RISK ASSESSMENT

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INTRODUCTION

Uncertainty is present in all environmental problems, but it is not always dealt with explicitly. Most environmental impact assessments (EIA) use a single number to represent the range of values that a measured parameter actually can have. The decision may be to use the average (mean) or expected value or, alternatively, to use a worst-case value. The implied choice may be conservative or optimistic and is usually internally consistent. When uncertainties are large and important to the outcome of the problem analysis (e.g., the chance of an accidental spill of a toxic material), the assessment **is** not completely informative, and it can be potentially quite misleading to express biophysical measurements or modeling results with single numbers. The correct and appropriate way to characterize data is to describe the statistical distribution of a range of values and the confidence with which that range is held to be true. *Environmental risk assessment* **(ERA)** makes it practical to carry throughout the problem analysis, following the rules of probability theory, an expression of the likelihood of all possible values of each parameter. **ERA** is also known as probabilistic risk assessment **(PRA)** and probabilistic quantitative risk assessment **(PQRA).**

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EIA and **ERA** advise managers antl decision makers about the *frequency* and *severity* of adverse consequences to the environment from their activities or planned interventions. If thesc officials are not comfortable with these predictions. then changes can be made to mitigate or eliminate the impact and/or to reduce the risk; e.g., to use a different site or alternative technology, to implement risk management or emergency response capability. Since **risk** assessment adds to the costs of **EIA,** close coordination between analyst antl manager is necessary to decide whcn and **how** much to do. There should be only one environmental assessment report; **EIA** should include ERA when risk is important. This chapter presents the elements of performing **ERA** and illustrates how it can be effective in improving environmental protection and management.

All societies become aware that there are more requests for government action and expenditure in the area of public health and safety, than revenue to pay for them. Some method of allocating available resources, not only money hut personnel **antl** management attention, is essential. Since health and safety are sensitive political issues, choices and priority decisions are often made in response to alarming events and perceived risks, rather than actual risks. Decisions in these circumstances can result in wasted resources, unjustified fears, and social disruption (Ahearne **1993).** Risk assessment is now seen as a tool for more rational antl effective environmental management (Glickman and Gough 1990). **A** risk-based strategy can show which actions will result in the most risk reduction per unit expenditure and which uncertainties are most important for additional scientific study (US-EPA 1993). ERA is objective advisory information that can enhance the participative political process where values and preferences are properly integrated into the final administrative program for protecting lives and ecosystems. This is the opportunity in public policy for environmental risk assessment.

HISTORY

Risk has been a vital part of management information in insurance antl investment for centuries. Technological risks began to be specially analyzed during World War II in military operations research, and thereafter in the nuclear energy and space exploration fields. The concern was mainly with infrequent but catastrophic events. Since then, the number of severe industrial accidents that have captured headlines has increased. **At** the same time, environmental concerns have become a central theme in public policy discussions. Factory explosions, oil tanker spills, chemical tank car derailments, and petroleum product fires have generated a public demand for prevention and a profound concern for victims and damage to the natural environment. Official responses have included:

- 1980 The Scientific Committee on Problems of the Environment (SCOPE) of the International Congress of Scientific Unions (ICSU) published the landmark report *Environmental Risk Assessment* (Whyte and Burton 1980).

- 1982 The European Economic Community issued the *Seveso Directive* on potential industrial hazards, following a serious dioxin release incident in Seveso, Italy (EEC 1982).

- 1984 The World Bank, after the Bhopal (India) methyl isocyanate disaster, issued guidelines and a manual to help control major hazard accidents (World Bank 1985a, 1985b).

- 1987 The Organization for Economic Cooperation and Development compiled a report (Hubert 1987) on risk assessment in the OECD countries with sections on the nuclear industry, chemicals, petroleum processing, transportation of hazardous materials, and dam–reservoir projects.

- 1987 The much-referenced Brundtland report of the World Commission on Environment and Development (WCED 1987) called for the further development of technology assessment and risk assessment methodologies in pursuing sustainable development.

- 1992 More than 50 commercial banks signed a statement that, as part of their credit risk procedures for both domestic and international lending, they would recommend EIA and ERA (UNEP 1992).

The most frequently cited risk assessment framework was developed by the U.S. National Research Council (1983) for use by the U.S. Environmental Protection Agency (US–EPA). About the same time, the hazard and operability (HazOps) study method evolved, among others, in the chemical process industry as an outgrowth of quantitative probabilistic risk assessment that had matured in the nuclear industry. The US–EPA made a decision to base its programmatic priorities on comparative risk and asked its scientific advisory board to review the state of the art of risk assessment. The subsequent reports set the stage for risk assessment to enter into public policy in a major way (US-EPA 1987, 1990, 1992). As of May 1994, more than 25 U.S. states and regions have undertaken projects in comparative risk assessment for risk-based strategic planning of government programs in environmental protection (*The Comparative Risk Bulletin* 1994).

Many U.S. laws call for environmental regulations that are based on risk antl their implementation has motivated much of the methods development in the field. The clean-up of hazardous waste sites under the so-called Superfund program has been accompanied by a substantial research program on all phases of risks to human health and ecosystems (US-EPA 1988a).

Because cancer is such a dreaded disease. it attracts considerable political interest antl as a result, the U.S. risk assessment history is dominated (and distorted) by carcinogenic chemical concerns. The increased incidence of cancer, with death as the expected outcome, is the focus of attention, while risks from other diseases have been given less research. Ecological degradations deal with complex, self-organizing communities of plants and animals, and are relatively less quantifiable.

DEFINITIONS AND SCOPE

Hazard is a danger, peril, or source of harm. *Risk* is an expression of chance, combining both frequency and severity of tlamage from hazards. *Uncertainty* is caused by natural variation and the lack of knowledge or understancling about cause-effect relationships in an existing or future condition. *Assessment* is an evaluation in order to decide.

Environmental risk assessment addresses four questions:

1. What can go wrong to cause *adverse consequences*?
2. What is the probability of *frequency* of occurrence of adverse consequences?
3. What is the range and distribution of the *severity* of adverse consequences?
4. What can be done, at what cost, to *manage and reduce unacceptable risks* and damage?

Environmental impact assessment should answer the first question and give at least a qualitative expression of the magnitude of the impacts. Thus, the major additional consideration in ERA is the frequency of adverse events. Risk management is integrated into ERA because it is the attitudes and concerns of decision makers that set the scope and depth of the study. ERA attempts to quantify the risks to human health, economic welfare, and ecosystems from those human activities and natural phenomena that perturb the natural environment,

The 5-step sequence in performing ERA is:

1. Hazard identification
2. Hazard accounting
3. Scenarios of exposure
4. Risk characterization
5. Risk management

This sequence shows that ERA, like **EIA,** is a management advisory process with iteration and continuity, rather than a single analytical report (Carpenter et al. 1990). It systematizes the approach to hazard, determines what is more or less risky, and optimizes risks as compared to benefits (Rimington 1993).

Hazard Identification

Hazard identification is akin to the qualitative prediction of impacts in EIA and begins to answer the question of what can go wrong. It lists the possible sources of harm, usually identified by experience elsewhere with similar technologies, materials, or conditions. This is, in fact, a preliminary risk assessment and is immediately useful to managers in appraising the project or activity upon which they are embarking.

Typical hazards associated with economic development projects are:

- Toxic chemicals
- Failure of mechanical equipment
- Flammable or explosive materials
- Failure of critical controls
- Highly corrosive or reactive substances
- Natural disasters
- Extreme conditions of temperature or pressure
- Ecosystem damage (eutrophication, soil erosion)
- Collisions in transportation

When to include risk assessment

The need to extend an **EIA** to include **ERA** depends on whether identified uncertainties are large and important. Of course, if the uncertainties can be resolved by readily acquiring more information, then the assessor should do so. Examples of questions or uncertainties about the above hazards that might trigger an ERA are:

- Potential release of hazardous materials (rate and amount)
- Accidental fires and explosions
- Dilution and dispersion mechanisms and rates
- Transport and fate of pollutants in the environment
- Failure rates of equipment and structures
- Dose/response relationships based on animal studies
- Human behavior (reactions, errors)
- Natural hazard occurrence and frequency
- Alterations in the landscape due to changes in landuse patterns

Uncertainties arise from:

- Lack of theory, explanatory paradigms, antl basic understanding
- Inadequate monitoring of parameters of environmental conditions
- Sampling and analytical errors
- Lack of baseline environmental data at a project site
- Models that **do** not completely correspond to reality because they cannot consider all variables **antl** are therefore (over)simplified
- Novelty of technology. materials, **or** siting
- Inherent variation and stochastic events in complex natural systems
- Control antl replication problems in ecological research

Hazardous chemicals arc **a** major topic for **ERA** and elaborate screening procedures have been devised to judge when a chemical merits full investigation (Carpenter **et** al. 1990). **US-EPA (1988b)** and **the** World Bank (1985a) issue threshold guidelines based **on** frequently revised lists of highly toxic chemicals, and the amounts of each if present at any one location, that trigger risk assessment and emergency planning. Similar quantity-related guidelines are issued for highly reactive and flammable materials.

Hazard Accounting

Hazard accounting considers the total system of which the particular problem is a part, **antl** begins to answer **the** questions **of** how frequent antl how severe are the likely adverse impacts. It also sets the practical bountlaries for the assessment. The scoping of an EIA will cover much of hazard accounting. For example, a hazardous chemical may pose a risk in any stage of its life cycle, i.e., from mining and refining or synthesis through manufacturing, processing and compounding, storage and transportation, use and misuse, and finally, to post-use waste disposal or recycling (Smith et al. 1988).

Risk managers must state their concerns and indicate possible linkages of operations to mitigation measures. Some of the scoping choices to be made

Geographic boundaries
Time-scale of impacts
Stages of the causal chain of events
Phase or phases of the technological activity
Routine releases or accidents
Workforce, neighboring community, or wider population
Definitive end points for health or ecosystem effects
Cumulative effects and interactive risks that result from interaction with other projects

The scope should include the social and natural systems around a project and not just a single pollutant path. For example, it would be wrong to assess the risk posed by small concentrations of halomethanes produced incidentally to the chlorination of drinking water without comparison of the risks to the same public from *not* killing the pathogenic organisms.

The time covered should include all phases of an activity where risk is important and not just the operational period. Construction, maintenance, and dismantling may pose special hazards; for example, it is well known that the Chernobyl nuclear reactor was being tested and normal safety systems were disabled at the time of the disaster (Park 1989). Toxic effluents such as heavy metals may circulate for a long time and nuclear wastes may have half-lives of thousands of years. It is common practice to look at least one lifetime into the future, about 75 years. The important point is that the time horizon should be consciously chosen and recorded as one of the assumptions of the ERA.

A causal chain for a risk may stretch from an original decision to satisfy some wants and needs, through the choice of technologies, to adverse events, to exposure conditions, and finally to health impacts. In a sense, the Bhopal accident originated with India’s desire to be self-sufficient and to invite the local manufacture (incidentally by a multinational concern) of pesticides necessary for the protection of food crops. Such a comprehensive analysis of all related human activities is difficult and infrequently attempted.

Scenarios of Exposure

Scenarios of exposure are experiential or imaginative constructions of how the hazard might be encountered. For the environmental pathway, the bodily dose/response calculation is only one step. Knowledge of earlier parts of the exposure sequence can reveal chances to reduce risk. For example, while a toxic chemical may ultimately poison people by inhalation, **ERA** seeks information on a wide range of related variables, such as:

- Inventory of the type, amount. location, and storage conditions
- Releases to the environment, both deliberate or accidental
- How people are exposed and for **how long**
- Ambient concentrations
- The actual bodily dose
- The physical condition of victims that might affect how they respond

Reasonable sequences of events and environmental pathways are devised through which the source of harm could impact health and welfare, including the condition of ecosystems. For example, a toxic chemical might move from any point in its life cycle through air, water, plants and animals, or soil to cause an exposure by skin contact, inhalation or ingestion.

Frequency and severity

Methotlically observing or estimating the likelihood of occurrence and the severity of impacts for each scenario can produce curves plotting the probability of *frequency* of adverse events of a given *severity* versus the severity per event, e.g., the number of fatalities (see figure 1). Known as *F/N* curves, they present the 'how often' and 'how bad' aspects of risk. However, the integral, or area under the curve, is not the whole story. In figure 1, the hypothetical project (policy, technology, or site) **A** has a lower mean risk than does **B**, but **A** also has a larger probability of a catastrophic accident. In an example of the siting of a chemical plant, Site B in a rural area will have risks associated with a spill or fire from a tank truck in transit, while Site **A**. an urban site will have risks associated with the explosive dispersion of a toxic material in a highly populated area. There is no objective way to combine these two criteria antl different societies or individuals will make different choices between the two. However, the explicit depiction of risk is valuable information.

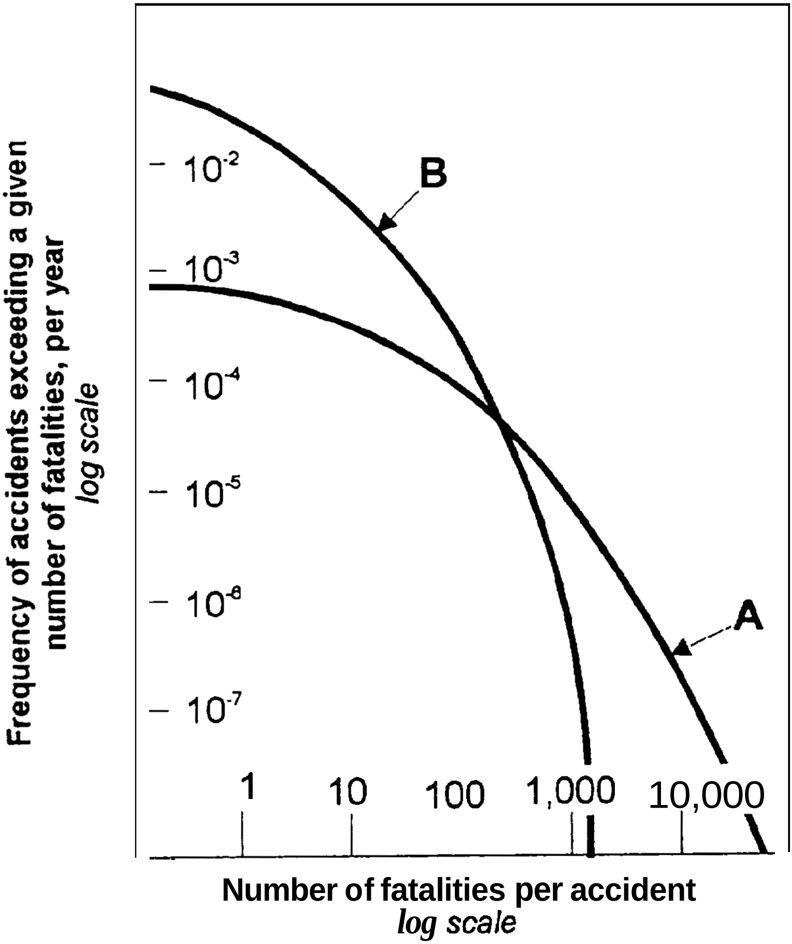
Risk may also be indicated by the breadth and shape of the distributions or probability densities of the severity values. If the standard deviation is small and the distribution approximately log-normal (bell-shaped), then the mean can adequately represent the impact. But if the standard deviation is large and there is a pronounced positive skew (tail) with low frequency but high severity outcomes, then an expression of this risk and a more thorough investigation are warranted.

Even a qualitative presentation of risk is useful. It is obvious that whenever frequent occurrence is combined with catastrophic or critical severity, the risk must be reduced if the project is to proceed. Occasional or infrequent adverse events that have only negligible or marginal consequences may be acceptable because of the benefits of the project or activity. (See the section on ecological risk for an application using expert judgment to express relative risk when quantification is not possible.)

Accident scenarios and their likelihood are analyzed with methods that evolved from the nuclear energy industry. Hazard and operability studies (HazOps) investigate deviations from the intent of engineering design. A multidisciplinary team identifies all credible accident scenarios using detailed design information, operating characteristics, and actual operating experience with engineering components and systems.

The Fault Tree procedure begins with an accident and determines with 'reverse analysis', the equipment failures or events that could lead to it. The Event Tree procedure begins with a component failure and follows a 'forward analysis' to determine if a major accident could result. Maintenance of publicly available databases on industrial accidents is carried out by the European Economic Community, US–EPA, and the American Institute of Chemical Engineers. In the USA, it is estimated that 140,000 plant sites will perform some sort of process hazard analysis by 1997 under requirements of the U.S. Occupational Safety and Health Administration (Illman 1993).

Figure 1.



This figure shows the risk distribution for two hypothetical alternative industrial facilities. Plant A has a lower mean risk (expected value of damage) than Plant B. Plant A, at the same time, has a considerably larger probability (although still small) of causing a large accident that kills many people. There is no objective way to combine these two criteria (expected value and distribution), and different groups of people will make different choices.

Risk Characterization

Risk characterization facilitates the judgment of the acceptability of the risk. Risks to health are typically characterized in terms of:

Exposure period
Potency of a toxic material
Number of persons involved
Quality of models
Quality of data, assumptions, and alternatives
The uncertainties and confidence in the assessment
Appropriate comparisons with other risks

Useful risk characterization expressions include:

- Probability of the frequency of events causing some specified number, or more, of prompt fatalities
- Annual additional risk of death for an individual in a specified population
- Number of excess (additional) deaths per million persons from a lifetime exposure
- Annual number of excess deaths in a population
- Reduction in life expectancy

Risk acceptability by the parties at interest is a fundamental management goal to which ERA contributes. Acceptability depends on a complex set of psychological factors that are beyond the scope of this chapter (see Slovic 1987). Whyte and Burton (1980) suggest the following comparisons to interpret the findings of ERA:

- Elevation of the risk above the natural background level
- Risk of alternative actions to achieve the same goal
- Other familiar risks
- Benefits of continuing the project and laking the risk

Comparisons must be carefully chosen because unacceptability is increased (Covello et al. 1988) when:

- Risks are involuntary or controlled by others
- The consequences are dreaded and delayed
- The benefits and risks are inequitably distributed
- The project is unfamiliar or involves complex technology
- Children are threatened
- Basic human needs (clean air, drinking water, food) are at risk

The communication of ERA results should take the form of decision analysis; i.e., what options are available, and for each option what are the risks, costs, and benefits, and how are these distributed within society. Proper comparison and communication can actually change laypersons' misperceptions of risks so that participative decision making may proceed on a more rational, less emotional basis.

Risk Management

Risk management is the use of the **ERA** results to mitigate or eliminate unacceptable risks. It is the search for alternative risk reduction actions and their implementation that appears to be most cost-effective. Most human activities are undertaken for obvious **and** direct benefits and risks are intuitively compared with these benefits. Avoiding one risk may create another (risk transference) and so net risk is a consideration facilitated by ERA.

There is a strong reiteration and feedback between risk management arid hazard accounting because changes in the scope of the ERA may be necessary to fully answer the questions of management, and because relatively simple changes in the project may alter the hazard and reduce risk (e.g., ***a*** different site).

HUMAN HEALTH RISK ASSESSMENT METHODS

Cancer

About one out of every three persons in the United States can be expected to contract cancer during their lifetime. Use of tobacco and dietary excesses (e.g., fats) account for about 90 percent of the cancer burden in the western world (Weisburger 1993). Cancers traced to direct, involuntary exposure to environmental pollution are estimated to constitute about 2 percent of total cancer risks (Doll and Peto 1981). The other major causes of cancer are lifestyle choices and genetic mutations.

The US-EPA has sponsored the development of methods for estimating the *additional* risk of an individual's contracting cancer from exposure to some human-introduced carcinogen in the environment. Several hundred chemical compounds have been tested using animals. The procedure used is to expose a group of test animals to high (maximum tolerated) dosage levels of the suspected carcinogen (by inhalation, ingestion, or skin absorption) for a period of time (usually the animal's normal lifetime). Postmortem inspection of each test animal is made for tumors or malignant neoplasms (i.e., cancers).

The percentage (or probability) of animals developing cancer at each dosage level is recorded. The slope of this curve is then extrapolated to the low doses expected to be encountered by human beings who may be exposed to the chemical. Various assumptions are made as to the shape of the extrapolated dose/response curve as it approaches zero dose and zero response (e.g., whether a threshold exists or not). The slope becomes a *unit cancer **risk** factor,* or potency, expressed in terms of $(mg/kg/day)^{-1}$. There is considerable controversy within the scientific community as to the validity of this method because of the high doses and extrapolation assumptions used (Ames and Gold 1990), let alone the ethical concerns about the use of animals for scientific experimentation and vivisection. Another assumption is that human beings react in the same way as do the animal test species. Nevertheless, currently there is no alternative available for estimating the dose/response relationship.

When the unit cancer risk factor is multiplied by a dose to an individual, expressed as mg/kg/day, the units cancel and the resulting number is the additional risk to the individual (chance or probability) of contracting cancer during a lifetime of exposure at that dose level to the toxic agent in question. This represents an excess risk over the sum of all other risks of contracting cancer (0.3333). Most cancer risk (other than genetic mutations) is caused by lifestyle choices; e.g., smoking, drinking, diet, and sunbathing. If, for example, a lifetime exposure of a person to a carcinogenic material in the environment is calculated to yield an added risk of 1×10^{-4}, then the new total cancer risk for that person is 0.3334. This is a small additional risk but, but it is important to determine. Individuals are exposed to many natural and artificial carcinogenic substances, some of which are highly potent. Many naturally occurring substances in food are more carcinogenic than are the contaminants from industrial chemicals (Ames et al. 1987).

It is assumed that risks are additive unless there is strong evidence for synergism or antagonism. Some exposures of the general public are involuntary (e.g., polluted air) and not avoidable by individual choice. Such risks, no matter how small, are generally not acceptable, because they are perceived to be unaccompanied by any benefit, and people feel helpless.

The expressed risk of contracting cancer is not the same as the risk of death. All cancers are not ultimately fatal. Toxic substances cause tumors at various sites in the body and different cancers have different mortality rates. About 50 percent of cancer patients survive at least five years. One out of four deaths in the United States is caused by cancer, so the overall risk of death by cancer is 0.25 (American Cancer Society 1992).

Another useful way of expressing risk is the *annual cancer incidence due to exposure to some specific carcinogen*, i.e., the additional number of new cases of cancer in a population each year. This carcinogen-specific incidence depends on the number of people exposed to varying concentrations of that carcinogen. The US-EPA (1990) has made estimates for the national population for a number of cancer-causing agents.

Noncancer Diseases

Risks of contracting diseases other than cancer from exposure to toxic agents in the environment are estimated (according to US-EPA guidelines) by using a potency factor called a reference dose (RfD) or reference concentration (RfC)—the maximum daily exposure *unlikely* to cause deleterious health effects. The RfD is also derived from animal test data as described earlier. Because of the variety of effects short of death that are associated with noncancer diseases, morbidity categories also are established for comparing health effects:

Observable effects—detectable but may not show a disability (e.g., a change in enzymes or blood biochemistry, or low weight gain in infants)

Serious effects—development or behavior abnormalities and/or dysfunction of an organ

Catastrophic effects—prompt death or shortened life, severe disability

An average reasonable exposure scenario (not a worst-case scenario) for the general population is usually chosen for the risk characterization. In some instances, a specially identified subpopulation may be exposed differently and its risk assessed separately. An exposure from a maximum plausible accident sometimes may be included to test the sensitivity of a scenario.

Criteria for Comparative Ranking of Health Risks

The large uncertainties in risk assessment preclude reliance on the absolute quantitative risk numbers that are generated. For example, a scenario following US–EPA procedures may produce an estimated exposure dose to a population, which, when multiplied by a unit cancer risk factor, infers that 100 excess cancer cases may be expected due to a specific carcinogen. This is based on the so-called '95 percent confidence limit, upper bound' estimate, which contains various conservative assumptions, so that it is certain not to be exceeded more than 1 in 20 incidences. Actually carrying through all uncertainties of exposure, potency, and individual response might produce a wide range of possible excess cancer cases, and that range might not be normally distributed. There might well be a positive skew, or tail, of low frequency/high cancer incidence outcomes. The upper bound would then be in this area of remotely possible, very bad news. Thus, the mean and the standard deviation should also be given in order to provide the appropriate information to the decision maker.

If consistent assumptions and models are carefully used for different scenarios, carcinogenic substances, and populations, then a comparison among the similarly calculated risks is a valid way of ranking risks. Uncertainties tend to cancel out. There can be confidence in estimating the relative future risk of a project scheme that is revised in order to reduce risk. A difference of at least an order of magnitude (e.g., 100 vs. 10 calculated cases) is significant management information. All else being equal, more risk-reduction attention should be devoted to the scenario that yields a calculated 100 cases than to the scenario that yields 10. If the difference is less than a power of ten, then other factors in the environmental problem analysis may dominate the choice of action to be taken.

Despite these limitations, it is necessary to loosely anchor comparative (higher or lower) risk rankings to an absolute scale. This can avoid absurdities such as ranking a risk of 10^{-8} excess cancer cases as higher than a risk of 10^{-9} when both are *de minimus* (trivial); or arguing whether to reduce a 10^{-3} risk or a 10^{-2} risk when both need urgent attention.

Throughout the world, different communities have adopted generally similar absolute values for acceptable risks to human life from involuntary, technology-caused, anthropogenic hazards. Lifetime excess risks greater than 10^{-4} (1 in 10,000)for the individual are considered high and unacceptable (Travis et al. 1987). Excess risks less than 10^{-6} (1 in a million) are low and acceptable—*de minimus* in legal terms—'the law docs not deal with trivialities'. **As** a reference, the risk of being struck by lightning is about **I** in a million in the **USA.** For excess risks of between 10^{6} to 10', decisions as to whether to take reduction action are based **on** additional consitlerations such as direct project benefits or costs of avoidance.

For noncancer disease risks, the ratio of the exposure dose to the reference dose determines acceptability, with the latter being defined (i.e., $< 10^{-6}$) to prevent the risk of unacceptable health damage. If the ratio is less than I.0, the risk is acceptable. The likelihood of exposure and the type of endpoint (morbidity or death) considered by the RfD are also factors in acceptability.

Risk Comparison

The effectiveness, **antl** efficiency, of risk management depends on deploying limited resources where they are **most** needed. Comparing risks and the costs for their reduction is a valuable decision tool (**US-EPA** 1993). For example, hazardous waste sites are perceived by many citizens as posing a high health risk antl large expenditures are made to clean them up. Yet, when quantitative probabilistic risk assessment is conducted in relation **to** these sites, they usually **turn** out to be relatively lower threats. This is because, in most cases, the chance of exposure is slight, due to their isolation from drinking water supplies and prevention of public access to these sites. In contrast, the risk from indoor air pollutants is found to be relatively high and worthy of greater reduction efforts than the public might demand. People spend most of their time indoors, often in poorly ventilated areas, exposed to vapors of household products that are often hazardous, sometimes exposed to tobacco smoke (both actively and passively), antl, in some locations, to radon.

The U.S. Department **of** Energy is undertaking an enormous environmental remediation effort, treating and disposing of hazardous and radioactive **wastes** at hundreds of sites all over the world, and at a cost of hundreds of billions of dollars. Risk assessment will be used to set priorities for the decades of work to be done. The public will be involved in the risk assessment from the outset in order to improve acceptability of the plans (National Research Council 1994).

An example of misallocation of risk management effort is reported on the London Underground (Rimington 1993). Fire as a hazard continues to receive the largest preventative expenditures. but fire actually constitutes only I percent of the residual risk, given existing precautions. This illustrates the essential importance of updating ERA as continuing management information is acquired, and separating the residual risks from the total risk of any one hazard.

Finding a small residual risk does not mean that the management activities that have brought the risk down should be decreased, although they should be reviewed for cost effectiveness. It is the further expense of reducing the small residual risk that is subject to question. For example, in the case of public water supply in most western countries, the low risk is testimony to good sanitation and water treatment practices. However, often proposed drastic and expensive measures necessary to remove trace amounts of pesticides that may pose only a small residual risk should be judged against other opportunities for protecting public health. Cost effectiveness may be illustrated by calculation of the cost per life saved. For example, the banning by law of unvented kerosene-fueled spaceheaters costs $100,000 per premature death averted, whereas regulations keeping petroleum refinery sludge out of landfills cost $27.6 million per life saved (Ahearne 1993).

Guidelines for Comparison

The following guidelines can help bring consistency to the ranking exercise. A periodic comprehensive intercomparison of all major hazards in a governmental jurisdiction can lead to improved budget allocation and administration of risk reduction efforts. Where quantitative, probabilistic risk assessment is possible, comparison is straightforward. Where only qualitative information is available, group consensus among technical professional experts is attempted.

An ordinal ranking would be inappropriate considering the uncertainties of ERA, and is unnecessary. Three levels of risks are sufficient to suggest priorities for government attention. Environmental health problems (sources of hazard) are assigned to comparatively higher, medium, or lower risk levels, but are not ranked within each level. The demarcations are not distinct and scientific uncertainties enter into the judgment of comparative risk. In general, where available data indicate that two risks are about the same calculated magnitude, the more certain of the two would be given the higher priority for attention. This guideline recognizes that health protection standards can vary in absolute risk by as much as four orders of magnitude. Also, some regulations include consideration of the cost and feasibility of risk management. The laws mandating these standards usually specify that human health is to be protected with an adequate margin of safety. Therefore, whenever government regulations, environmental quality standards, or exposure limits are based on risk and deemed to be complied with, the risk must, *ipso facto*, be placed in the lower category for comparison purposes. If there is evidence of noncompliance, then the risk should be based on a much higher exposure, of course.

The factors considered in health risk ranking are:

Cancer

a. The excess risk of contracting cancer for an individual in the general public (or in a specially exposed population) from lifetime exposure to the estimated reasonably expected concentration of a carcinogen in the environment;
b. The excess annual incidence of cancer in the general population; and
c. The degree of epidemiological association of an environmental contaminant with excess incidence of cancer.

Noncancer diseases

a. The ratio of the estimated reasonable average exposure dose to the reference dose or reference concentration;
b. The morbidity category for the toxic agent; and
c. The proportion of the population exposed.

For cancer to warrant a higher priority ranking:

a. The risk to an individual should be greater than 1×10^{-5} (1 in 100,000);
b. The predicted excess annual incidence in the USA population should be greater than 2,500 cases; or
c. The epidemiological association should be strong.

A medium ranking would result if:

a. The annual incidence was increased by more than 250 cases;
b. The individual excess risk in the general population was between 1×10^{-6} and 1×10^{-5}; or
c. The individual risk in a special population was 1×10^{-4} or greater.

A lower ranking would be given where:

a. Health protection regulations are met; or
b. The individual lifetime excess risk was less than 1×10^{-6}

For noncancer diseases to warrant a higher priority ranking:

a. The ratio of dose to reference dose should be greater than 1;
b. The morbidity category should be catastrophic; and also
c. The general population consistently exposed.

A medium ranking would result if:

a. The dose/RfD was greater than 1, but
b. The morbidity category was serious but not life-threatening, or only specially exposed populations were at risk, or the exposure was sporadic.

The risk would be ranked at the lower level if

a. The dose/RfD is less than 1 (i.e., regulations are met); or
b. The morbidity category is only 'observable'.

Issues in Environmental Health Risk Assessment

Animal testing of potential carcinogens

The transferability of animal response data to humans continues to be a matter of scientific controversy. More importantly, perhaps, the use of the 'maximum tolerated dose' (MTD) concept has raised the question as to whether an observed tumor is the consequence of carcinogenicity, or the rapid cell division that occurs as the animal attempts to repair general toxicity damage of the test. **A** two stage model of carcinogenicity separating pre-neoplasmic changes from cancer induction is gaining favor. Although MTD may continue to be one level of testing, a lower level may be necessary too. But additional lower levels might require unacceptably greater costs in using more animals and time to obtain statistically significant findings. Thus, the fundamental basis for estimating the potency of chemical hazards is now being debated (Ames et al. 1993).

Overly conservative exposure assumptions

The use of the 95 percent upper bound of statistical distributions and 'worst-case' (often inconsistent) scenarios is challenged as being unwarranted and philosophically pessimistic. Even more, these assumptions are seen to be potentially counter productive because they may shift limited risk reduction efforts from some significant risks to small, but exaggerated risks. Risk management is, in this view, a zero sum game and transfers among risks are inevitable. Being overly conservative inhibits optimization of risk management. The mean values should be carried and presented throughout an ERA to show more about the magnitude of the uncertainties, just as the low probability-high consequence information is necessary when there is evidence of non-normal distribution.

Risk communication, perception, and acceptability

The public appears to expect and demand a zero risk along with the benefits of a highly technological civilization and burgeoning economy. Risk professionals must patiently do more and better explanation of the probabilistic nature of science and the realities of risk in our complex civilization. The unwillingness to consider taking even infinitesimal and vague levels of involuntary risk (Kaplan and McTernan 1993) must somehow be overcome in a participatory democratic way. The correct choice of familiar risks with which to compare new risks is all important. Risk cost-benefit analysis should be further developed as a presentational technique for the results of ERA.

Biomarkers

Sophisticated microbiological techniques are being developed to ascertain effects of toxic substances on fundamental processes such as enzyme production and cell level behavior in humans and animals. These indicators may offer short cuts to predicting health impairment, but the skills and equipment required for these analyses are formidable.

ECOLOGICAL RISK ASSESSMENT

The U.S. National Research Council in its 1993 report, *Issues in Risk Assessment*, notes:

> Ecological risk assessments have no equivalent of the lifetime cancer-risk estimate used in health risk assessment. The ecological risks of interest differ qualitatively between different stresses, ecosystem types, and locations. The value of avoiding these risks is not nearly so obvious to the general public as is the value of avoiding exposure to carcinogens. . . the function of risk assessment is to link science to decision making, and that basic function is essentially the same whether risks to humans or risks to the environment are being considered.

The objectives of comparative environmental risk assessment as applied to ecosystems are to rank a comprehensive set of environmental problems and ecosystem sites relative to one another into broad groupings of risk, and to target response actions toward those geographical areas or ecosystem sites that are at greatest risk (Barnthouse et al. 1986). The US–EPA and the Oak Ridge National Laboratory (ORNL), among others, have sponsored conferences, reports, and research to foster a consistent approach for the developing field of ecological risk assessment. There is as yet no widely applicable, established procedure. Several approaches have been used.

Reductionist ecological methods

These attempt to compartmentalize ecological processes and effects into a myriad of understandable units and linkages. Generally these lack, and do not allow, evaluation of synergism. An example is tracking the flow of nutrients from their sources through the ecosystem. Quantification of the flow is possible, but drawing implications about effects at the regional level is complex. Reductionist approaches are useful in defining how individual stressors affect individual species and (sometimes) biological communities, and how they can be detected and monitored. With two or more stressors operating on the same system, the analysis and interpretation become increasingly more difficult.

Bottom-up methods

These rely on the use of models and laboratory data to quantify biological and ecological processes and impacts, primarily at the species and community levels. This can be useful at site specific locations, but extrapolating the results to ecosystem and regional levels is more difficult, especially if two or more ecosystems and stressors are involved. A standard water column model comprising many biogeophysical parameters is used at ORNL "to extrapolate the results of laboratory toxicity data into meaningful predictions of ecological effects in natural aquatic ecosystems" (Bartell et al. 1992).

Top-down methods

These evaluate structural and functional changes at the ecosystem and regional levels and are most easily applied where there is large-scale homogeneity in both the ecosystem and the stressor that affects it. Conversely, these methods break down when a region is a mosaic of many stressors and ecosystems. Normally there is a lack of sufficient data from a broad region to allow quantification.

Practical methods

A recent review has recognized the need to design and accomplish practical comparative ecological risk assessments useful to decision makers, politicians. and nonscientists. To meet this goal, comparative ERA need not be quantitative, and it may actually he preferable to keep it qualitative. A combination of the best judgment of ecologists and professional land and water managers with on-site experience, and the systematic evaluation of risks from available information, should be pursued. Effective communication to decision makers is accomplished through use of maps, simplified scoring systems, clearly defined evaluative criteria, antl a manageable set of ecological stressors. Defining the specific problem areas and classifying the ecosystems of the study region are important early steps in this approach to comparative ecological ERA.

Health risk assessments (with heavy emphasis on public health) differ from ecological risk assessments in several significant ways. For ecosystems, the ERA must consider effects beyond just individual organisms or a single species. No single *set* of ecological values and tolerances applies to all of the various types of ecosystems. Stressors are not only chemicals or hazardous substances, they also include physical changes and biological perturbations. For public health purposes. all humans are treated equally, but with ecosystems some sites and types are more valuable and vulnerable than others. Accommodating these factors complicates comparative ecological risk assessments and renders them more subjective.

Qualitative Methodology

Risks to ecosystems are based on the values (intrinsic and anthropocentric) of actual individual sites and the probability that stressors from human activities will significantly degrade these values in the near future. Uncertainties about value. frequency of adverse impacts, and severity of response to stress are identified and evaluated as a part of the ERA. The ability of the ecosystem occurrence (site) to recover is also considered (Carpenter et al. 1092; Maragos 1992). Just as the individual human being is the focus of health risk assessment, the individual ecosystem site is evaluated in ecological risk assessment. Ecosystems are bounded biotic communities in interaction with their physical surroundings of energy, air, water, minerals, soil. and other ecosystems. Usually, an ecological risk assessment treats only natural, more or less intact. ecosystems that are lightly managed or essentially undeveloped. Urban antl agricultural areas that are substantially modified, intensively managed, and where economic value dominates all others are considered dedicated.

Procedure for Ranking Risks

The following steps create relative rankings that can be used to inform public debate, set budget allocations, focus administrative attention, and establish site specific priorities for remediation, restoration, or protection. Since uncertainties are explicitly recognized and preserved in the assessment, areas where further research and monitoring would be worthwhile to decision makers are also illuminated. **A** multiple site comparative ERA can also reveal which stressors are the most common and damaging, which activities generate the most stress, and which types of ecosystems are most vulnerable.

1. *Establish an ecosystem classification:* Define and select a manageable number of ecosystem types that are identifiable (mappable) through currently available databases and reports, and categorized by biophysical properties (climate, rainfall, topography and elevation, vegetation, geology and geomorphology, hydrology, soils, etc.). Examples of marine and terrestrial ecosystem types are: coral reef, freshwater stream, wetland, lowland dry scrub, montane wet forest, and subalpine dry grassland.

2 *Inventory and map the ecosystem occurrences (sites):* Gather data concerning the location, extent, and status of resources, degree of disturbance, and level of protection. Previous research and monitoring and personal interviews may suffice for the inventory, but new field studies are often necessary. In the **USA,** the state 'heritage programs' and surveys performed by The Nature Conservancy are a good source.

3 *Develop criteria of value for each ecosystem type:* Determine individual criteria for the components of value for each of the different ecosystem types. Value components include: economic productivity, recreation, biodiversity, cultural and aesthetic significance. Criteria would include, for example, the wetlands classifications of the U.S. Fish and Wildlife Service, the presence of endangered species, rarity, ratio of native to exotic (introduced) species, and tourism visitor counts. Seek out previous valuation studies, measurable attributes, and changes to those attributes which degrade the resources.

4. *Estimate the value of each ecosystem occurrence:* Assign numerical scores to each value component at each site on the basis of a simple scalar using quantitative measurements of the criteria where available and professional judgements. The certainty of the score of each value component is recorded. Sum the component scores for an overall value score.

5. *Develop a list of stressors:* Determine which consequences of, and perturbations from, human activities may plausibly cause unwanted negative impacts on the natural ecosystems. Examples of stressors are: exotic species, toxic chemicals, excessive nutrients, erosion antl sedimentation. water diversion, fire. antl human crowding.

6. *Gather data on stressors and estimate the risk from each:* Collect information on past, present, antl near-future human activities that impact the specific ecosystem sires chosen for this study. Environmental experts and site managers estimate the frequency (F) of occurrence and severity (S) of tlamage from stressors to each site with which they are familiar. The uncertainty of the estimates is also recorded. Scalars arc used to roughly quantify these judgments and the product (F x S = R) becomes a risk score lor that stressor at that site.

7. *Map all of the information:* Manually create map overlays or use computerized geographic information systems to display all data relevant to risk at each site. Examples of data to be displayed include: location and site boundaries, values, stressors, risk scores, and geographic attributes such as present land use, native forest distribution, rare or endangered species habitat, historic/cultural sites, exotic species distribution, public recreation areas, and concentrated fisheries.

8. *Rank sires comparatively according to risk:* Compare a site's overall priority-for-attention score, which is the product of a site's value score and total risk score. Scores should differ by at least 20 percent of their absolute value to he regarded as different in priority.

9. *Rank stressors and ecosystem types:* Compare the stressors as to importance in a region, and compare different ecosystem types as to degree of risk. Remedial actions can be guided by learning which stressors arc widely felt and which ecosystem types are most susceptible to damage.

Example of Ecological Risk Assessment

In a Hawaii study (Carpenter et al. 1992), several hundred selected sites were evaluated throughout the islands but a detailed assessment was made only of Molokai. A well-known area, Hanauma Bay on Oahu, is briefly presented here to illustrate the method. Value components were rated on a 3-level scalar: 1 = low, 2 = medium, and 3 = high. Certainty about all ratings was indicated by a 2-level scalar: 1 = poor and 2 = satisfactory.

The scores for Hanauma Bay were:

Component	Value	Certainty
Biodiversity	3	2
Recreation	3	2
Economic productivity	3	2
Cultural/æsthetic	3	2

The total value score = 12, with uniformly satisfactory certainty.

This is the highest possible value score and is to be expected for this bay and its fringing reef, a prime tourist destination that is designated an underwater park with no fishing allowed. Stressors or sources of harm were identified as toxic chemicals, excess nutrients, erosion/sedimentation, and human crowding. A panel of environmental scientists familiar with the bay was convened to rate the likelihood and severity of these stressors causing adverse impacts to the values of the bay.

A 6-level scalar for frequency (F) of occurrence was: 1=remotely possible, 2=plausible, 3=likely in the near future, 4=occasionally, 5=ongoing, and 6=progressively increasing.

A 6-level scalar for the severity *(S)* of damage was: 1=minor loss with rapid recovery, 2=partial loss with recovery, 3=partial loss with long-time recovery, 4=major loss with long recovery, 5=total loss with eventually some recovery, and 6=irreversible loss of the unique resource.

Each expert independently rated the stressors on the site and the results were then discussed by the group. Consensus was reached on the following ratings:

Stressor	Frequency	Severity	Certainty	F x S
Toxic chemicals	2	3	Satisfactory	6
Excess nutrients	5	4	Poor	20
Erosion/ sedimentation	4	2	Satisfactory	*8*
Human crowding	6	**4**	Poor	24

The F x S scores (only the top three stressors for any site) were totalled to yield a risk score of 52. This was multiplied by the value score of 12 to yield a priority-for-attention score of 624. The average of all priority scores in the study was 300 so that Hanauma Bay clearly warranted prompt action. The agencies with jurisdiction decided to close the park one morning each week, pump all sewage out to a collector sewer and close all septic tanks, ban feeding of fish, begin a good-behavior education program for visitors (e.g., do not walk on the reef)),and increase monitoring and research at the site in order to reduce uncertainties about the impacts and their synergism.

In many of the site rating meetings, the experts were divided into two teams and their results compared. The method appears to have a replicability of about ± 10 percent of the priority score. and so it was decided to ignore differences in risks of < 20 percent in assigning overall action priorities. Despite the qualitative nature of this risk assessment, it has been well received and **found** useful by government agencies, opinion leaders, environmental groups, and in public forums on future planning for Hawaii.

Issues in Ecological Risk Assessment

Endpoints

In dealing with ecosystems there is no equivalent to the premature death of an individual human being that so dominates health risk assessment. Species extinction is analogous but whole communities of many species and their surroundings are of interest. Most risks have to do with the probability of observing an unwanted effect as a result of exposure to a toxic chemical (Bartell et al. 1992). But an endpoint must specify a measurable effect that is relevant to society's concerns. The measurement problem is often complicated by uncertainty. For example, it may be impractical, because of the large number of observations required for statistical significance, to determine the decrease in biomass of a species population more closely than 25–50 percent whereas a decrease of 10–15 percent might be serious from an ecological viewpoint. The important endpoint might be the disruption of an ecosystem function that was controlled by a diverse group of organisms.

Single specie, single chemical data

The laboratory experiments to determine exposure–response relationships are usually restricted to one or a few species and one or a few suspected toxic materials, whereas in the real world, pollutants are more often a mixture of chemicals and many species, even entire ecosystems, are at risk. Further, the mixture usually varies over time and space so that estimating actual exposure levels is even more difficult. Research is proceeding on bioassays using actual polluted water, and on the fundamental chemistry and toxicology of the most toxic constituents of pollutant mixtures (Bartell et al. 1992).

Recoverability

It is important to risk managers to know the extent to which a damaged ecosystem may recover, with or without assistance. Different species show different behavior. Recovery is also related to the endpoint chosen. There may be no recovery because ecosystems can have more than one stable state. Where native communities are displaced by exotic species, recovery is unlikely.

Scale

The spatial and temporal scales that can be practically covered in an ERA are much smaller than those of interest to managers. Extrapolation from observed areas and experimental time periods to regional scale and the long term future requires models which are not yet reliable, partly due to the inadequacy of ecological theory.

Uncertainty

In addition to measurement uncertainties, ecosystems appear to be self-organizing and nondeterministic. This 'true uncertainty', where even the probability of an event is uncertain, cannot be reduced by more effort.

Ecosystems are extremely complex and evolve in unpredictable, near chaotic fashion.

Validation of predictive tools

A lack of long-term monitoring and research has hampered the improvement of models. More retrospective examination of environmental management actions is needed to establish confidence and to reject misleading relationships.

Risks to Economic Welfare

Ecosystems have economic value because people derive utility from their use or their existence. A healthy ecosystem generates market values by providing goods and services, and also provides nonmarket values such as clean air, soil antl water quality, flood protection, biological diversity, recreational and educational opportunities, aesthetics, and quality of life. Although some of these economic values are nonmonetary, they are important. Pollution, resource extraction, overuse, and exotic species invasion can degrade an ecosystem and reduce its economic value. International concern for the health of the global environment has been growing and attention has focused on tropical forests and fragile island and marine ecosystems. Market values for timber **antl** nontimber forest products, particularly foods and medicines, are used **to** quantify antl monetize the values and damages to existing ecosystems. Analyses of the services provided by the environment, such as soil stabilization, watershed protection, climate regulation, and flood protection, are far less developed.

Recent work in risk to economic welfare because of environmental degradation has indicated the importance of conserving biodiversity by demonstrating the contribution that biological resources make to social and economic development **(antl** losses to society when they are damaged). The dollar value of biological resources may be estimated using actual, option, and existence values. Dixon and Hufschmidt (1986) illustrate the use of benefit-cost analysis **antl** other techniques in a number of case studies, including assessment of water resources and watershed protection, and lake and marine bay fisheries projects. Aesthetic vistas, clean air view distances, and presence of wilderness or specific flora and fauna are far more difficult to value and are often discussed in qualitative terms or estimated with existence valuation methods.

Economic studies on environmental quality specifically in tourist destination areas address three major issues: (1) the impacts of pollution on tourism-related economic values; (2) environmental degradation caused by tourism; and **(3)** ecotourism. Evaluation has been more qualitative than quantitative because of difficulties in monetizing the large number of services provided by the natural environment. The impacts of pollution on tourist areas are well documented in a U.S. Department of Commerce (1983) study of the Amoco Cadiz oil spill in Brittany, France. Due to oiled beaches, major losses in tourist industry revenues and consumer welfare were recorded.

Tourists today are far more environmentally aware (and concerned) than their predecessors and are demanding higher standards of environmental quality. Tour operators now call for boycotts of degraded sites in favor of other destinations. Ecotourism (environmentally conscious visitors to unique or outstanding natural areas) is a small but growing sector of the tourism market that is increasing the value of biological diversity, endangered species, and naturally functioning ecosystems. Successful ecotourism depends on a high-quality environment; however, tourism development itself may degrade those qualities. The problem of maintaining a balance between tourism and long-term environmental health (the issue of carrying capacity) was documented by the OECD (1980), where environmental deterioration in Majorca, Spain, caused a shift of tourists to other destinations.

Valuation Methods for Economic Damage to Ecosystems

The literature on economic valuation techniques for environmental degradation is considerable, and applied theory is continually evolving. For comprehensive overviews of techniques, the reader is referred to reviews on contingent valuation and comprehensive summaries of techniques by OECD (1989) and Hufschmidt et al. (1983). Economic damages represent the monetary value of environmental impacts from residual pollution problems. Direct ecosystem values include production (e.g., fishery, forestry, agriculture), commercial services, and unpriced amenities. Other values are indirect or involve potential use (option value) or nonuse (existence value) of ecosystems. Where ecosystem damages cannot be valued in monetary terms, damages should be discussed qualitatively.

The primary method for valuing productivity losses from environmental degradation is *change in productivity.* The method calculates the difference in production, valued at market prices, from a natural system with and without degradation. The resource restoration cost method calculates actual or predicted expenditures to restore the damaged resource to its former condition.

The *loss in income* method can be used to estimate welfare damages to commercial firms affected by environmental degradation. This method calculates the difference in the net income of commercial enterprises with and without resource degradation.

The most generally applicable method of valuing such amenity losses is *contingent valuation*. This approach involves direct questioning of consumers to ascertain the willingness of individuals to pay for environmental improvements, or, alternatively, their demand for compensation for environmental losses.

Travel cost and *property value* are two other methods of estimating amenity values. The travel cost approach utilizes information on differences in travel costs and visitation rates from different communities to estimate a demand curve for a recreation area. The property value method uses multiple regression analysis to estimate how proximity to amenities such as good beaches or urban parks influences surrounding property values.

Indirect ecosystem values often benefit society at large rather than individuals or businesses. For example, the indirect ecosystem values of watershed and wetlands include regulation of freshwater supplies, nutrient cycling, protection of soils, maintenance of atmospheric quality, and climate control. *Option value* measures the willingness of individuals to pay in order to retain the option of having future access to a species or resource. *Existence value* is the value people attach to the existence of species or habitat that they may have no intention of ever using or visiting, but get satisfaction in knowing that they exist.

Contingent valuation is a common method economists use to estimate indirect, option, and existence values. Contingent ranking is a related approach but provides an ordinal ranking rather than cardinal values.

Many of the valuation methods mentioned have theoretical and practical limitations and require careful interpretation. However, uncertain scientific knowledge about what services ecosystems provide and how ecosystem services are affected by stressors is probably a more serious problem in actually performing economic welfare analysis. Uncertainties in cause–effect relationships and quantification of impacts preclude useful economic valuation in many instances of ecosystem degradation from human activities.

Oil Pollution: An Example of Environmental Risks to Economic Welfare

Recent studies (Lee 1992; Carpenter et al. 1992) in Hawaii illustrate the policy relevance of ERA when economic valuation is added to the biophysical assessment. The Hawaiian islands depend on imported oil and also concentrate considerable additional shipping traffic. Thus, Hawaii's environment is particularly vulnerable to offshore oil spills. Between 1987 and 1991, collisions, groundings, and accidental leaks in Hawaiian coastal waters caused 250 oil spills ranging from 1 to 120,000 gallons. The risk to economic welfare is a function of the costs of a large spill and its probability of occurrence. Costs include at-sea response, clean-up, waste oil disposal, vessel damage, lost visitor revenues, and environmental damage remediation.

No Hawaii-specific studies of visitor revenue losses have been done but extrapolation from other coastal spill episodes indicates that most of the 10 billion dollar per year tourist industry would be drastically affected for many months. The probability of a 10,000- to 20,000-gallon spill in Hawaiian waters is estimated, from shipping experience, to be about once every two years; a 40,000- to 50,000-gallon spill every 4.5 years; and a devastating 10 million-gallon spill (equivalent to an Exxon Valdez spill) every 135 years. The current oil response capability of the U.S. Coast Guard in Hawaii is 42,000 gallons and the state has no spill prevention plan. The recommendations of the ERA were for a prompt review of regulations and response capability, and to undertake surveys of local businesses and visitors to refine the estimates of tourism losses.

Issues in Risks to Economic Welfare

Nonmarket and even nonuse values are important to this element of ERA but the social science research techniques to establish the monetary worth of such amenities are still being developed. The dilemma of increasing tourism revenues, rising visitor counts, and environmental stability that allows continued economic benefits presents one of the major issues for future research in risks to economic welfare. Contingent valuation surveys and interviews are dependent on how questionnaires are phrased and administered. Also, the willingness to pay is affected by the ability to pay so that socioeconomic factors must be taken into account. The subjective nature of this field is an obstacle to its utility.

CONCLUSION

Environmental risk assessment is developing rapidly and there is no one clearly superior approach to its performance. Adherence to probability theory is the one essential in adding this explicit presentation of uncertainty to the management information package begun about 20 years ago as environmental impact assessment. Frequency and severity of adverse impacts should be investigated antl interprcted for decision makers and the interested public if policies and action programs are to be effective and efficient.

Health risks antl ecosystem risks differ substantially in the endpoints chosen for risk characterization (i.e., the individual person compared with the biological community), and in the uncertainties accompanying experimental data. Human health risk assessment is far more advanced in methodology. However, both are dominated by concern with toxic chemicals. Both require close communication between environmental scientists and risk managers. A common but flexible framework for hazard identification, exposure pathway analysis, antl hazard accounting is useful because the underlying treatment of uncertainty and the decision process is the same for both.

A major application of ERA is in allocating limited budgets and setting priorities for risk reduction program. Therefore, the economic valuation of damages from adverse events antl the cost of reducing or avoiding the risks is essential. Public acceptability of risks is assisted by ERA if proper comparisons are made with the benefits of technological activities, the risks of alternative economic development strategies, and familiar risks in other parts of modern lifestyle. ERA can help correct misperceptions of risk and avoid unnecessary public anxiety. Environmental risk assessment is maturing as a practical antl valuable addition to the set of management and policy tools needed in a complex world.

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