

Among the many catastrophic damages inflicted on our environment, recent events include the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, and the 2011 earthquake and tsunami that destroyed the Fukushima Daiichi nuclear power plant. The Macondo well operated by British Petroleum, aided by driller Transocean Ltd. and receiving cement support from Halliburton Co. blew out on 20 April 2010, leading to eleven deaths. The subsequent 87 day flow of oil into the Gulf of Mexico dominated news in the U.S. for an extensive period of time, polluted fisheries in the Gulf as well as coastal areas of Louisiana, Mississippi, Alabama, Florida, and Texas. The cause was attributed to defective cement in the well. The Fukushima nuclear plant disaster led to massive radioactive decontamination, impacting 30,000 km² of Japan. All land within 20 km of the plant plus an additional 2090 km² northwest were declared too radioactive for habitation, and all humans were evacuated. The Deepwater Horizon spill was estimated to have costs of \$11.2 billion actual containment expense, another \$20 billion in trust funds pledged to cover damages, \$1 billion to British Petroleum for other expenses, and risk of \$4.7 billion in fines, for a total estimated \$36.9 billion.¹ The value of total economic loss at Fukushima range widely, from \$250 billion to \$500 billion. About 160,000 people have been evacuated from their homes, losing almost off of their possessions².

The world is getting warmer, changing the environment substantially. Oil spills have inflicted damage on the environment in a number of instances. While oil spills have occurred for a long time, we are becoming more interested in stopping and remediating them. In the United States, efforts are under way to reduce coal emissions. US policies have tended to focus on economic impact. Europe has had a long-standing interest in additional considerations, although these two entities seem to be converging relative to policy views. In China and Russia, there are newer efforts to control environmental damage, further demonstrating convergence of world interest in environmental damage and control.

We have developed the ability to create waste of lethal toxicity. Some of this waste is on a small but potentially terrifying scale, such as plutonium. Other forms of waste (or accident) involve massive quantities that can convert entire regions

into wasteland, and turn entire seas into man-made bodies of dead water. Siting facilities and controlling transmission of commodities lead to efforts to deal with environmental damage lead to some of the most difficult decisions we face as a society.

Recent U.S. issues have arisen from energy waste disposal. Nuclear waste is a major issue from both nuclear power plants as well as from weapons dismantling.³ Waste from coal plants, in the form of coal ash slurry, has proven to be a problem as well. The first noted wildlife damage from such waste disposal occurred in 1967 when a containment dam broke and spilled ash into the Clinch River in Virginia.⁴ Subsequent noted spills include Belews Lake, North Carolina in 1976, and the Kingston Fossil Plant in Tennessee in 2008. Lemly noted 21 surface impoundment damage cases from coal waste disposal, five due to disposal pond structural failure, two from unpermitted ash pond discharge, two from unregulated impoundments, and twelve from legally permitted releases.

Some waste is generated as part of someone's plan. Other forms arise due to accident, such as oil-spills or chemical plant catastrophes. Location decisions for waste-related facilities are very important. Dangerous facilities have been constructed in isolated places for the most part in the past. However, with time, fewer places in the world are all that isolated. Furthermore, moving toxic material safely to or from wherever these sites are compounds the problem.

Many more qualitative criteria need to be considered, such as the impact on the environment, the possibility of accidents and spills, the consequences of such accidents, and so forth. An accurate means of transforming accident consequences into concrete cost results is challenging. The construction of facilities and/or the processes of producing end products involve high levels of uncertainty. Enterprise activities involve exposure to possible disasters. Each new accident is the coincidence of several causes each having a low probability taken separately. There is insufficient reliable statistical data to accurately predict possible accidents and their consequences.

Specific Features of Managing Natural Disasters

Problems can have the following features:

1. Multicriteria nature

Usually there is a need for decision-makers to consider more than mere cost impact. Some criteria are easily measured. Many, however, are qualitative, defying accurate measurement. For those criteria that are measurable, measures are in different units that are difficult to balance. The general value of each alternative must integrate each of these different estimates. This requires some means of integrating different measures based on sound data.

2. Strategic nature

The time between the making of a decision and its implementation can be great. This leads to detailed studies of possible alternative plans in order to implement a rational decision process.

3. Uncertain and unknown factors

Typically, some of the information required for a natural disaster is missing due to incomplete understanding of technical and scientific aspects of a problem.

4. Public participation in decision making

At one time, individual leaders of countries and industries could make individual decisions. That is not the case in the twenty-first century.

While we realize that wastes need to be disposed of, none of us want to expose our families or ourselves to a toxic environment.

Framework

Assessing the value of recovery efforts in response to environmental accidents involves highly variable dynamics of populations, species, and interest groups, making it impossible to settle on one universal method of analysis. There are a number of environmental valuation methods that have been developed. Navrud and Pruckner⁵ and Damigos⁶ provided frameworks of methods. Table 15.1 outlines market evaluation approaches.

There are many techniques that have been used. Table 15.1 has three categories of methods. **Household production function** methods are based on relative demand between complements and substitutes, widely used for economic evaluation of projects including benefits such as recreational activities.

The **Travel Cost Method** assumes that the time and travel cost expenses incurred by visitors represent the recreational value of the site. This is an example of a method based on revealed preference.

Hedonic price analysis decomposes prices for market goods based on analysis of willingness-to-pay, often applied to price health and aesthetic values. Hedonic price analysis assumes that environmental attributes influence decisions to consume. Thus market realty values are compared across areas with different environmental factors to estimate the impact of environmental characteristics. Differences are assumed to appear as willingness to pay as measured by the market. An example of hedonic price analysis was given of work-related risk of death and worker characteristics.⁷ That study used US Federal statistics on worker fatalities and

Table 15.1 Methods of environmental evaluation

Household production function methods	Revealed preference	Travel cost method
Hedonic price analysis	Revealed preference of willingness to pay	Benefit transfer method
Elicitation of preferences	Stated preference	Contingent valuation

worker characteristics obtained from sampling 43,261 workers to obtain worker and job characteristics, and then ran logistic regression models to identify job characteristic relations to the risk of work fatality.

Both household production function methods and hedonic price analysis utilize revealed preferences, induced without direct questioning. Elicitation of preferences conversely is based on stated preference, using hypothetical settings in contingent valuation, or auctions or other simulated market scenarios. The benefit transfer method takes results from one case to a similar case. Because household production function and hedonic price analysis might not be able to capture the holistic value of natural resource damage risk, contingent valuation seeks the total economic value of environmental goods and services based on elicited preferences. Elicitation of preferences seek to directly assess utility, to include economic, through lottery tradeoff analysis or other means of direct preference elicitation.

Cost-benefit analysis is an economic approach pricing every scale to express value in terms of currency units (such as dollars). The term usually refers to social appraisal of projects involving investment, taking the perspective of society as a whole as opposed to particular commercial interests. It relies on opportunity costs to society, and indirect measure. There have been many applications of cost-benefit analysis around the globe. It is widely used for five environmentally related applications,⁸ given in Table 15.2:

The basic method of analysis is cost-benefit analysis outlined above. Regulatory review reflects the need to expand beyond financial-only considerations to reflect other societal values. Natural Resource Damage Assessment applies cost-benefit analysis along with consideration of the impact on various stakeholders (in terms of compensation). Environmental costing applies cost benefit analysis, with requirements to include expected cost of complying with stipulated regulations. Distinguishing features are that the focus of environmental costing is expected to reflect a marginal value, and that marginal values of environmental services are viewed in terms of shadow prices. Thus when factors influencing decisions change, the value given to environmental services may also change. Environmental accounting focuses on shadow pricing models to seek some metric of value.

Cost-benefit analysis seeks to identify accurate measures of benefits and costs in monetary terms, and uses the ratio benefits/costs (the term benefit-cost ratio seems more appropriate, and is sometimes used, but most people refer to cost-benefit analysis). Because projects often involve long time frames (for benefits if not for costs as well), considering the net present value of benefits and costs is important.

Table 15.2 Environmental evaluation methods

Project evaluation	Extended cost-benefit analysis—normative
Regulatory review	Metric other than currency—normative
Natural Resource Damage Assessment	Stakeholder consideration—compensatory
Environmental costing	Licensing analysis
Environmental accounting	Ecology-oriented

We offer the following example to seek to demonstrate these concepts. Yang⁹ provided an analysis of 17 oil spills related to marine ecological environments. That study applied clustering analysis with the intent of sorting out events by magnitude of damage, which is a worthwhile exercise. We will modify that set of data as a basis for demonstrating methods. The data is displayed in Table 15.3:

This provides five criteria. Two of these are measured in dollars. While there might be other reasons why a dollar in direct loss might be more or less important than a dollar lost by fisheries, we will treat these at the same scale. Hectares of general ocean, however, might be less important than hectares of fishery area, as the ocean might have greater natural recovery ability. We have thus at least four criteria, measured on different scales that need to be combined in some way.

Cost-Benefit Analysis

Cost-benefit analysis requires converting hectares of ocean and hectares of fishery as well as affected population into dollar terms. Means to do that rely on various economic philosophies, to include the three market evaluation methods listed in Table 15.1. These pricing systems are problematic, in that different citizens might well have different views of relative importance, and scales may in reality involve significant nonlinearities reflecting different utilities. But to demonstrate in simple form, we somehow need to come up with a way to convert hectares of both types and affected population into dollar terms.

Table 15.3 Raw numbers for marine environmental damage

Event	Direct loss (\$million)	Fishery loss (\$million)	Polluted ocean area hectares	Polluted fishery area (hectares)	Population affected (millions)
1	60	12	216	77	20.47
2	11	14	53	10	2.20
3	31	14	217	48	14.65
4	36	11	105	40	11.48
5	14	17	69	12	4.65
6	16	16	17	3	1.96
7	15	15	164	25	13.77
8	38	13	286	90	23.94
9	8	15	24	0	3.88
10	26	13	154	41	16.40
11	9	16	59	15	6.40
12	19	12	162	55	18.82
13	27	11	68	11	8.15
14	18	16	38	4	6.44
15	14	15	108	13	12.89
16	11	17	6	3	5.39
17	5	20	32	0	3.99

We could apply tradeoff analysis to compare relative willingness of some subject pool to avoid polluting a hectare of ocean, a hectare of fishery, and avoid affecting one million people. One approach is to use marginal values, or shadow prices to optimization models. Another approach is to use lottery tradeoffs, where subjects might agree upon the following ratios:

Avoiding 1 ha of ocean pollution equivalent to \$0.3 million

Avoiding 1 ha of fishery pollution equivalent to \$0.5 million

Avoiding impact on 1 million people equivalent to \$6 million

Admittedly, obtaining agreement on such numbers is highly problematic. But if it were able to be done, the cost of each incident is now obtained by adding the second and third columns of Table 15.2 to the fourth column multiplied by 0.3, the fifth column by 0.5, and the sixth column by 6. This would yield Table 15.4:

This provides a simple (probably misleadingly simple) means to assess relative damage of these 17 events. By these scales, event 8 and event 1 were the most damaging.

Wen and Chen¹⁰ gave a report of cost-benefit analysis to balance economic, ecological, and social aspects of pollution with the intent of aiding sustainable development, National welfare, and living quality in China. They used GDP as the measure of benefit, allowing them to use the conventional approach of obtaining a ratio of benefits over costs. Cost-benefit analysis can be refined to include added features, such as net present value if data is appropriate over different time periods.

Table 15.4 Cost-benefit calculations of marine environmental damage demonstration

Event	Direct loss (\$million)	Fishery loss (\$million)	Polluted ocean (\$million)	Polluted fishery (\$million)	Population affected (\$million)	Total (\$million)
1	60	12	64.8	38.5	122.82	298.12
2	11	14	15.9	5	13.2	59.1
3	31	14	65.1	24	87.9	222
4	36	11	31.5	20	68.88	167.38
5	14	17	20.7	6	27.9	85.6
6	16	16	5.1	1.5	11.76	50.36
7	15	15	49.2	12.5	82.62	174.32
8	38	13	85.8	45	143.64	325.44
9	8	15	7.2	0	23.28	53.48
10	26	13	46.2	20.5	98.4	204.1
11	9	16	17.7	7.5	38.4	88.6
12	19	12	48.6	27.5	112.92	220.02
13	27	11	20.4	5.5	48.9	112.8
14	18	16	11.4	2	38.64	86.04
15	14	15	32.4	6.5	77.34	145.24
16	11	17	1.8	1.5	32.34	63.64
17	5	20	9.6	0	23.94	58.54

Contingent Valuation

Contingent valuation uses direct questioning of a sample of individuals to state the maximum they would be willing to pay to preserve an environmental asset, or the minimum they would accept to lose that asset. It has been widely used in air and water quality studies as well as assessment of value of outdoor recreation, wetland and wilderness area protection, protection of endangered species and cultural heritage sites.

Petrolia and Kim¹¹ gave an example of application of contingent valuation to estimate public willingness to pay for barrier-island restoration in Mississippi. Five islands in the Mississippi Sound were involved, each undergoing land loss and translocation from storms, sea level rise, and sediment. A survey instrument was used to present subjects with three hypothetical restoration options, each restoring a given number of acres of land and maintaining them for 30 years. Scales had three points: status quo (small scale restoration), pre-hurricane Camille (medium restoration), and pre-1900 (large scale restoration). Dichotomous questions were presented to subjects asking for bids set at no action, 50 % baseline cost, 100 %, 150 %, 200 %, and 250 %. These were all expressed in one-time payments to compare with the level of restoration, asking for the preferred bid and thus indicating willingness to pay.

Carson¹² reported on the use of contingent valuation in the Exxon Valdez spill of March 1989. The State of Alaska funded such a study based on results of a 39 page survey, yielding an estimate of the American public's willingness to pay about \$3 billion to avoid a similar oil spill. This compared to a different estimate based on direct economic losses from lost recreation days (hedonic pricing) of only \$4 million dollars. Exxon spent about \$2 billion on response and restoration, and paid \$1 billion in natural resource damages.

Conjoint Analysis

Conjoint analysis has been used extensively in marketing research to establish the factors that influence the demand for different commodities and the combinations of attributes that would maximize sales.¹³

There are three broad forms of conjoint analysis. **Full-profile analysis** presents subjects with product descriptions with all attributes represented. This is the most complete form, but involves many responses from subjects. The subject provides a score for each of the samples provided, which are usually selected to be efficient representatives of the sample space, to reduce the cognitive burden on subjects. When a large number of attributes are to be investigated, the total number of concepts can be in the thousands, and impose an impossible burden for the subject to rate, unless the number is reduced by adoption of a fractional factorial. The use of a fractional design, however, involves loss of information about higher-order interactions among the attribute. Full profile ratings based conjoint analysis, while setting a standard for accuracy, therefore remains difficult to implement if

there are many attributes or levels and if interactions among them are suspected. Regression models with attribute levels treated with dummy variables are used to identify the preference function, which can then be applied to products with any combination of attributes.

Hybrid conjoint models have been developed to reduce the cognitive burden. An example is **Adaptive Conjoint Analysis (ACA)**, which reduces the number of attributes presented to subjects, and interactively select combinations to present until sufficient data was obtained to classify full product profiles.

A third approach is to **decompose preference** by attribute importance and value of each attribute level. This approach is often referred to as trade-off analysis, or self-explicated preference identification, accomplished in five steps:

1. Identify unacceptable levels on each attribute.
2. Among acceptable levels, determine most preferred and least preferred levels.
3. Identify the critical attribute, setting its importance rating at 100.
4. Rate each attribute for each remaining acceptable level.
5. Obtain part-worths for acceptable rating levels by multiplying importance from step 3 by desirability rating from step 4.

This approach is essentially that of the simple multiattribute rating theory.¹⁴ The limitations of conjoint analysis include profile incompleteness, the difference between the artificial experimental environment and reality. Model specification incompleteness recognizes the nonlinearity in real choice introduced by interactions among attributes. Situation incompleteness considers the impact of the assumption of competitive parity. Artificiality refers to the experimental subject weighing more attributes than real customers consider in their purchases. Instability of tastes and beliefs reflects changes in consumer preference.

For studies involving six or fewer attributes, full-profile conjoint methods would be best. Hybrid methods such as Adaptive Conjoint Analysis (ACA) would be better for over six attributes but less than 20 or 30, with up to 100 attribute levels total; and self-explicated methods (trade-off analysis of decomposed utility models) would be better for larger problems. The trade-off method is most attractive when there are a large number of attributes, and implementation in that case makes it imperative to use a small subset of trade-off tables.

Conjoint analysis usually provides a linear function fitting the data. This has been established as problematic when consumer preference involves complex interactions. In such contingent preference, what might be valuable to a consumer in one context may be much less attractive in another context. Interactions may be modeled directly in conjoint analysis, but doing so requires (a) knowing which interactions need to be modeled, (b) building in terms to model the interaction (thereby using up degrees of freedom), and (c) correctly specifying the alias terms if one is using a fractional factorial design. With a full-profile conjoint analysis with even a moderate number of attributes and levels, the task of dealing with interactions expands the number of judgments required by subjects to impossible levels, and it is not surprising that conjoint studies default to main-effects models in

general. Aggregate-level models can model interactions more easily, but again, the number of terms in a moderate-sized design with a fair number of suspected contingencies can become unmanageable. Nonlinear consumer preference functions could arise due to interactions among attributes, as well as from pooling data to estimate overall market response, or contextual preference.

Shin et al.¹⁵ applied conjoint analysis to estimate consumer willingness to pay for the Korean Renewable Portfolio Standard. This standard aims at reducing carbon emissions in various systems, to include electrical power generation, transportation, waste management, and agriculture. Korean consumer subjects were asked to tradeoff five attributes, as shown in Table 15.5:

There are $3^5 = 243$ combinations, clearly too many to meaningfully present to subjects in a reasonable time. Conjoint analysis provides means to intelligently reduce the number of combinations to present to subjects in order to obtain well-considered choices that can identify relative preference. One sample choice set is shown in Table 15.6:

Attributes were presented in specific measures as well as the stated percentages given in Table 15.6. The fractional factorial design used 18 alternatives out of the 243 possible, divided into six choice sets, including no change. None of these had a dominating alternative, thus forcing subjects to tradeoff among attributes. There were 500 subjects. Selections were fed into a Bayesian mixed logit model to provide estimated consumer preference.

When preference independence is not present, Clemen and Reilly¹⁶ discuss options for utility functions over attributes. The first approach is to perform direct assessment. However, too many combinations lead to too many subject responses, as with conjoint analysis. The second approach is to transform attributes, using

Table 15.5 Conjoint structure for Korean carbon emission willingness to pay

Attribute	Low level	Intermediate level	High level
Electricity price	2 % increase	6 % increase	10 % increase
CO ₂ reduction	3 % decrease/year	5 % decrease/year	7 % decrease/year
Reduction in unemployment	10,000 new jobs/year	20,000 new jobs/year	30,000 new jobs/year
Power outage	10 min/year	30 min/year	50 min/year
Forest damage	530 km ² /year	660 km ² /year	790 km ² /year

Table 15.6 Sample questionnaire policy choice set

Attribute	Policy 1	Policy 2	Policy 3	Do nothing
Electricity price	2 % increase	6 % increase	6 % increase	0 increase
CO ₂ reduction	7 % decrease	5 % decrease	7 % decrease	0 increase
Reduction in unemployment	30,000 new jobs	20,000 new jobs	30,000 new jobs	No new jobs
Power outage	50 min/year	10 min/year	30 min/year	No decrease
Forest damage	660 km ² /year	660 km ² /year	530 km ² /year	No reduction

measurable attributes capturing critical problem aspects. Another potential problem is variance in consumer statement of preference. The tedium and abstractness of preference questions can lead to inaccuracy on the part of subject inputs.¹⁷ In addition, human subjects have been noted to respond differently depending on how questions are framed.¹⁸

Habitat Equivalency Analysis

Habitat equivalency analysis (HEA) quantifies natural resource service losses. The effect is to focus on restoration rather than restitution in terms of currency. It has been developed to aid governmental agencies in the US to assess natural resource damage to public habitats from accidental events. It calculates natural resource service loss in discounted terms and determines the scale of restoration projects needed to provide equal natural resource service gains in discounted terms in order to fully compensate the public for natural resource injuries.

Computation of HEA takes inputs in terms of measures of injured habitat, such as acres damaged, level of baseline value of what those acres provided, losses inferred, all of which are discounted over time. It has been applied to studies of oil spill damage to miles of stream, acres of woody vegetation, and acres of crop vegetation.¹⁹ The underlying idea is to estimate what it would cost to restore the level of service that is jeopardized by a damaging event.

Resource equivalency analysis (REA) is a refinement of habitat equivalency analysis in that the units measured differ. It compares resources lost due to a pollution incident to benefits obtainable from a restoration project. Compensation is assessed in terms of resource services as opposed to currency.²⁰ Components of damage are expressed in Table 15.7:

Defensive costs are those needed for response measures to prevent or minimize damage. Along with monitoring and assessment costs, these occur in all scenarios. If resources are remediable, there are costs for remedying the injured environment as well as temporary welfare loss. For cases where resources are not remediable, damage may be reversible (possibly through spontaneous recovery), in which case welfare costs are temporary. For irreversible situations, welfare loss is permanent.

Table 15.7 Resource equivalency analysis damage components²¹

Condition	Remedial	Irremediable
Reversible	Defensive costs Costs of monitoring & assessment Remediation costs Interim welfare costs	Defensive costs Costs of monitoring & assessment Interim welfare costs
Irreversible	Defensive costs Costs of monitoring & assessment Remediation costs Interim welfare costs	Defensive costs Costs of monitoring & assessment Permanent welfare losses

HEA and REA both imply adoption of compensatory or complementary remedial action, and generation of substitution costs.

Yet a third variant is the **value-based equivalency** method, which uses the frame of monetary value. Natural resource damage assessment cases often call for compensation in non-monetary, or restoration equivalent, terms. This was the basic idea behind HEA and REA above. Such scaling can be in terms of service-to-service, seeking restoration of equivalent value resources through restoration. This approach does not include individual preference. Value-to-value scaling converts restoration projects into equivalent discounted present value. It requires individual preference to enable pricing. This can be done with a number of techniques, to include the travel cost method of economic valuation.²² Essentially, pricing restoration applies conventional economic evaluation through utility assessment.

Summary

The problem of environmental damage and risk assessment has grown to be recognized as critically important, reflecting the emphasis of governments and political bodies on the urgency of need to control environmental degradation. This chapter has reviewed a number of approaches that have been applied to support decision making relative to project impact on the environment. The traditional approach has been to apply cost-benefit analysis, which has long been recognized to have issues. Most of the variant techniques discussed in this chapter are modifications of CBA in various ways. Contingent valuation focuses on integrating citizen input, accomplished through surveys. Other techniques focus on more accurate inputs of value tradeoffs, given in Table 15.1. Conjoint analysis is a means to more accurately obtain such tradeoffs, but at a high cost of subject input. Habitat equivalency analysis modifies the analysis by viewing environmental damage in terms of natural resource service loss.

Burlington²³ reviewed natural resource damage assessment in 2002, reflecting the requirements of the US Oil Pollution Act of 1990. The prior approach to determining environmental liability following oil spills was found too time consuming. Thus instead of collecting damages and then determining how to spend these funds for restoration, the focus was on timely, cost-effective restoration of damaged natural resources. An initial injury assessment is conducted to determine the nature and extent of damage. Upon completion of this injury assessment, a plan for restoration is generated, seeking restoration to a baseline reflecting natural resources and services that would have existed but for the incident in question. Compensatory restoration assessed reflects actions to compensate for interim losses. A range of possible restoration actions are generated, and costs estimated for each. Focus is thus on cost of actual restoration. Rather than abstract estimates of the monetary value of injured resources, the focus is on actual cost of restoration to baseline.

Notes

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