental lifetimes, and interference with the large scale geo-chemical cycles which could produce buffering. This bias is sometimes called the precautionary principle.(7)

This approach is to be found in much of modern environmental legislation. The legislation may require that attention be paid to not exceeding specified environmental quality standards. These are set with a degree of safety margin, will require environmental monitoring to ensure compliance, and correspond to conventional risk management strategy of monitoring and response. Within this outer framework of regulation, the emissions of certain substances are required to be reduced further to the level that best available technology could reasonably be thought to achieve. These emissions are in effect subject to a precautionary approach. Examples of such substances are the Red List substances in UK legislation for discharges to water.

Decision Making in Environment Regulation

After this review of environmental regulation and risk assessment it is worth taking stock. First while truly random processes do occur in environmental issues, they are not as dominant a part of the story as in safety policy. The main issue addressing risk assessment in environmental regulation is one of describing the degree of confidence that we have about one man's effect on another man's natural environment. In almost every case this uncertainty increases as we move from the physics to the chemistry and from the chemistry to the biology.

Scientific enquiry has a key role to play by providing a proxy for the state of the environment, because the natural environment cannot speak for itself. However science reduces but does not eliminate uncertainty. Indeed it would be classic risk management philosophy to assess at each stage the balance of collecting more information but otherwise doing nothing and taking some action with the risk that it may not later prove to have been necessary. This management decision is no less social and political in context than any other regulatory process.

Risk assessment is probably more exposed to criticism in environmental issues because there are few opportunities for addressing through some second stage any shortcomings or approximations in the assessment. Workers will continue their negotiation of their pay rate after a risk assessment of their task has been completed. The local populace, who are about to have the risk they bear for the benefit of society at large to be judged "acceptable", are seldom in that position. Unlike workers whose job is re-classified as high risk, who will probably make some economic gain the wage bargain, the neighbourhood may actually lose money. It may not then be surprising that the appetite for quantified risk assessments exhibited by some does not always appear amongst those bearing environmental risks. Environment law is about who owns or has the stewardship for what. Ignoring distributional effects – including the redistributions of risks and gains – was a major defect of 1970's technical evaluations of many environmental issues. Distribution effects *are* environment policy.

In fact every new element of environment policy (biotech regs, transboundary air pollution, CFC's) is a renegotiation of societal property rights and liabilities. It is no wonder that environmental risk analysis when generalised from the risk to a specific individual to risk to society as a whole gets itself into such deep water.

The Need for Better Methodology

To argue that some of the earlier rule-based "rational" approaches to environmental decision making proposed in the 1970's had serious shortcomings, is not to argue against continuing the search for a generally more systematic approach. There are a number of reasons why the need for a better systematic approach is more urgent now than ever before.

- Most countries have a serious problem of "vintage" in their environmental legislation. The priority for a piece of legislation may have reflected a particular event in a particular media, and frozen handling in that area ever after.
- The legislation may specify a "no harm" condition, before the stochastic hazard of carcinogens was identified.
- legislation may have been ambiguous about whether maximum concentrations referred to the limit of measurement at that time or to the threshold of effect.
- legislation may reflect different bargains on precaution at different times favouring either the polluter or the protected to different degrees.
- some countries e.g. those in Central and Eastern Europe, cannot tackle all their environmental problems at once and need tools to help them set priorities and direct limited resources most effectively.

When environmental regulations represented only a few legal instruments, these difficulties could perhaps be tolerated. Now that they represent such a major stock of legislation, the difficulties of fitting all these pieces together is becoming a major challenge.

Major reviews are under way in a number of regulatory fora. The US EPA has begun a major review across its fields of operation.(8) The UK took its own first steps with the 1990 Environmental Protection Act which brought together waste, air pollution, integrated pollution control, dangerous substances and genetically modified organisms within one act. The Government's White Paper on the Environment in the same year laid out a plan for some 300 targets for the environment and was one of the most comprehensive approaches that has ever been attempted. Integrated pollution control in particular requires one regulatory agency to assess the impact of a scheduled process on all media at one pass and therefore establishes the basis for a more consistent approach. We hope to see a parallel integrated permitting Directive within the European Community soon. These revisions require appropriate decision making tools. As a first step, and as one of the 1990 White Paper commitments, the DoE has produced a guide to Policy Appraisal and the Environment, which you will find discussed elsewhere in this conference.(9)

Some areas of environment regulation are technology based, and the decision making tools must be closely related to other risk based approaches to process control. Some examples from this area, like radwaste disposal, already make their contribution to risk management theory. How far can risk assessment help provide this missing synthesis of approach in other areas of regulatory process?

I believe there are a number of themes running through my review of risk assessment in environment policy that shows that it could have a useful role to play in unifying our treatment of environment policy. At the same time there are areas which will still need much development. It is not clear despite courageous efforts that this methodology is fully portable across all environmental issues, yet there is a clear need for a better systematic approach. The challenge is to import the best of existing approaches, and to unify terminology, but to develop extensions where a conventional risk approach would be artificial. It would be a backward step to discredit an established approach like risk assessment, by trying to apply it to an area where it is not completely applicable.

To escape from the abstract I will try to demonstrate my thesis by reference to an example drawn from a current cause celebre. At the same time I hope to suggest areas for the development of decision making tools.

An Example — man-made climate change

There is no point choosing anything simple. Rather I will try a 4-minute risk analysis of man-made climate change.(10) It neatly brings all the new issues to the fore.

In risk assessment terms the physical hazard is well established. Certain gases — the so called greenhouse gases — transmit short-wave radiation but absorb long wave radiation. When the hazard is realised through an increase in the atmospheric concentrations of these gases, they will change the earth's energy balance. When the Intergovernmental Panel on Climate Change reviewed the science in 1990, it was, characteristic of all risk assessments, this hazard which they identified as their most certain conclusion.

In one sense the hazard analysis is straight forward since these greenhouse gases are being released into the atmosphere all the time. However transferring emissions into realised greenhouse gas concentrations proves not to be that easy as increases in some gases is thought to change the removal mechanisms and hence concentrations of others.

We saw in the case of incidental exposure that the next step in the assessment was to try and scale the hazard against some benchmark. Our nearest scale is fluctuations in the earth's radiation budget caused by natural fluctuations. These are largely caused by fluctuations in aerosols, from volcanic eruptions and fluctuations in the solar output. We note at this point, as with other hazard analysis, that we do not need to complete a consequence analysis to compare absolute hazards. As the IPPC found the expected change in the radiation imbalance in the next decade due to greenhouse gases was likely to be comparable with natural fluctuations. This establishes the prime facie case for risk assessment.

The next step we saw for risk management was to identify the dynamics of the hazard to establish whether monitoring and corrective action was sufficient. For some gases such as methane with short atmospheric lifetimes this might be possible. However two important gases, carbon dioxide and nitrous oxides are very stable with long atmospheric lifetimes. Thus even if emissions of these gases were stopped tomorrow their atmospheric concentration would drop only slowly. This quasi-irreversibility suggests that the risk management should be precautionary.

This conclusion is reinforced when we begin the consequence analysis. The change in radiation balance changes the average temperature of the earth's surface. However thermal inertia of the surface, principally the oceans, slows this warming so that it lags behind the radiation imbalance. Thus even if the emissions were to stop, not only would the greenhouse gas radiation imbalance drop only slowly, but the earth's temperature would continue to rise for say a decade or more. If this were not enough the hazard is not strictly the emission as much as the operation of the fossil fuel plant and the changes in land use practices. These take a long time to change. The IEA quote a figure of 25-50 years based on the historical analysis of Marchetti.(11)

If, following the international climate change negotiations the aim is to avoid a dangerous interference with climate, then the risk assessment shows that we cannot simply monitor its arrival and then take action. We need to take action well ahead of its onset. "Well ahead" must be defined by the models we use to undertake the consequence analysis. However these models are not only enormous, taking over whole Cray XMP's but have limited validation in the real world. The basic problem is that the world has not had this imbalance in greenhouse gases forcing for over 100,000 years and we are therefore extrapolating beyond empirical experience.

This raises two issues for the consequence analysis. First while the models are invalidated we cannot even eliminate with confidence the prospect that we are approaching a new climate transition. This is a characteristic of chaotic systems, and for all we know might occur rapidly. The second issue is that if our models are unreliable but the climate record is beginning to be contaminated by anthropogenic emissions then the historic records on which general climate risk analysis is based become of less and less use. A risk analysis does show up one surprising short coming of other analyses. Much is often made of the wide uncertainty in the outcome of different models of the consequence of climate. These differ over a factor of three. However risk analysis would naturally ask not only how wide the range of outcomes would be, but also whether they embrace a dividing line below which the consequences were of no concern. If even the lower range of climate change was in some sense "unacceptable" this would influence the risk management strategy significantly.

It is not surprising that the international community has agreed that some form of action to contain emissions is called for now while the modelling effort is improved. It is not too surprising that they have found it difficult to reach full agreement on what premium to pay for this "insurance" and who should "pay".

The first difficulty is to express what we know at present. The Intergovernmental Panel on Climate Change has resisted expressing its conclusions as probabilities on possible outcomes, despite the fact that many of its distinguished contributors come from meteorology where probabilistic descriptions are common place. There seems good reason for this. We are not trying to work out the average fate of the planet. Nor should we suppose that the average of the output of different models is a better judge of the future than the "best" model. IPPC has consistently used ranges to express the state of knowledge of key variables a method also advocated(12) elsewhere. However as each new fragment of knowledge is acquired it is difficult to judge the effect on the overall picture. Advocates for more or less action may find it tempting to play up the significance of each finding, and public understanding of the issue dissolves in confusion. There is a need to explore new ways of expressing our developing state of knowledge in non-probabilistic situations in a value free way. The more complex our environmental models become, the more pressing is this need.

In national debates on the environment, the regulator will often take the role of Solomon and decide the final balance between winners and losers. This is not happy country as we have seen for risk analysis. In negotiations between sovereign states the true nature of the bargaining process is explicit. In climate change case even the largest emitter accounts for only a quarter of the climate forcing that is changing its own climate. The best it can do is inspire others to action. The bargains that have to be made are much closer to the conflict resolutions exercises used in some countries as complemenatry to regulatory intervention. We find that some of the tricks of conventional analysis, particularly aggregation unhelpful. There is not a great deal of point calculating the change in "global welfare" consequent on climate change. Individual countries wish to know what happens to them, and how those who may believe they are winners intend to help those who are losers.

What this debate reveals is that we have limited tools for presenting the substance of the issue, particularly when there is considerable uncertainty. It is clearly an area for development.

Overall the general pattern of risk assessment and risk management fits well even in this unique and difficult problem. Traditional approaches do provide insight's and rapidly evolve strategies. There are limits, which reflect how environmental bargains are struck, and how knowledge about environmental problems is to be presented. These are the challenges.

Conclusions

There has been a significant growth in environmental legislation over the last two decades. The EC alone has almost 300 environment related directives. This growth leads to strong pressures for better consistency and smoother machinery. There may not be one single "risk of mortality" in all this legislation but it would be reasonable to ask for an audit trail that leads from one legislative framework to another in a consistent way. The climate is ripe for better use of risk management techniques suitably adapted. This review has shown that the framework of risk assessment can be structured to cover a whole range of environmental problems. It is sometimes only the habit of generating a new technical dialect for each area that obscures the similarities. We can even see how applying this framework to the unique and pressing problem in environment policy adds some transparency and order to the reasoning.

However, there are dangers. Risk management is a well established technique in some areas, and there is a real possibility that it may become tarnished if it is transferred uncritically. I would offer three areas which are in need of attention:

Expressing Uncertainty

Uncertainty about the consequences of our actions, is the hall mark of an environmental risk assessment. This contrasts with traditional safety and reliability assessments where the issue is one of probable outcomes of random processes with well defined probability distributions. If probability is the natural way to describe stochastic processes, is it necessarily the best way to formulate uncertainty? Many of our concepts in risk analysis come from systems engineering. There we find a number of more general techniques, of which our familiar probability axioms turn out to be a special case.

This has been an active area of research in Artificial intelligence work, where the aim is to codify expert knowledge and design computer programmes that can update that codification as new data arrives. Some areas of risk assessment have begun to explore the possible uses of such systems. One AI approach is to use so-called fuzzy logic.(13) This logic relaxes the additive and multiplicative properties of probability theory. Another approach is to employ intervals rather than single probabilities to describe our degree of belief.(14,15) Perhaps these new artificial intelligence techniques could help us improve the neutrality with which we describe uncertainty.

Risk and Conflict Resolution

A lack of opportunity to address distributional effects outside the assessment was another hallmark of the environmental risk assessment. This raises the question as to whether it is necessary to take the computation as far as estimating societal aggregates, such as "social welfare" at all? Is not transparency in calculation and public debate a better way to use risk related data than to subsume these in some grand weighted sum called "the social welfare function"? Would this not open the use of risk techniques in conflict resolution and a better national discussion on environmental issues? In which case how should the assessment be modified?

Chaos and Probability

In some important areas of environment policy the systems of concern may show chaotic rather than random dynamics. What is the risk assessment and risk management methodology of such systems? Might they actually be easier to analyse because of the opportunity to use non-parametric techniques?

In embarking on risk assessment we have to be clear as to its purpose. It may be to provide a rule based system so that a regulator, or the regulated, can be given a clear prescribed method to carry out required duties. In such a case it may be necessary to accept some compromises between accurately describing the real world and obtaining a workable system.

On the other hand, in using risk based approaches to develop policy, we may need a more generalised approach that is not open to criticism of technical compromise. However there are common risk assessment themes across the wide range of environmental issues. There are some major areas that are in need of further methodological development. There is also an expensive appetite for data in environmental risk assessment that needs to be contained. Nevertheless there should be optimism that refinements in traditional risk assessment techniques will be a major contribution to improving the consensus in environmental issues, and the identification of priorities.

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References

1. See for example the Health and Safety Executive (1990) Tolerability of Nuclear Power HMSO.
2. Department of the Environment (1986) Assessment of best practicable environmental options for management of low and intermediate level solid radioactive wastes HMSO London.
3. Royal Commission on Environmental Pollution (1983) 9th Report HMSO.
4. Department of the Environment (1989) Dioxins in the Environment Pollution Paper 27 HMSO.
5. Royal Commission on Environmental Pollution (1989) The Release of Genetically Engineered Organisms to the Environment HMSO.
6. Royal Commission on Environmental Pollution (1991) GENHAZ, HMSO.
7. Royal Commission on Environmental Pollution (1988) 13th Report pp. 10-12 HMSO.
8. USEPA (1990) Future Risk SAB EC 88 040.
9. Department of the Environment (1991) Policy Appraisal and the Environment DOE HMSO.
10. For a full account Intergovernmental Panel Climate Change (1990) Scientific Assessment CUP; Intergovernmental Panel on Climate Change (1992) Supplementary Report CUP.
11. IEA (1990) Energy and the Environment Paris.
12. op cit.
13. Zadeh L. A. (1965) Fuzzy Sets. Information and Control **8** 338-53.
14. Shafer G. A. (1976) A mathematical theory of Evidence Princeton University Press.
15. Gordon J, Shortcliffe E. H., (1985) A method of managing evidential reasoning in a hierarchial hypothesis space Artificial Intelligence **26** 323-57.