

Evaluation of Restoration Alternatives for Natural Resources Injured by Oil Spills

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PREPARED UNDER CONTRACT BY:

PIETER N. BOOTH

D. SCOTT BECKER

ROBERT A. PASTOROK

JENNIFER R. SAMPSON

WENDY J. GRAHAM

PTI ENVIRONMENTAL SERVICE

15375 SE 30TH PLACE, SUITE 250

BELLEVUE, WA 98007

**American
Petroleum
Institute**



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Executive Summary

The appropriateness of a habitat restoration alternative following an oil spill depends on a variety of factors, including 1) the predicted rate of natural ecological recovery without restoration, 2) the actual effectiveness of the restoration alternative for enhancing the natural recovery rate, and 3) the cost of implementing restoration actions relative to the natural resource damages from the oil spill.

This report builds upon previous work in the field of oil spill impact assessment and habitat restoration to assess the technical feasibility and practicability of proactive restoration following oil spills and presents an approach for evaluating tradeoffs between natural recovery and active restoration.

The following major tasks were completed as part of this study:

- Evaluation of measures of natural recovery, factors affecting natural recovery, and recovery rates in selected aquatic ecosystems after oil spills
- Evaluation of technical feasibility, practicability, and ecological impacts of restoration techniques
- Evaluation of natural resource damages relative to the costs of restoration under scenarios of low-intensity restoration, high-intensity restoration, and natural recovery (no active restoration).

Scenarios used to evaluate the tradeoffs between natural recovery and restoration were based on selected case studies. The scenarios were developed to represent a broad spectrum of possible oil spills. They also represent several of the historical oil spill cases with the largest body of knowledge regarding environmental impacts, restoration, and natural recovery.

Natural Recovery

Full recovery of an ecosystem may be achieved by natural processes without restoration efforts by humans. The rate at which natural recovery occurs will be a function of habitat type (e.g., rocky shoreline vs. salt marsh), amount and type of petroleum (e.g., crude

oil vs. refined products), geographic location (e.g., arctic vs. tropics), and other location-specific factors (e.g., sediment grain size, tidal flushing, exposure).

Assessment of natural recovery may include measures of physical-chemical habitat recovery (e.g., concentration of petroleum hydrocarbon residues), biological community recovery (e.g., species abundances or community indices), and resource services recovery (i.e., recovery of environmental attributes that are valued by humans). From a natural resource damages perspective, resource services recovery is often most important. Physical-chemical recovery can generally be expected to occur more rapidly than biological recovery (largely because biological recovery is often dependent on habitat recovery). Estimates of biological recovery times have been derived in the scientific literature on oil spills and range from approximately 2–3 years for rivers, streams, and exposed marine shores to approximately 10–20 years for mangrove forests. Recovery of resource services may occur more slowly or more rapidly than biological recovery, depending on the relationships between the services and the elements of the environment (e.g., habitats and species) that are affected by an oil spill.

Technical Feasibility and Physical Practicability of Restoration

For the purposes of this study, the term *restoration* includes oil spill cleanup techniques used before or in support of activities that are intended to directly enhance animal or plant populations. Technically feasible activities that can be applied as restoration techniques include chemical dispersal, sorption, flushing, substrate removal, manual oil removal, vacuum pumping of oil, enhanced biodegradation of oil, wildlife rehabilitation, introduction of plants or animals, and physical habitat enhancement. Natural recovery is a technically feasible option for all spill circumstances, although recovery times may be long for large spills in sheltered habitats such as marshes and mangrove swamps. Technical and physical factors may need to be evaluated on a case-by-case basis to determine when a particular restoration option is practicable.

Impacts of Restoration Techniques

Oil spill case histories have shown that restoration efforts may fail and result in delayed recovery because of adverse impacts mainly related to physical effects on habitat structure, redistribution of spilled oil or other contaminants present before the spill, and alteration of biological assemblages. However, there are several low-impact restoration techniques that may be applicable to a variety of habitats. If restoration activities are implemented properly, low-impact techniques include sorption, flushing, vacuum pumping, enhanced biodegradation, wildlife rehabilitation, introduction of plants or animals, and physical habitat enhancement.

Evaluation of Natural Recovery and Restoration Tradeoffs

Natural recovery processes are generally the dominant factors controlling the recovery of oiled habitats regardless of restoration efforts. Hypothetical restoration costs and natural resource damages (i.e., lost resource value) were developed for oil spill scenarios in the following habitats:

- Soft-bottom
- Exposed rocky shoreline
- Salt marsh
- Low-energy river or stream
- High-energy river or stream.

Hypothetical scenarios were developed because existing data from case histories were inadequate for evaluating restoration costs and natural resource damages.

When the objective of a spill response (including restoration components) is to minimize the total cost to society of a spill, and the total cost of a spill is quantified based on the sum of restoration costs and natural resource damages, natural recovery is typically the preferred option for marine habitats and low-energy river and stream habitats based on hypothetical scenarios. Restoration is favored in the high-energy river and stream habitat scenario primarily because of the assumed effectiveness of sediment agitation as the restoration action. In most oil spill cases with low natural resource

values, it is likely that active restoration will not be economically efficient.

In general, available restoration techniques are not very effective for enhancing natural recovery. Moreover, human intervention to clean habitats or restore key species has sometimes retarded recovery, especially in sedimentary habitats or sensitive vegetated habitats where oil may be inadvertently mixed into sediments and organisms may be injured by foot traffic and heavy machinery. In these cases, restoration activities may cause more severe impacts than those caused by the oil spill alone.

1. Introduction

Most ecological systems have the ability to recover naturally from perturbations such as oil spills (e.g., Neff 1987; Baker et al. 1990). However, in certain circumstances active restoration of habitats following a spill may enhance the rate of natural recovery. The appropriateness of habitat restoration following an oil spill depends on the predicted rate of ecological recovery without restoration, the effectiveness of restoration techniques for enhancing the natural recovery rate, and the cost of implementing restoration activities. Habitat restoration following an oil spill may not be appropriate when 1) natural recovery will occur within a reasonable period of time; 2) restoration techniques are not technically feasible; 3) restoration is not physically possible because of environmental, political, or safety considerations; 4) restoration activities may further injure biological communities and the habitat; or 5) restoration costs would be grossly disproportionate relative to the value of the affected resources.

Approaches to evaluating habitat restoration options for application to oil spill sites are in an early stage of development (e.g., Cairns and Buikema 1984; Cicchetti 1989, pers. comm.). In addition, information on rates of natural recovery after oil spills and the feasibility of using restoration to enhance natural recovery is inadequate for many habitats.

This report represents an initial effort to assess technical feasibility and practicability of habitat restoration following oil spills and to develop an approach for evaluating tradeoffs between natural recovery and restoration.

Objectives

The objectives of this study are to determine circumstances under which 1) active restoration of natural resources following oil spills should be pursued or 2) partial active restoration or no active restoration would be preferred alternatives. These objectives were met by developing a conceptual model for evaluating restoration alternatives and applying the model to five hypothetical spill scenarios. The following tasks were completed as part of this study:

1. Introduction

- Develop a conceptual model for evaluation of habitat restoration vs. natural recovery
- Review selected case studies of oil spills in marine and river and stream habitats
- Evaluate measures of natural recovery, factors affecting natural recovery, and recovery rates in selected aquatic ecosystems after oil spills
- Evaluate technical feasibility, practicability, and ecological impacts of restoration techniques
- Evaluate natural resource damages relative to the costs of restoration under low-intensity restoration, high-intensity restoration, and natural recovery scenarios.

Regulatory Background and Definitions

The legal basis for recovery of natural resource damages caused by a release of a hazardous substance or an oil spill is primarily the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), 42 U.S.C. 9601 et. seq., as amended by the Superfund Amendments and Reauthorization Act, and the Clean Water Act (CWA), 33 U.S.C. 1251 et. seq. Under regulations promulgated pursuant to Section 9651(c) of CERCLA, parties responsible for an oil spill may be held liable for damages to natural resources in addition to cleanup costs, in claims brought under Section 311 of CWA, 33 U.S.C. Section 1321. Guidelines for performing a natural resource damage assessment (NRDA) under CERCLA were developed by the U.S. Department of the Interior and were originally published as a Final Rule in the Federal Register on August 1, 1986 (51 FR 27674).

In response to state, industry, and environmental group petitions, the U.S. Court of Appeals for the District of Columbia Circuit reviewed the 1986 NRDA regulations in Ohio v. U.S. Department of Interior, 880 F. 2d 432 (D.C. Cir. 1989) and Colorado v. U.S. Department of Interior, 880 F. 2d 481 (D.C. Cir. 1989). Based on its review, the court remanded the regulations to the U.S. Department of the Interior for revision.

Revisions to the Final Rule were published as a Notice of Proposed Rulemaking on April 29, 1991 (56 FR 19752). The proposed changes to the rule have undergone public review, and it is anticipated that the revised Final Rule will be issued in early 1992.

The Type A procedures (a computer model requiring minimal field investigation) for coastal and marine environments are currently being modified and are scheduled for proposed rulemaking in December 1991 (56 FR 19753). A proposed Type A rule for the Great Lakes environment is scheduled for release in the winter of 1991.

While the NRDA regulations were being revised under CERCLA, the U.S. Congress passed the Oil Pollution Act of 1990 (Public Law 101-380). This new law authorizes the National Oceanic and Atmospheric Administration (NOAA) to write regulations that address liability for natural resource damages incurred as a result of oil spills. Once the NOAA regulations are completed, the CERCLA NRDA regulations will apply only to releases of hazardous substances.

Definitions of key terms used in the NRDA regulations are provided below. In the NRDA regulations, *response* is distinguished from *restoration* as follows:

- *Response* means removal, remedy, and remedial actions [§ 11.14(jj)]. *Removal* means the cleanup of released hazardous substances from the environment; actions necessary to monitor, assess, and evaluate the release; the disposal of removed material; or actions necessary to prevent, minimize, or mitigate damage to the public health or welfare or to the environment that may otherwise result from the release. *Remedy* or *remedial action* means those actions consistent with a permanent remedy taken instead of or in addition to removal actions in the event of a release, to prevent or minimize the release so it does not migrate to cause substantial danger to present or future public health or welfare or the environment. Such actions may include storage, confinement, perimeter protection, neutralization, cleanup, recycling, destruction, incineration, or monitoring (CERCLA Part 101).
- *Restoration* or *rehabilitation* means actions undertaken to return an injured resource to its baseline condition (the condition that would have existed had the discharge not occurred, or the "without-spill condition") as measured in terms of the injured resource's physical, chemical, or biological properties or the services it previously provided, when such actions are in addition to response actions, and when such actions exceed the level of response action determined to be appropriate for the site

pursuant to the National Contingency Plan (NCP) [§ 11.14(l)].

The division or break point between response actions and restoration activities is far from distinct. Certain oil spill cleanup techniques may be implemented as either response actions or restoration actions, depending on the timing of the activity relative to initial response and the use of the technique in combination with species enhancement efforts as part of a specific restoration plan. For example, seawater flushing of an intertidal seagrass habitat might be interpreted as a restoration activity if it is conducted 1) after the on-scene coordinator [the Coast Guard or U.S. Environmental Protection Agency (EPA)] has decided, pursuant to the NCP, that the initial response effort is complete and 2) before replanting of seagrass, to enhance the survival of introduced plants. On the other hand, some activities are clearly restoration efforts according to the definitions of response and restoration above. For example, direct enhancement of species populations (e.g., replanting of seagrass or marsh vegetation or restocking of a clam species) would definitely fall under the category of restoration.

For the purposes of this report, the term *restoration* includes oil spill cleanup techniques used before or in support of activities that are intended to directly enhance animal or plant populations. The terms *low-intensity restoration* and *high-intensity restoration* are used to denote the relative level of effort expended on active restoration.

Natural recovery is the return of habitats and biological communities to a baseline state as a result of unassisted natural physical, chemical, and biological processes. Natural recovery processes are likely to be the dominant factors controlling the recovery rate of an impacted area regardless of whether restoration efforts are undertaken. Restoration techniques are often implemented simply to enhance natural recovery. In this report, the term *natural recovery* refers to cases in which no active restoration activities have taken place.

Specific terms are used to distinguish oil spill effects on ecological systems from economic values assigned to those effects. For example:

- *Injury* means a measurable adverse change, either long- or short-term, in the chemical or physical quality or the viability of a natural resource, resulting either directly or indirectly from exposure to a discharge of oil [43 CFR § 11.14(v)].

- *Damages* means the amount sought as compensation for injury, destruction, or loss of natural resources [43 CFR § 11.14(l)].
- *Services* means the physical and biological functions performed by the resource, including the human uses of those functions. These services are the result of the physical, chemical, or biological quality of the resource [43 CFR § 11.14(nn)].

Report Scope and Organization

This report focuses on development of conceptual models to evaluate trade-offs between natural recovery and restoration. The models were applied to the evaluation of restoration following oil spills in marine shoreline habitats and in river and stream habitats. Specific habitats within these general categories were selected to represent the range of possible oil spill scenarios. Certain marine shoreline habitats, such as salt marshes and mangrove swamps, are discussed because they may be particularly sensitive to oil spills. Other marine habitats, such as exposed rocky shores and cobble beaches, are less vulnerable to oil spills and may recover more rapidly. River and stream habitats were selected to represent freshwater systems because most of the available freshwater case histories address oil spills in flowing waters, not in lakes and vegetated freshwater habitats such as marshes, swamps, and bogs. Freshwater marshes are addressed as part of the evaluation of salt marsh habitats and low-energy river and stream systems. A brief summary of restoration techniques and their impacts, based on the comprehensive reviews of API (1985) for marine habitats and Byroade et al. (1981) for freshwater habitats, is also provided.

Scenarios used to evaluate the tradeoffs between natural recovery and restoration were partially based on the selected case studies presented in Section 3. The scenarios were developed to represent a broad spectrum of possible oil spills in terms of aquatic location, the natural resources affected, and the restoration techniques employed. They also represent several of the cases with the largest body of knowledge regarding environmental impacts, restoration, and natural recovery. The case of the *Exxon Valdez* oil spill in Prince William Sound is generally not addressed in this report because of limitations on the availability of data regarding impacts and restoration, and natural resource damages.

1. Introduction

This report considers only lost-use valuation of resource services for estimating damages from oil spills. Nonuse values (e.g., existence value) are not considered because 1) there is no reliable information in existing case histories on lost nonuse values from oil spills and 2) nonuse values are likely to be highly variable and significant only in unique and rare cases (e.g., potential extinction of a species).

2. Conceptual Approach

The key issue in evaluating habitat restoration alternatives after an oil spill is whether natural recovery alone would return the ecosystem to a without-spill state (i.e., conditions that would be expected in the absence of the spill) rapidly enough, or whether restoration would enhance the recovery rate sufficiently to be warranted. The return of the ecosystem to a without-spill state through natural recovery processes alone or in combination with active restoration is often important for the habitat to be able to provide without-spill levels of services. In natural systems a measure of ecological state, such as species abundance, may fluctuate in a regular cycle (i.e., steady state system) or remain relatively constant at some single equilibrium value. In either case, a species population may exhibit some stability in terms of its resistance to departures from equilibrium due to disturbance (e.g., introduction of oil) and its resiliency (i.e., ability to recover rapidly after an impact due to oil). Species populations that exhibit relatively stable equilibria (either constant or fluctuating) tend to be characteristic of late successional or climax communities (e.g., the mangrove species in a mangrove swamp). These species generally have long generation times, low reproductive rates, and limited ability for dispersal. In contrast, species populations that are characteristic of early successional communities tend to vary more in abundance. These species often have high reproductive rates and rapid dispersal mechanisms that allow them to recover rapidly from disturbance or to colonize disturbed areas.

A conceptual model is developed below that describes the behavior of an ecological system after an oil spill. This model serves as the basis for an evaluation of tradeoffs between natural recovery and restoration. In the context of an economic analysis, the criterion of economic efficiency may be used to assess the appropriateness of alternatives.

Oil Spill Impact and Recovery

Figure 1 illustrates a hypothetical case in which an oil spill has occurred and a natural resource has been injured. This injury, measured by one of several possible indices of ecological state, will occur immediately following the spill and will persist for some time into the future. The biological community will ultimately reach a

2. Conceptual Approach

new steady state (i.e., a stable equilibrium as in Figure 1-A or a dynamic fluctuating system) if left to recover naturally without the benefit of any initial cleanup or restoration activities. The rate at which this natural recovery occurs will be a function of habitat type, amount and type of petroleum spilled, geographic location, and other location-specific factors such as grain size of beach sediments, tidal flushing, or length of exposure. The final equilibrium point will depend on the initial magnitude of the injury and the potential for alternative steady-state communities within the region of the spill.

Restoration activities may modify the scenario in Figure 1-A. The dashed curve in Figure 1-B illustrates the ecological state following "Restoration Plan A." In this case, the initial injury to the environment is greater than that expected in the case of natural recovery, but the rate of recovery following cleanup operations is faster. For

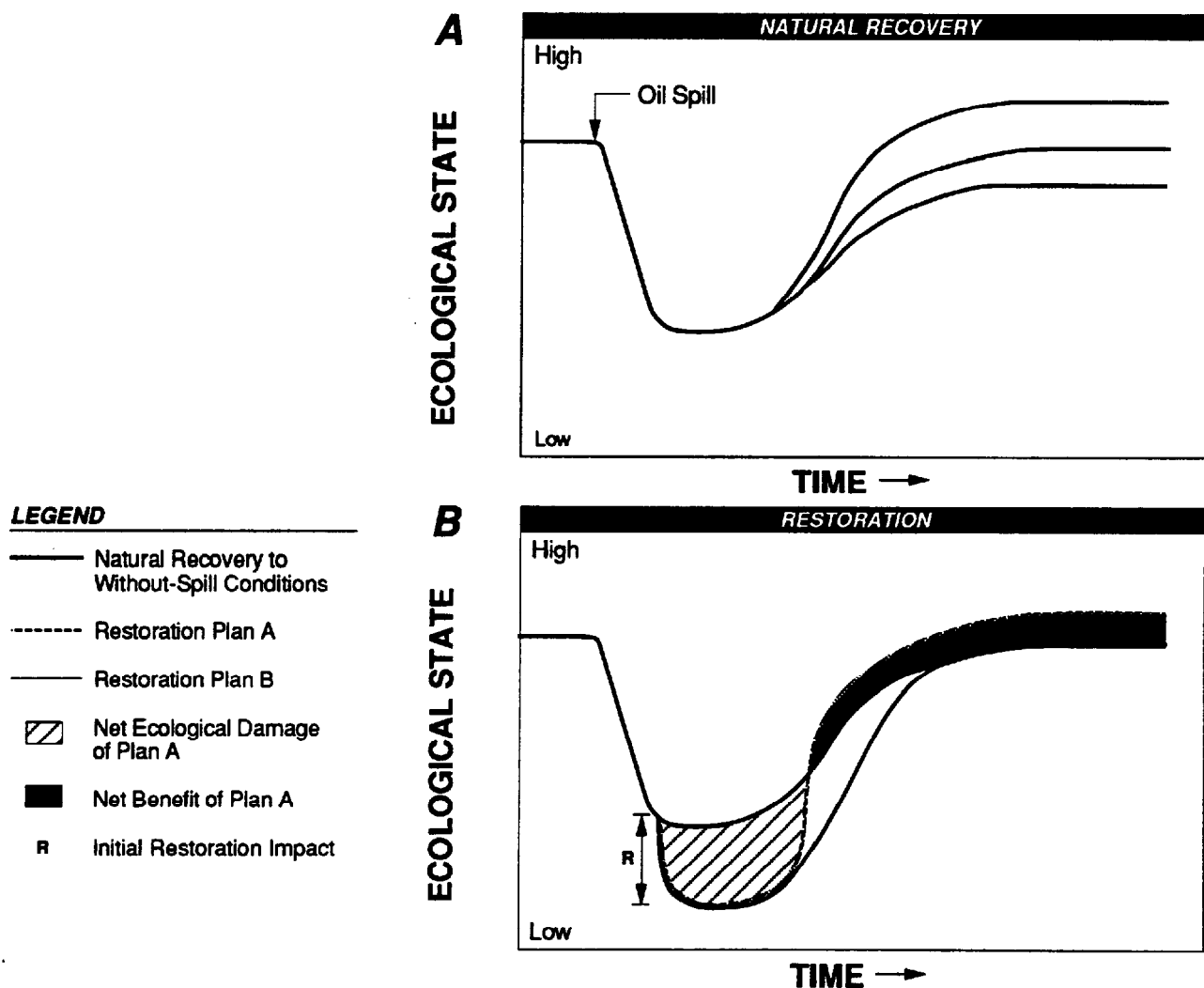


Figure 1. Conceptual model of spill impacts and recovery.

“Plan B” there is no net ecological benefit, and the initial impact of restoration lasts a longer time. The striped area in Figure 1-B represents the impact of Plan A, which must be compared with the benefits shown by the shaded area to determine the appropriateness of the restoration activities. By contrast, Plan B is inappropriate because it results in no benefit.

Marginal Economic Analysis

From an economic perspective, the optimal amount of resource restoration is that which minimizes the total costs to society associated with a spill. These costs include cleanup and restoration costs and any damage to the natural resources affected by the spill. There is a tradeoff, of course, between these two sets of costs: generally, an increase or decrease in cleanup and restoration costs leads to a corresponding decrease or increase in natural resource damages. However, in many cases a point will be reached above which the cost associated with any additional restoration will exceed the benefits of the restoration associated with that additional expenditure. Any restoration beyond this point would, in the view of economists, violate the goal of economic efficiency. The following discussion briefly introduces the concept of natural resource damages, discusses the idea of economic efficiency, and describes a conceptual model—referred to as marginal analysis—for determining the optimal amount of cleanup and restoration.

Estimation of Natural Resource Damages

The economic value of a resource is derived from the services that the resource provides to society. Economic loss occurs if the level of services that the resource provides is reduced. In theory, the value of this reduction in service can be measured in dollar terms. That is, for every individual affected by a natural resource impact, there is a specific dollar amount that would exactly compensate that individual for his or her losses. There are various techniques for estimating these losses. This report does not address those techniques, but rather focuses on losses that have been quantified in the existing literature on natural resource economics.

2. Conceptual Approach

Balancing Restoration Costs and Resource Damages: The Concept of Economic Efficiency

Given a certain amount of restoration, the net value of a resource that has been injured as a result of an oil spill is defined as the sum of the economic value of the resource following restoration efforts, minus the costs of restoration. The tenet of economic efficiency proposes a simple rule for choosing among different restoration alternatives. That is, it is economically efficient to select the restoration option that maximizes the net present value of the restored resource (i.e., the net present value of the services provided by the resource). Adherence to this rule ensures that the only actions taken are those actions whose benefits exceed their costs.

Polinsky and Shavell (1989) present several restoration/replacement scenarios for a theoretical spill to illustrate the principle of economic efficiency (Table 1). In their theoretical case, a natural resource is valued at \$30 million in an uninjured state. As a result of a natural resource injury, the resource value falls to \$10 million (i.e., natural resource damages total \$20 million), and the value will remain at this amount if no restoration is undertaken. "Restoration Plan A" costs \$6 million to implement and restores the resource to a value of \$20 million. "Restoration Plan B" costs \$25 million and restores the resources to a value of \$30 million. Polinsky and Shavell select Plan A as the economically efficient alternative because it results in the greatest net resource value¹.

TABLE 1. DETERMINATION OF NET RESOURCE VALUE^a

	Pre-Injury Resource Value (millions) (a)	Restored Resource Value (millions) (b)	Restoration Cost (millions) (c)	Net Resource Value (millions) (b - c)
No restoration	\$30	\$10	\$ 0	\$10
Plan A	\$30	\$20	\$ 6	\$14
Plan B	\$30	\$30	\$25	\$ 5

^a Adapted from Polinsky and Shavell (1989).

- 1 This example and other illustrative examples (including the hypothetical scenarios developed in Section 7) incorporate the simplifying assumption that resource values are constant over time, when they may, in fact, vary significantly in response to various socioeconomic factors.

Cicchetti (1989, pers. comm.) presents a similar example of economic efficiency. In his analysis, Cicchetti compares restoration/replacement costs to residual natural resource damages (i.e., damages expected to remain after restoration/replacement) to define a least-cost restoration scenario. In this example, total costs are defined as the sum of restoration/replacement costs and residual natural resource damages. Table 2 reproduces this example. As can be inferred from a review of this table, Alternative IV would be selected as the economically efficient restoration choice because it results in the least *total* cost.

TABLE 2. COMPARISON OF RESTORATION AND RESIDUAL NATURAL RESOURCE DAMAGES UNDER FOUR SCENARIOS

Scenario	Percent Restored (a)	Cost of Restoration (millions) (b)	Residual Damage (Percent of Baseline) (c)	Value of Residual Damages (millions) (d)	Total Cost (b + d) (millions)
I	0	\$ 0	100	\$ 10	\$ 10
II	100	\$30	0	\$ 0	\$ 30
III	80	\$15	20	\$1.5	\$16.5
IV	50	\$ 4	50	\$ 3	\$ 7

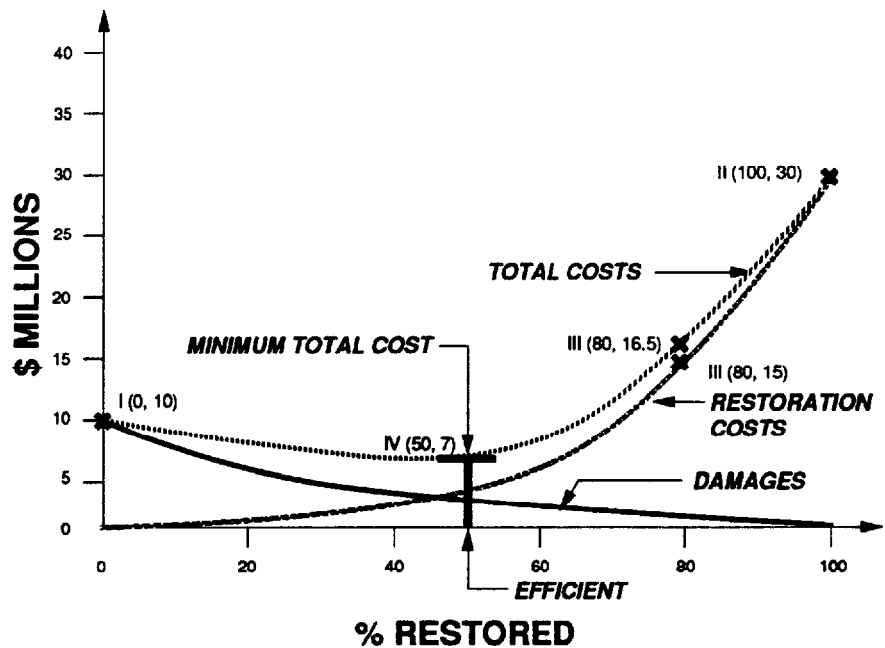
* Source: Cicchetti (1989, pers. comm.).

Determination of Economic Efficiency

To determine economic efficiency, the cost of all restoration/replacement alternatives (where feasible) should be compared to all resource damages that would remain after undertaking the different levels of restoration. It is economically efficient to pursue an additional amount of restoration as long as the further reduction in natural resource damages, or the *marginal benefit* of restoration, exceeds the increase in restoration costs, or the *marginal cost* of restoration. As long as this is the case, the total costs of responding to a spill (i.e., the total restoration costs plus residual natural resource damage) will continue to fall. The economically efficient option is then to undertake restoration activities up to that point where the marginal benefits of conducting further restoration activities equal the marginal cost of conducting those further restoration activities. At this level of restoration effort, the total cost will be at a minimum. This concept is illustrated in Figure 2, which incorporates the data set forth in Table 2.

The timing of recovery is an important complicating factor in the effort to determine the economically efficient level of restoration. In oil spill cases, some or all of the services provided by a natural

2. Conceptual Approach



Note: Cicchetti, C.J. (13 November 1989, personal communication).

LEGEND

- \\ Annual natural resource^a damages
- Annual value of restored resource
- Annual cost of restoration

^a For the purpose of this illustration, no distinction is made between use and nonuse values. Annual damage is thus defined to mean the undamaged resource value (\$40 million) minus the restored resource value for that year.

Figure 2. Determination of economic efficiency.

resource will recover naturally without human intervention. Natural recovery has the obvious advantage of being less costly than active restoration in terms of resources spent; however, human intervention may restore a greater level of services or restore the same level of services in a shorter period of time than would occur if the resource were allowed to recover naturally. The importance of timing in determining the economically efficient level of restoration is illustrated in the following example (see Figure 3 and Table 3).

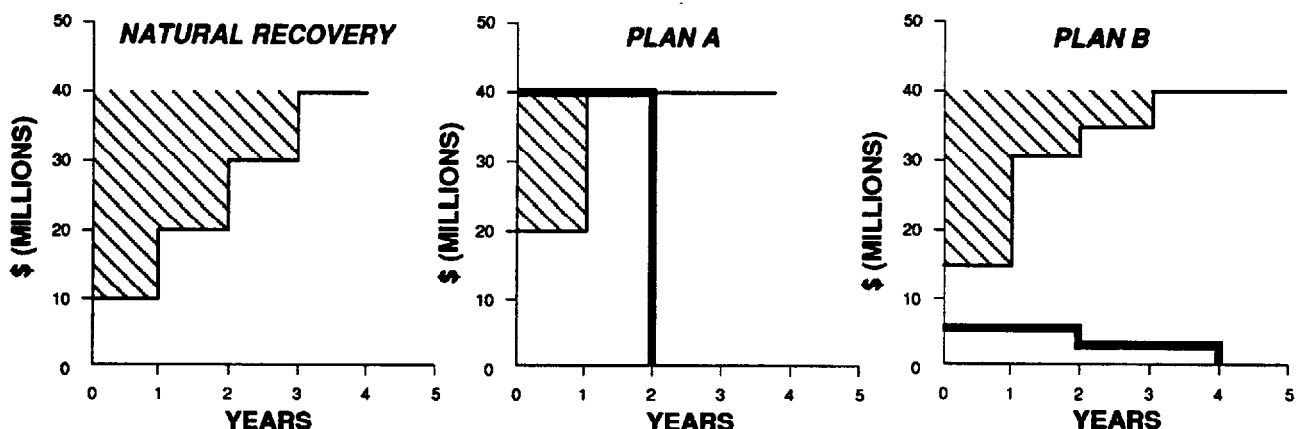


Figure 3. Annual natural resource damages and restoration costs under a scenario of natural recovery and two restoration alternatives (Plan A and Plan B).

**TABLE 3. COMPARISON OF COST OF NATURAL RECOVERY
VS. RESTORATION UNDER THREE SCENARIOS**

Year Following Spill	Annual Value of Restored Resource (millions)	Annual Natural Resource Damages ^a (millions)	Annual Restoration Cost (millions)	Total Annual Cost of Spill ^b (millions)
Natural Recovery				
Year 1	\$10	\$30	\$0	\$30
Year 2	\$20	\$20	\$0	\$20
Year 3	\$30	\$10	\$0	\$10
Year 4	\$40	\$0	\$0	\$0
				\$60
Plan A				
Year 1	\$20	\$20	\$40	\$60
Year 2	\$40	\$0	\$40	\$40
Year 3	\$40	\$0	\$0	\$0
Year 4	\$40	\$0	\$0	\$0
				\$100
Plan B				
Year 1	\$15	\$25	\$5	\$30
Year 2	\$30	\$10	\$5	\$15
Year 3	\$35	\$5	\$2	\$7
Year 4	\$40	\$0	\$2	\$2
				\$54

^a For the purposes of this illustration, no distinction is made between use and nonuse values. Annual lost resource value is thus defined to mean the undamaged resource value (\$40 million) minus the restored resource value for that year.

^b Total annual cost of spill is defined to mean the annual restoration cost plus the annual lost resource value.

The without-spill value of a resource is \$40 million/year. Following a spill, the annual value of the resource falls to \$0. The resource will naturally recover to its full service value level in 4 years at a rate of \$10 million/year. At the end of this 4-year period (ignoring discounting), the cost associated with restoring the total value of the injured resource will be \$60 million. Because this alternative does not include any restoration activities (and hence no restoration costs), the total cost of the spill includes only the loss in economic values (natural resource damages) up to the point that complete recovery is achieved. This \$60 million in total cost thus consists of the \$30 million in natural resource damages (as evidenced by a reduction in services) present at the end of year 1 plus the \$20 million in damages present at the end of year 2, plus the \$10 million in damages at the end of year 3.

2. Conceptual Approach

Plan A

Under this scenario, high-intensity restoration efforts are undertaken, and restoration is complete in 2 years. The cost of restoration for each of these 2 years equals \$40 million for a total cost (ignoring discounting) of \$80 million. Combining the natural resource damages at the completion of year 1 (\$20 million) with the cost of restoration, the total cost of the spill under this scenario is equal to \$100 million².

Plan B

Under this scenario, low-intensity restoration efforts are undertaken, and recovery is complete in 4 years. During years 1 and 2, \$5 million is spent each year on restoration (\$10 million ignoring discounting), and \$2 million is spent each year during years 3 and 4 (\$4 million ignoring discounting). Adding the natural resource damages over the 4 years (\$40 million ignoring discounting) to the amount spent on restoration, the total cost of the spill under this scenario equals \$54 million. Assuming that 4 years is an acceptable period of time for an injured resource to fully recover following an oil spill incident, Plan B would be selected as the economically efficient alternative.

This example provides some important information with regard to the influence of time (as well as differing levels of restoration effort) on achieving recovery. However, this example also oversimplifies the relationships between cost and restoration and between recovery and damages. For example, the unit cost of many restoration activities may be independent of the number of units to be restored. For example, if the restoration of a small fish population is drawn from an endless supply of hatchery fish, the cost of restoration will be constant per hatchery fish supplied. Similarly, natural resource damages (i.e., lost services) may respond to recovery in a linear or other continuous fashion, rather than in a stepwise fashion as shown in this example.

A precise evaluation of economic efficiency can be accomplished using marginal analysis only to the extent that there are reliable data for describing 1) the relationship between restoration and natural

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- 2 This example focuses on the level of recovery present at the end of a given year. Thus, under this scenario, at the end of year 1, and after spending \$40 million, half of the resource value is restored. The loss in resource value for the first year (\$20 million) thus equals half of the total value of the resource (\$40 million). At the end of the second year, and after an expenditure of another \$40 million, restoration is complete. The loss in value at the end of year 2 is thus \$0. This same reasoning applies to the loss in value reflected in the Plan B scenario.

recovery, 2) the relationship between recovery and damages, and 3) temporal variation in natural resource status, restoration effort, resource value, and resource damages. Data from case histories are inadequate to describe these relationships. Therefore, scenarios are developed in Section 7 whereby examples of restoration costs and damages can be used to illustrate economic efficiency. For each scenario in Section 7, economic efficiency is illustrated as the lowest total cost restoration alternative (i.e., restoration cost plus residual natural resource damages), where each alternative evaluated would represent a point on the *Total Cost* line in Figure 2.

2. Conceptual Approach

3. Overview of Selected Oil Spill Case Histories

Selected oil spill case histories were reviewed to identify factors important to spill restoration planning. Case histories provide an important historical perspective, which may improve decisions concerning use of available restoration technologies, risks and benefits of enhanced vs. natural recovery, and values of impacted resources. Case histories are used in this report to illustrate the implications of restoration decisions. These particular case histories were selected because they represent a variety of possible oil spill impact and restoration scenarios for marine and river and stream environments. Additional criteria for the selection of case histories used in the analysis include the following: 1) adequate documentation was available either on natural recovery or restoration and 2) sufficient time had elapsed between the spill and subsequent investigations for meaningful observation, analysis, and documentation of the incident.

Case Histories of Oil Spills in Marine Habitats

Table 4 provides a summary of the marine oil spills most frequently cited in this report. The variables that determine the ultimate ecological and monetary costs of an oil spill event, such as the type of habitat, kind and extent of restoration measures, duration of impact, oil type, and spill conditions, are represented by this spectrum of marine case histories. For example, the *Amoco Cadiz* spilled a large volume of light crude oil and impacted several habitat types (e.g., marshes, sandy beaches, and rocky shores). After the *Amoco Cadiz* spill, the restoration actions included beach cleaning, enhanced biodegradation, vegetation transplanting, substrate removal, and others. Recovery of Brittany coastal marshes was nearly complete after 8 years, despite use of damaging restoration techniques such as substrate removal (Baca et al. 1987). In contrast, the *Florida* incident involved a relatively small amount of fuel oil in a low-energy environment and minimal restoration activities. In that case, some sediment samples exhibited concentrations of petroleum hydrocarbons greater than 1,200 mg/kg after 7 years (Burns and Teal 1979).

3. Overview of Selected Oil Spill Case Histories

TABLE 4. SUMMARY OF SELECTED OIL SPILLS
IN MARINE ENVIRONMENTS

Spill	Date	Oil Type	Impacted Habitat
<i>Arco Anchorage</i>	December 1985	Alaska north slope crude (medium gravity, viscous)	Sheltered intertidal (sandy beaches)
<i>Arrow</i>	February 1970	Bunker C fuel oil	Sheltered intertidal (sandy beaches and rocky shoreline)
<i>Amoco Cadiz</i>	March 1978	Light crude (free-flowing)	Sandy and rocky beaches, marches, mudflats, and rocky headlands
<i>Florida</i>	September 1969	No. 2 diesel (free-flowing)	Sheltered intertidal areas and salt marshes
<i>Metula</i>	August 1974	Light crude, Bunker C (free-flowing)	Beaches, mudflats, salt marshes, rocky shores, and kelp beds
<i>Tsesis</i>	October 1977	No. 5 fuel, Bunker C (heavy, tarlike)	Rocky shores and sheltered sandy bays
<i>Torrey Canyon</i>	March 1967	Kuwait crude (low viscosity, free-flowing oil)	Rocky and sandy intertidal
<i>Zoe Colocotronis</i>	March 1973	Medium crude (medium gravity, viscous)	Sheltered intertidal (mangroves and seagrass)
<i>Puerto Rican</i>	October 1984	Bunker C, refined oil products	Sheltered and exposed intertidal
Baffin Island project	August 1981	Venezuelan crude (medium gravity, viscous)	Sheltered intertidal (Arctic beach)

Extensive documentation of the events of the *Florida*, *Arrow*, *Amoco Cadiz*, and *Tsesis* spills provides details of the ecological impacts of oil and oil spill cleanup and restoration activities, the transport and fate of petroleum in the marine environment, and recovery time of impacted habitats. Other case histories illustrate impacts in different types of coastal habitats (e.g., the *Metula* spill and the *Zoe Colocotronis* spill), alternative cleanup and restoration techniques employed (the *ARCO Anchorage* spill), and long-term ecological impacts (the *Torrey Canyon* spill).

Case Histories of Oil Spills in River and Stream Habitats

Few comprehensive case studies of oil spills on flowing freshwater were available for use in this report. However, the case histories

3. Overview of Selected Oil Spill Case Histories

summarized in Table 5 represent several possible scenarios of oil spills in river and stream environments. Several important restoration techniques are represented, including vegetation cropping (St. Lawrence River), stream bed agitation (Wolf Lodge Creek) and habitat enhancement (Little Panoche Creek). The habitats represented by the case histories provide important services such as tourism and commercial and recreational fisheries.

**TABLE 5. SUMMARY OF SELECTED OIL SPILLS
IN RIVER AND STREAM ENVIRONMENTS**

Location	Date	Oil Type	Impacted Habitat
Savannah River	December 1986	No. 6 fuel (viscous, tarlike)	<i>Spartina</i> marsh, estuary, and wildlife refuge
Wolf Lodge Creek	June 1983	Unleaded gas (free-flowing)	Human and livestock drinking water and salmonid habitat
Monongahela River (Ashland oil spill)	January 1988	Diesel (free-flowing)	Human drinking water and fish and waterfowl habitat
St. Lawrence River	June 1976	No. 6 fuel (viscous, tarlike)	Marsh
Little Panoche Creek	September 1983	Heavy crude (viscous, tarlike)	Marsh, waterfowl, and endangered species habitat (kit fox)

3. Overview of Selected Oil Spill Case Histories

4. Natural Recovery

Most ecological systems have the ability to recover naturally from perturbations such as oil spills. However, natural recovery rates can vary substantially depending upon many variables. The primary kinds of variables that influence natural recovery following an oil spill are related to both the severity of the impacts of the spill and the inherent ability of the oiled ecosystem to respond to perturbation. If natural recovery following an oil spill is expected to be unusually slow, restoration techniques may be used to accelerate recovery.

This section evaluates the ability of various marine and freshwater systems to recover from an oil spill in the absence of restoration efforts. Natural recovery is defined, and the various techniques used to evaluate recovery are described. The factors that affect the potential for resources to recover are then discussed, and a summary of expected recovery rates is presented for various marine and freshwater habitats.

Definition of Natural Recovery

The definition of natural recovery of injured ecosystems has been debated in the scientific literature. Perhaps the most useful definition of this process is the return of an impacted ecosystem to its former state within the limits of natural variability (Ganning et al. 1984). That is, once the process of natural recovery is complete following an oil spill, the fully recovered ecosystem would be indistinguishable from its without-spill state, allowing for any ecosystem changes that would have occurred in the absence of the oil spill (this state is referred to as “baseline” in this report to be consistent with 43 CFR Part 11). This definition recognizes the inherent tendency for ecosystem characteristics to vary over space and time (Sousa 1984).

For the purpose of this report, there are three major components to natural recovery:

- **Habitat recovery**—the return of physical and chemical habitat characteristics to without-spill conditions within the limits of natural variability

4. *Natural Recovery*

- Biological recovery—the return of biological assemblages to without-spill conditions within the limits of natural variability
- Recovery of resource services—the return of services provided by public resources to without-spill levels (i.e., baseline services) within the limits of expected variability.

The first two categories are discussed because most scientific evaluations of natural recovery have addressed entire ecosystems or their individual physical, chemical, or biological components. However, from an NRDA standpoint, recovery is based on resource services and is not necessarily dependent on the full recovery of injured resources (43 CFR Part 11). The determination of when recovery is complete can be very different for habitats, biological assemblages, and resource services.

Habitat recovery usually involves the removal of oil from the spill area. Oil removal can occur through 1) physical processes such as washing by waves and currents, 2) chemical processes such as photo-oxidation, and 3) biological processes such as microbial degradation. In many cases, habitat recovery must proceed to a certain level before biological recovery can occur. The degree to which habitat recovery must precede biological recovery depends on the severity of oiling and the characteristics of the biological assemblages and resource services. For example, the physical and chemical characteristics of an oiled beach may have to recover to a substantial degree to allow subsequent colonization by benthic macroinvertebrates (biological recovery). However, recovery of resource services may or may not depend on habitat recovery. For example, benthic macroinvertebrates such as clams might provide services in the form of recreational shellfish harvesting. These services are highly dependent on biological recovery, and, in this instance, resource services recovery would be expected to take longer than habitat recovery. In contrast, the same beach may provide services in the form of swimming and sunbathing. These services could recover as soon as oil is no longer visible on the sand. This recovery period could be considerably shorter than the period of time required for habitat recovery.

Biological recovery involves the re-establishment of community structure that would be expected in the absence of a spill. Biological recovery usually must be preceded by a high degree of habitat recovery, but may begin during the initial stages of habitat recovery. For example, surface-dwelling organisms may colonize a habitat as

soon as oil has been removed from substrate surfaces (e.g., rocks), but the return of burrowing organisms may be delayed considerably until subsurface microhabitats recover to the appropriate degree. However, as with habitat recovery, biological recovery may or may not affect the recovery period for resource services.

The recovery of resource services is specific to NRDA considerations and may or may not be closely related to habitat or biological recovery. From an NRDA standpoint, recovery may be considered complete when services provided by the injured resources return to levels that would be expected in the absence of the spill (without-spill service levels; 43 CFR Part 11). Because the criteria for the recovery of resource services are related to economics, it is possible for the recovery of resource services to occur long before or long after habitat and biological recovery are complete. However, in many cases, resource services are directly derived from the oiled habitat and its resident biological assemblages, and the recovery of resource services will correspond closely with habitat and biological recovery.

Evaluation of Natural Recovery

In general, there have been few systematic and quantitative evaluations of the natural recovery of oiled marine habitats (Teal and Howarth 1984). There is an even smaller amount of information for oiled freshwater habitats (Baca et al. 1985; Wallace 1987). Most historical evaluations of natural recovery have largely been conducted in an *ad hoc* manner to meet a variety of objectives. In addition, most of these past studies have evaluated habitat and biological recovery. There are few historical evaluations that specifically address the recovery of resource services. It is generally recommended that future evaluations of natural recovery be conducted in a more standardized and rigorous manner, while building on the information accumulated during past studies (Cairns and Buikema 1984; Teal and Howarth 1984). The three major kinds of evaluations conducted in historical studies are as follows:

- Qualitative assessments
- Comparisons to pre-spill conditions
- Comparisons to reference (or control) conditions.

Most historical evaluations of natural recovery have relied on qualitative assessments of habitat and biological recovery. In

general, qualitative assessments have limited usefulness because they can be highly subjective and do not produce the quantitative data that are essential for objectively determining when natural recovery is complete. Many historical studies relied on qualitative assessments because they were conducted opportunistically, with little prior planning and limited funding. Despite their limitations, qualitative assessments have been useful for identifying the kinds of adverse effects that are most likely to occur in various habitats as the result of oil spills.

A common method of quantitatively evaluating environmental impacts of oil spills is to compare the environmental conditions that occur in a habitat following an impact with the conditions that were present in the same habitat prior to the impact (Green 1979). This approach is commonly referred to as the "baseline" approach in the scientific literature, but will be referred to as the "pre-spill approach" to avoid confusion with the definition of "baseline" used in 43 CFR Part 11 and established above. However, the pre-spill approach has not been commonly used in historical studies because of insufficient information on pre-spill conditions (Ganning et al. 1984; Hutchinson 1989; Jackson et al. 1989).

The major advantage of the pre-spill approach is that the evaluation of natural recovery is conducted in the same habitat that has been oiled. However, all deviations between pre-spill and post-spill environmental conditions are usually attributed by researchers to the effects of the oil spill. Therefore, the major disadvantage of the pre-spill approach is that it does not account for the inherent tendency of ecosystems to change over time in response to a variety of environmental variables, such as natural perturbations (e.g., storms, droughts), climatic shifts, and biological processes (e.g., larval recruitment, immigration, competition, predation, disease). Therefore, as the time interval between the oil spill and the environmental assessment increases, uncertainty generally increases as to whether the pre-spill conditions are accurate estimates of what the current conditions would be in the absence of the oil spill. A second disadvantage of the pre-spill approach is the requirement that habitats be fully characterized prior to an oil spill. This requirement may be feasible for habitats having a high probability of being oiled (e.g., areas near refineries, tank farms, and major shipping lanes) or habitats located near marine laboratories, but generally is not feasible for areas in which oil spills are unpredictable (Hutchinson 1989).

A second common method of quantitatively evaluating environmental impacts such as oil spills is based on comparisons between the

environmental conditions that occur in a habitat following an impact with the conditions that are present in a representative reference area (defined as "control area" in 43 CFR Part 11). In most cases, the reference area is sampled concurrently with the impacted habitat. To successfully use this approach, it is essential that the reference or control area be as similar as possible to the impacted habitat with respect to all or most major physical, chemical, and biological characteristics. This method is consistent with the concept of a return to without-spill conditions in the definition of natural recovery described above, if the reference or control area is considered to be a surrogate for the impacted habitat under without-spill conditions.

The major advantage of the reference or control area approach is that assessments can be made simultaneously with the studies conducted in the impacted habitat. Therefore, if it is assumed that natural variability in the two habitats is parallel, the use of concurrent information from the two areas should account for most of the natural variations that would have occurred in the impacted habitat between the time of the oil spill and the time of the environmental assessment. A second advantage of the reference or control area approach is that it does not require that the impacted habitat be fully characterized prior to an oil spill. The major disadvantage of the approach is that it is frequently difficult to find an appropriate reference or control area for an impacted habitat (largely because of the complexity of most ecosystems). Instead, areas are generally selected that are as similar as possible to the impacted habitats. In many cases, lack of complete similarity adds uncertainty to the estimate of the without-spill conditions in the impacted area. A second disadvantage of the reference or control area approach is that it generally cannot be used to evaluate impacts to unique habitats, since by definition similar habitats usually are not available.

In summary, it is preferable that future studies of natural recovery following oil spills be conducted using quantitative techniques. Qualitative assessments should probably be conducted only when quantitative evaluations are not possible. The ideal strategy for the quantitative assessment of natural recovery in an oiled habitat would be to use both the pre-spill and reference or control area approaches (Green 1979; this strategy is also recommended by 43 CFR Part 11 to determine baseline conditions). In this manner, the advantages of each approach can be combined. However, this strategy is likely to be impractical under most circumstances because it requires that each habitat be fully characterized prior to the oil spill and that a suitable reference or control area also be selected. In addition, the

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reference or control area should be characterized at the same time as pre-spill conditions are evaluated, to ensure that the reference or control area is an appropriate surrogate for the impacted habitat under nonspill conditions. Although this strategy of combined approaches is highly desirable, it is unlikely that sufficient funding is available to characterize baseline conditions and associated non-spill reference conditions in the multitude of habitats that have a probability of being oiled. Therefore, most quantitative assessments of natural recovery are likely to rely solely on comparisons with reference or control conditions that are characterized after an oil spill. The combined approach also may not be feasible for unique habitats, because appropriate reference or control areas may not be available. In such cases, it is ideal if pre-spill conditions be characterized.

Measures of Environmental Recovery

Many environmental indicators are used in historical studies to evaluate the natural recovery of oiled habitats. These measures of environmental state are used to characterize pre-spill conditions, reference or control area conditions, and conditions encountered in the habitats impacted by oil. In this section, commonly used approaches for measuring environmental state and environmental recovery are described for assessments of habitat recovery, biological recovery, and recovery of resource services. A more thorough review of available information on habitat and biological recovery is presented in NRC (1985) and Shales et al. (1989).

Habitat Recovery

Most measurements used to assess habitat recovery following oil spills include physical and chemical evaluations of the amount of oil remaining in the oiled habitats. These measurements range from gross qualitative assessments of whether oil is visible, to highly sensitive, quantitative analyses of the concentrations of individual oil-related compounds. In vegetated habitats where plants provide much of the physical habitat structure (i.e., seagrass beds, marshes, mangrove forests), measurements of habitat recovery include the sizes, densities, and distributions of the key plant species.

Biological Recovery

Most measurements of biological recovery in oiled habitats include evaluations of community structure, population characteristics, and adverse effects on individual organisms. These measurements range from qualitative assessments of the presence or absence of

organisms to quantitative evaluations of community structure and biochemical responses of individual organisms.

The most common measures of community structure include total abundance, total biomass, species richness, species diversity, and evenness (i.e., distribution of individuals among species). All of these community variables represent different characteristics of overall communities. Classification analyses are often conducted to compare recovering communities with pre-spill or reference or control communities. These analyses use similarity indices based on species abundances to group stations with similar communities into clusters. When the recovering communities can be grouped with the pre-spill or reference or control communities at a prescribed level of similarity, recovery is considered complete.

The most frequently used measures of population recovery are species abundance and biomass. Both of these variables primarily address the status of a population at the time the measurement was made. To project the future status of populations, variables that address population dynamics are commonly used. These variables include age and size distributions, sex ratios, measures of reproductive potential, juvenile recruitment, and migration. Many of the studies conducted on populations have implications with respect to the status of overall communities.

Most of the measurements used to assess biological recovery following oil spills are related to the characteristics of individual organisms. These measurements address mortality of individuals, as well as a wide variety of sublethal effects. The sublethal endpoints include the following general categories of measurements:

- Reproduction (e.g., fecundity)
- Development (e.g., embryonic or larval development)
- Growth (e.g., biomass, scope-for-growth)
- Physiology (e.g., respiration, metabolic rate, ion transport, enzyme function)
- Genetic alterations (e.g., chromosomal alterations)
- Histopathology (e.g., neoplasms, other lesions)
- Behavior (e.g., avoidance, feeding efficiency).

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Many of the studies conducted on individuals have implications for the status of populations and overall communities. However, there are many uncertainties in extrapolating effects on individuals (particularly sublethal effects) to effects at the population or community levels.

Resource Services Recovery

Most measurements used to assess the recovery of resource services in oiled habitats have included evaluations of resources that directly support consumptive and nonconsumptive uses. In these cases, resource services recovery is closely linked to biological and habitat recovery. Examples of species that directly support consumptive uses include fish and shellfish that are pursued by recreational anglers. Other species such as migratory waterfowl can directly support both consumptive uses (e.g., hunting) and nonconsumptive uses (e.g., bird-watching). Many species or habitats likely to become impacted by spilled oil do not directly support services to humans, rather they provide services such as spawning substrate and forage to other species with direct links to resource services. An example of this indirect linkage is an eelgrass bed that provides spawning habitat for herring and other sportfishes.

Evaluation of resource services recovery may first require an understanding of how key species or habitats may become impacted by an oil spill. The primary species that support recreational fisheries include large bivalve molluscs (e.g., clams, oysters, mussels), large decapod crustaceans (e.g., shrimp, crabs, lobsters), and sportfishes. Of these species, bivalve molluscs are probably the most vulnerable to oil spills because the juvenile and adult life stages of these organisms are largely sedentary. Therefore, most bivalves rely upon localized areas as their primary habitat for most of their life cycle, and they cannot migrate away from those areas to avoid being adversely affected by an oil spill. Services provided by molluscs may be totally lost in heavily oiled areas, and services recovery may lag behind both habitat recovery and biological recovery. Services recovery can be measured by conducting site visitation surveys.

By contrast, the juvenile and adult life stages of decapods and sportfishes are highly mobile, allowing these organisms to range over relatively large areas and to migrate away from oil spills to avoid being adversely affected. Because the embryonic and larval life stages of many bivalves, decapods, and sportfishes are planktonic, oil spills can adversely affect single year classes in the water column in localized areas. However, it is unlikely that multiple year classes would be affected, because the water-column impacts

of most oil spills are not persistent (Vandermeulen 1982; Teal and Howarth 1984). In such cases, disruption of resource services may coincide with life cycle patterns of the species affected. For example, resource services for a migrating fish species may be disrupted on a 3-year cycle corresponding to the impacted year class.

Although marine mammals and birds provide direct and often highly valued services, there is little evidence that oil spills have measurable effects on populations of these organisms. This lack of evidence is due in part to the high costs and numerous technical difficulties encountered in assessing the population status of marine mammals and birds. Despite the difficulty in assessing impacts, most of these organisms are highly mobile and can range over relatively large areas, and most oil spills would be expected to have minimal impacts at the population level (Clark 1984; Engelhardt 1987; Hunt 1987). However, individual organisms can be severely affected in localized areas if they are oiled. In addition, it is possible that adverse effects on populations could occur if an important breeding or nursery area was oiled. In many cases, resource services provided by marine mammals and birds may be affected more because of the knowledge that individual animals have been oiled than because of population-level effects. In such cases, resource services recovery may be difficult to determine because it is not linked to biological or habitat recovery.

Vegetated habitats represent some of the most ecologically important areas in aquatic systems and indirectly provide services to species. Their relatively complex physical structure provides a variety of microhabitats that allow the development of diverse resident biological assemblages. Vegetated habitats also act as nursery areas for nonresident species during the critical juvenile life stage. In this role, vegetated habitats usually act as both a food source and a refuge from predation for juvenile organisms. From an economic standpoint, vegetated habitats are probably most valuable as nursery areas for species such as fishes and crabs. In many cases, this function can be provided before biological recovery from an oil spill has been completed. Determination of resource services recovery in vegetated habitats requires an understanding of ecological relationships as well as the nature of resource services flows.

4. Natural Recovery

Factors Affecting Recovery Potential

There are numerous factors that affect the potential of an oiled habitat to recover naturally (Ganning et al. 1984; NRC 1985; Hutchinson 1989). In the most general sense, these factors can be categorized as those related to the oil spill and those related to the oiled habitat (Table 6). Because the interaction of all of these factors can vary substantially among different oil spill events, predictions of recovery potential for particular habitats must be based largely on the characteristics specific to each spill and each oiled habitat (Hutchinson 1989). Although it is not possible to predict how all of the factors will interact for a given oil spill event, it is instructive to consider how each factor can independently influence natural recovery.

TABLE 6. FACTORS THAT AFFECT THE POTENTIAL FOR NATURAL RECOVERY FROM AN OIL SPILL

Factor	Factor Applicability ^a	Predominant Effect on Recovery Potential	
		Positive	Negative
Oil Spill Characteristics			
Oil type	M, F	light	heavy
Oil state	M, F	dispersed, weathered	undispersed, fresh
Season	M, F	critical period absent	critical period present
Water state	M, F	rough	calm
Currents	M	offshore	onshore
Flow	F	high	low
Tidal range	M	small	large
Tidal period	M	neap	spring
Habitat Characteristics			
Temperature	M, F	high	low
Climatic variability	M, F	large	small
Habitat exposure	M, F	high	low
Habitat complexity	M, F	low	high
Substrate penetrability	M, F	low	high
Successional state	M, F	early	late
Proximity of colonizers	M, F	close	distant
Generation times	M, F	short	long

^a M - marine habitats

F - freshwater habitats.

**Factors Related to
Oil Spill
Characteristics**

The major factors affecting recovery potential that are related to the characteristics of each oil spill include the type of oil, its physical state, the season and environmental conditions present at the time of the spill, and the amount and distribution of oil that reaches the shoreline. Many of these factors are related to the conditions that exist before a habitat is oiled, which can strongly influence the severity of habitat oiling and thereby influence recovery potential.

Different types of oil can have different environmental effects. For example, lighter oils (e.g., fuel oil) tend to be more toxic than heavier oils (e.g., crude and Bunker oils). However, the severity of adverse effects from lighter oils may be reduced by the tendency of these types of oil to dissipate rapidly and leave comparatively little residue. By contrast, heavier oils can persist in some habitats for years. The physical state of oil can also influence its environmental effects. In general, dispersed oil has a reduced probability of reaching shore (Mackay 1987; Mackay and McAuliffe 1988) and weathered oil generally causes fewer impacts than fresh oil (Neff 1987).

Several spill-specific factors depend on the environmental conditions present at the time of the spill and shortly thereafter (Table 6). Because some of these environmental conditions are relatively ephemeral and unpredictable, they account for much of the uncertainty associated with predicting the potential severity of oil spills. Season can influence the effects of an oil spill, because many critical biological periods are seasonal in nature (e.g., bird nesting, fish spawning and migration, larval settlement of benthic macroinvertebrates). For example, Michaelis (1983) concludes that the biological effects of an oil spill in two rivers in New Zealand were reduced, in part, because the spill occurred after most insects had emerged and when trout were not spawning. Season can also influence patterns of resource use such as fishing, clamming, swimming, and hiking. The impacts of a spill could therefore be increased if the spill occurs during a critical period for biological activity or resource use. Season can also exert a more general effect on oil spills because this variable is often strongly related to the prevailing weather conditions. However, in many cases it is the more unpredictable short-term oceanographic, hydrologic, and meteorological conditions that determine the degree of environmental effects caused by an oil spill.

The primary oceanographic conditions that influence oil spills are sea state, currents, and tides. A rough sea state with a large amount of wave action can result in the physical dispersal of oil within the water column and a resulting reduction in the amount of oil that

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could potentially reach shore (Mackay and McAuliffe 1988). By contrast, an oil slick can remain relatively intact under calm sea conditions, allowing much of the oil to contact the shoreline if other environmental conditions (e.g., wind and current direction) are favorable. Currents can exert a substantial effect on oil spills by influencing the direction and speed of oil movement. The effects of an oil spill would likely be maximized if the prevailing currents carried an oil slick rapidly towards shore with little time for dispersion. For example, during the *Arrow* and *Amoco Cadiz* spills, onshore winds rapidly moved the spilled oil to shore and thereby increased the severity of oiling. By contrast, the prevailing currents during the *Argo Merchant* spill were offshore and moved most of the spilled oil out to sea, thereby minimizing shoreline impacts. Tides can influence an oil spill by controlling the amount of the intertidal zone that is oiled. This amount would likely be maximized during a spring tide in an area with a large tidal range. During the *Metula* spill, spilled oil was carried to unusually high levels of the intertidal zone by a spring flood tide and strong onshore winds. Because those areas are rarely flushed by the tides, the stranded oil remained in the high intertidal zone for over a decade.

In river and stream habitats, the primary hydrologic condition that influences oil spills is water flow. Baca et al. (1985) note that the movement of oil in rivers can be so fast that its ultimate fate cannot be determined. Michaelis (1983) concludes that the effects of an oil spill in two rivers in New Zealand were minimized, in part, because the high flow conditions that occurred immediately after the spill resulted in a rapid removal of the oil.

The primary meteorological condition that influences oil spills is the wind. The speed and direction of the wind can influence surface currents and thereby indirectly affect the movement of an oil slick. Wind speed can also indirectly affect the dispersion of oil within the water column by influencing sea state.

The degree and areal extent of shoreline oiling are spill-specific characteristics that can substantially affect the potential for natural recovery. In general, small areas that have been lightly oiled can recover quickly, whereas larger areas that have been more severely oiled may require a much longer recovery period.

Factors Related to Habitat Characteristics

The major factors affecting recovery potential that are related to each oiled habitat include climate and physical and biological characteristics (Table 6). The primary climatic factors are temperature and climatic variability. Temperature can influence the persis-

tence of oil in the environment by affecting its solubility in the water column and its rate of degradation through microbial activity. Temperature can also affect natural recovery by influencing the growth rate of colonizing organisms. Climatic variability can influence the frequency and degree of natural habitat disturbance (e.g., from storms, floods, droughts) and thereby potentially affect the inherent ability of biological assemblages to respond to an anthropogenic disturbance such as an oil spill.

The primary physical habitat characteristics that influence the impacts of oil spills include habitat exposure, habitat complexity, and substrate penetrability. The degree to which a habitat is exposed to waves and currents influences the potential for oil to be physically removed from that habitat. In most cases, oil is removed relatively rapidly from exposed habitats, but much more slowly from sheltered habitats (Vandermeulen 1982; Baca et al. 1985). Habitat complexity refers to the number and diversity of microhabitats included in a particular habitat. In many cases, biological complexity parallels habitat complexity. In general, it might be expected that natural recovery would be longer for more complex habitats because of the increased variety of microhabitats that must recover. Finally, substrate penetrability can influence the persistence of oil in a habitat, with persistence generally increasing with increasing penetrability.

The primary biological characteristics of habitats that influence the impacts of oil spills include successional state, proximity of colonizers, and generation times of individual species (i.e., time required for organisms to reach reproductive age). The successional state of the biological assemblages that reside in a habitat can influence the amount of time required for natural recovery to occur because, in general, longer periods of time are required to achieve later successional states. Therefore, assemblages characterized by late successional species would probably require a substantially longer recovery period than would assemblages dominated by early successional (i.e., colonizing or opportunistic) species. The proximity of colonizing organisms to an oiled habitat influences the potential for natural recolonization of that habitat. If an oiled habitat is relatively isolated and removed from potential colonizers, natural recovery may be prolonged. Finally, the generation times of the organisms that create or reside in a habitat can influence the length of the recovery period, with short-lived species generally recovering faster than long-lived species. For example, the short generation times of many benthic macroinvertebrates (< 1 year) and seagrasses (≥ 1 year) generally facilitate a faster recovery than do the longer generation times of many birds and mammals (> 2–3 years) and

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mangroves (≥ 3 years). Generation time is a particularly important factor when recolonization of an oiled habitat occurs largely from reproduction and growth of resident organisms, rather than from immigration of organisms from adjacent, unoiled areas.

Natural Recovery Rates

As discussed in the previous section, the potential for an oiled habitat to recover naturally is dependent on the interaction of numerous factors related to both the oil spill and the affected habitat. Because many of these factors are specific to the spill or habitat, it is difficult to precisely estimate expected recovery periods for different kinds of habitats. By using the information gained from studies of historical oil spills, it is possible to make gross estimates of the likely recovery periods for different habitats under most scenarios. However, these gross estimates are based on broad generalizations, and numerous spill-specific exceptions are possible. In addition, because each kind of habitat is composed of various microhabitats, generalizations made at the habitat level may not apply to every microhabitat.

A summary of maximum natural biological recovery times for the habitats considered in this report is presented in Figure 4. The estimates of biological recovery presented in Figure 4 were based on literature accounts of ecosystem recovery because most of the available historical information on oil spills addresses ecosystem recovery. The various recovery times shown on Figure 4 illustrate the differences that are possible both within and among the different

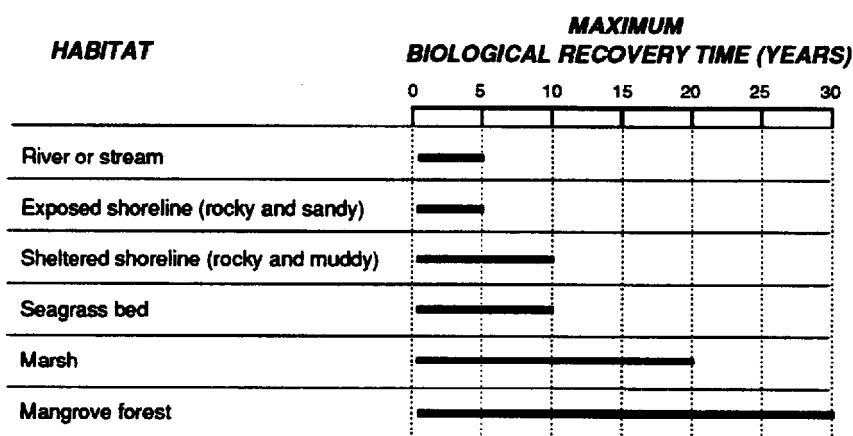


Figure 4. Estimated biological natural recovery times for various kinds of habitats.

kinds of habitats. The differences within habitats are largely related to the severity of oiling, whereas the differences among habitats are due to both the severity of oiling and the characteristics of the different habitats.

River and stream habitats and exposed rocky and sandy marine shorelines have the shortest maximum recovery periods, primarily because most of these habitats are highly exposed to waves or currents. The time required for natural recovery in these ecosystems generally ranges from < 1 to 5 years (Ganning et al. 1984; Baca et al. 1985; Hutchinson 1989; Baker et al. 1990), depending on the severity of oiling. In addition, the unidirectional water flow in river and stream habitats facilitates the movement and dispersion of oil away from the spill site. Oil is generally removed from these habitats rapidly, and long-term adverse effects are rarely found (Vandermeulen 1982; Baca et al. 1985). However, biological recovery can be longer than habitat recovery if long-lived organisms are killed by the oil spill. On exposed shorelines, recovery of resource services can also take longer than habitat recovery if the services are provided by organisms, such as mussels and oysters, that require several years of growth to reach harvestable size. Although river and stream habitats may include vegetated areas along the shoreline that could trap oil and thereby extend the recovery period, oiling is generally confined to the outer fringes of vegetation, which are flushed relatively rapidly (Baca et al. 1985).

Because sheltered rocky and muddy marine shorelines are not very exposed to waves and currents, they are generally more vulnerable to long-term adverse effects from oil spills than are exposed shorelines. Natural recovery can be delayed considerably if oil sinks into the subsurface sediments of sheltered beaches (Neff 1987). Depending on the severity of oiling, the time required for natural recovery of these ecosystems can range from < 1 to 10 years (Ganning et al. 1984; Neff 1987). Habitat recovery, biological recovery, and the recovery of resource services can all vary over a similar period. As in exposed habitats, sheltered shorelines composed primarily of rocky substrates are likely to recover faster than shorelines that are primarily composed of soft sediments.

Of the three kinds of vegetated habitats considered in this report, seagrass beds generally recover most quickly. Because seagrass beds primarily occupy subtidal habitats, they are largely devoid of the channels and intertidal areas that characterize marshes and mangrove forests and tend to trap oil. In many cases, the oil that enters seagrass beds remains in the water column or is deposited on the leaves of the plants, and very little oil contacts the sediment.