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Calculating Resource Restoration for an Oil Discharge in Lake Barre, Louisiana, USA

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ABSTRACT / Under the United States Oil Pollution Act of 1990, natural resource trustees are charged with assessing natural resource impacts due to an oil spill and determining the type and amount of natural resource restoration that will compensate the public for the impacts. Habitat equivalency analysis is a technique through which the impacts due to the spill and the benefits of restoration are quantified; both are quantified as habitat resources and associated ecological services. The goal of the analysis is to determine the amount of restoration such that the services lost are offset by services provided by restoration.

In this paper, we first describe the habitat equivalency analysis framework. We then present an oil spill case from coastal Louisiana, USA, where the framework was applied to quantify resource impacts and determine the scale of restoration. In the Louisiana case, the trustees assessed impacts for oiled salt marsh and direct mortality to finfish, shellfish, and birds. The restoration project required planting salt-marsh vegetation in dredge material that was deposited on a barrier island. Using the habitat equivalency analysis framework, it was determined that 7.5 ha of the dredge platform should be planted as salt marsh. The planted hectares will benefit another 15.9 ha through vegetative spreading resulting in a total of 23.4 ha that will be enhanced or restored as compensation for the natural resource impacts.

In May 1997, a Texaco Pipeline, Inc., transmission pipeline discharged 6561 barrels (1,252,725 liters) of crude oil into Lake Barre, Louisiana, USA. Lake Barre is roughly 43 km southeast of Houma, in Terrebonne Parish (Figure 1). Personnel from Texaco and state and federal agencies began oil skimming and booming operations the next day to control surface oil, remove oil from the environment, and protect sensitive estuarine and marsh ecosystems.

The response actions did not completely protect the natural environment from the discharged oil. Extensive areas of marsh were exposed to black oil or sheen, and birds were oiled. Dead shrimp were collected in a Louisiana Department of Wildlife and Fisheries' trawl from Lake Barre and small dead fish and invertebrates were found in shallow water marsh areas where oil was trapped.

Under the Oil Pollution Act (OPA) of 1990, natural resource trustees, appointed by the president and state governors, assess and recover damages to trust resources to compensate the public for the effects of the discharge of oil. Trust resources include the atmosphere, oceans, estuaries, rivers, and plant and animal species. Natural resource damages are based on the restoration of these public resources. Damages include the cost of restoration that returns injured natural resources and services to the baseline condition (primary restoration) and the cost of restoration that compensates for the interim loss of resources and services that occur from the time of the incident until recovery of such resources and services to the baseline condition (compensatory restoration). Restoration is any action or combination of actions to restore, rehabilitate, replace, or acquire the equivalent of injured natural resources and services. The other component of damages is the present value of damage assessment costs incurred by the trustees.

Natural resource trustees conducted a damage assessment for the discharge of oil into Lake Barre in cooperation with Texaco, the party responsible for the incident (subsequent to the oil spill, Equilon succeeded to the liabilities of Texaco; we reference Texaco throughout the paper as the responsible party to avoid confusion). The trustees invited Texaco to participate in the damage assessment process as required by the OPA regulations (the responsible party may contribute

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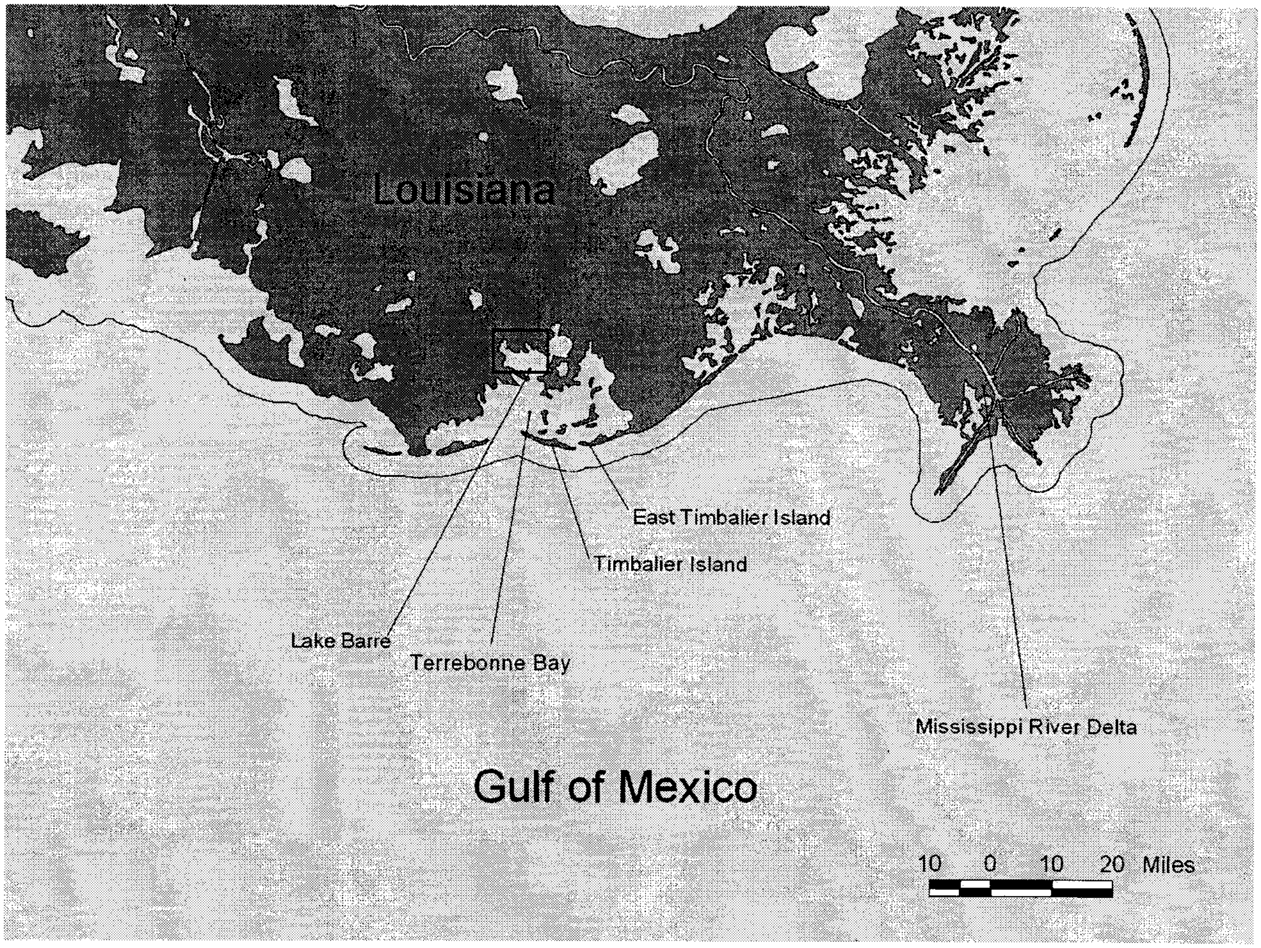

Figure 1. Lake Barre and surrounding area.

to the process in many ways, but final authority to make determinations rests solely with the trustees). Texaco participated actively in the damage assessment; it was involved in the design and implementation of many studies completed as part of this assessment. Coordination between the trustees and Texaco reduced duplication of studies, increased the sharing of information, and increased the cost-effectiveness of the assessment process.

The authors of this paper were representatives of the trustees and Texaco, respectively. Our task was to collaborate in developing a process for estimating the amount of compensatory restoration that would be acceptable to the trustees on behalf of the public and cost-effective.

This paper focuses on the interim loss of resources and services and the determination of how much compensatory restoration is necessary to compensate the public for natural resource injuries. First, we describe a model or framework for quantifying interim losses and determining the scale of compensatory restoration. We then describe how the framework was applied for the Lake Barre damage assessment. To emphasize, this paper presents the quantification tools used to determine the scale of compensatory restoration for an oil spill, not a fully rigorous scientific exploration of the effects of either the oil spill or the restoration project.

General Model Approach

Compensatory restoration projects should provide value equal to the value of the interim losses. The process of determining the necessary size of restoration projects is called restoration scaling. Restoration scaling requires a framework for quantifying the value of losses and for quantifying the benefits of restoration so the losses and benefits can be compared. Habitat equivalency analysis (HEA) is one framework for quantifying losses and benefits.

With HEA, interim losses are quantified as lost habitat resources and services, and the scale of the restoration projects is that which provides equivalency between the lost and restored habitat resources and services [see Unsworth and Bishop (1994) for a discussion of essentially the same framework]. The restored resources and services must be of the same type and quality and of comparable value as what was lost so the per unit values of the lost and replacement habitat resources and services are equal. Then, the value of restoration equals the value of interim losses and the public is compensated. HEA can be applied when lost and replacement resources and services are not of comparable value, so long as there is a common resource or service metric at the injury and restoration areas that accounts for value differences.

HEA requires injury parameters to quantify lost habitat resources and services. The parameters needed to estimate interim losses include the amount of adversely affected habitat area, the degree of injury within that habitat, and how that degree of injury changes over time. The degree of injury is determined by the condition of key or representative resources or services in the habitat (for example, primary production or macrofaunal density). The interim losses are quantified by year as lost service hectare-years, where a service hectare-year is the flow of services from one hectare of habitat for one year.

Because the interim losses occur in different time periods, they are not directly comparable. People have a rate of time preference and prefer to use or consume goods and services in the present rather than postpone their use or consumption to some future time. To make the losses that occur in different time periods comparable, a discount factor is applied to the losses to determine discounted service hectare-years.

Interest-bearing savings accounts are based on the same principle of discounting. In order to encourage people to save money (i.e., forgo present use or consumption), banks pay customers an additional amount of money in the form of interest. The interest rate, equivalent to the discount factor when considering goods and services, determines equivalency of dollars received (or services provided) over different time periods.

Other parameters are necessary to quantify the benefits of the compensatory restoration projects. They include when the habitat restoration project begins, the time until this habitat provides full services, the level of services provided between the time when the project begins and when it provides full services, and the relative services of the created or enhanced habitat compared to the injured habitat before the incident. Given the size of a project and the discount rate, these parameters define the discounted service hectare-year benefits that result from the project. The task is to determine the size of the projects such that the discounted service hectare-years just offset the interim losses.

The simplest form of the mathematical model states that the discounted value of habitat service losses is equal to the discounted value of the service gains. Thus,

$$L = G$$

where L is the discounted value of interim losses from the injured habitat, and G is the discounted value of gains from created habitat of the same type.

The term L is defined as:

$$L = V_L * \sum_{t=i}^{B} A_t * (1 + d)^{(T-t)}$$

where V_L is the economic value per hectare of the services from the injured habitat, A_t is the number of hectares of habitat forgone in year t, i is the year in which habitat service losses begin, B is the year in which habitat services return to baseline levels, T is the base year, and d is the discount rate.

The term G can be expressed with a similar formula:

$$G = V_G * \sum_{t=j}^{M} S_t * (1 + d)^{(T-t)}$$

where V_G is the economic value per hectare of the services from the newly created or improved habitat, S_t is the number of hectares of additional habitat provided by the replacement projects in year t, j is the year in which habitat service gains begin, M is the year in which habitat service gains terminate, T is the base year, and d is the discount rate.

Note that the economic value of habitat services appears in both of these equations. In order to apply HEA, the economic value per hectare of the forgone habitat services, V_L, must equal the economic value per hectare of the newly created or improved habitat, V_G. If not, an HEA-like model can still be applied as long as the scale of restoration is adjusted to account for the value difference.

Application in Lake Barre Assessment

Natural resource trustees in cooperation with Texaco (collectively the Cooperative Assessment Group, CAG) used the habitat equivalency model to determine the size of the restoration needed to compensate the

Table 1. Marsh injury quantification

Category of injury	Area of impact (ha)	Initial service loss (%)	Time to full recovery (yr)	Discounted service hectare-years lost
1. Light oiling, rapid recovery	1,685	10	4 months	17.0
2. Heavy oiling, moderate recovery	62.2	40	2 years	10.7
3. Heavy oiling, moderate recovery	3.3	75	2 years	1.9
4. Heavy oiling, slow recovery	0.11	100	20 years	1.0
Total				30.6

public for the interim loss of resources and services due to the discharge of oil into Lake Barre. Interim losses were assessed for oiled marshes and direct mortality to finfish, shellfish, and birds. These were the primary resources exposed to oil from the pipeline discharge, and they showed an observable and measurable change as a result; these are criteria that must be met in order to assess injury (15 CFR Section 990.51). After a review of several alternative projects, the trustees selected vegetative planting on dredge spoil to create salt marsh as the preferred restoration project. The benefits of the marsh were quantified and the size of the area for planting was determined using HEA.

Marsh Injury Assessment

To quantify the interim losses of the oiled marsh areas using the HEA framework, it was necessary to determine the areas of oiling, the degrees of injury, and the time until recovery to baseline in the oiled areas. The CAG conducted a marsh assessment field study to provide these parameters. Observations were made on oiling, vegetative status, and use of the areas by invertebrates at locations in oiled and unoiled areas of marsh in July and October of 1997 and June of 1998. A total of 32 one-meter-square quadrats were established where measurements were made on vegetative species composition, percent cover, and stem density and height. Each sampling quadrat was photographed for documentation. Qualitative observations of conditions present in each quadrat were recorded. Observations documented included: oiling of the vegetation and/or soils (e.g., presence of sheen, amount and location of oil on the plant surface), condition of the vegetation (e.g., general appearance, presence of chlorosis, presence of disease), and fauna observed (e.g., periwinkle, fiddler crabs). In addition to the quadrats, a number of transects were established, which also provided information on the condition of the vegetation. These data along with professional judgment based on previous experience provided the parameter estimates to determine the interim loss of marsh services, which accounts for reductions in the entire flow of marsh services including the reduction in bird and aquatic faunal production that were supported by the marsh.

Based on the marsh assessment field study and information from the initial response effort, the CAG observed that the marsh exposed to oil showed four broad patterns of severity of injury and recovery. While there is some variability within these categories, the CAG sought to balance the cost and complexity of the injury assessment with the need for accuracy in delineating these categories. The areas of oiling, the levels of service losses (i.e., the degrees of injury), and the recovery times for the four categories of injury are described below and summarized in Table 1.

1. Light oiling with rapid recovery. Approximately 1685 ha of marsh were exposed to sheen or to light oiling. Actual sheens were present at the water surface for approximately two weeks following the incident; sheen was not visible on the plants during the July 1997 field visit. The initial loss of services was judged to be 10% and after two weeks the service losses were estimated at 5%. Recovery to full service flows was estimated to have occurred by the October 1997 field visit (roughly four months following the spill). So, 96% of the total marsh affected had returned to baseline roughly four months after the spill. During the interim, only a fraction of the marsh services were impacted.

2. Heavy oiling with moderate recovery. Approximately 62.2 ha of marsh were exposed to heavier oiling than the first category, with a higher degree of service loss and a longer time to recovery. The initial loss in these areas was estimated at 40%. During the July 1997 site visit service losses were estimated at 30%. Again, service losses were based on vegetative status and the past experience of evaluators to determine marsh function. The CAG estimated that full recovery would occur two years following the incident.

3. Heavy oiling with slow to moderate recovery. Approximately 3.3 ha of marsh were exposed to heavier oiling than the first two categories, with a higher degree of service reduction and a longer time to recovery. The initial loss of services was estimated to be 75%. At the July 1997 site visit service losses were estimated at 65%.

Service losses in June 1998 were estimated to be at 20%. The CAG estimated that full recovery would occur two years after the incident.

4. Heavy oiling with slow recovery. Approximately 0.11 ha of marsh were exposed to very heavy oiling, with the above-ground vegetation killed. Service flows were expected to gradually improve toward baseline service provision. Given the limited areal extent of this category, the CAG decided that it was not cost-effective to continue the field study to monitor the gradual recovery for such a small area. The trustees and Texaco agreed to conservatively assume that full recovery for these 0.11 ha would not occur until 20 years following the incident.

For each category of injury, there is a flow of marsh interim service losses through time; combined, the flows are the total marsh service losses. The flows are calculated as service hectare-years. The lost marsh service flows were discounted in this case using a 3% discount rate. This rate is consistent with NOAA and DOI policy and with economic theory (Freeman 1993, Lind 1982) and was also recently affirmed in two separate court decisions (US District Court–Southern Florida District 1997, 1999). The discounted flow of marsh losses across the categories of injury totaled 30.6 discounted service ha-years.

Aquatic Fauna Injury Assessment

Aquatic fauna, including blue crabs, squid, and shrimp, and different species of fish were affected by the discharge of oil. Water samples collected close to the time of the spill indicated that polycyclic aromatic hydrocarbons (PAHs) were present in the water column for a few days at levels known to be toxic to aquatic organisms in laboratory tests. As evidence of the oil's impact, dead shrimp were collected in a Louisiana Department of Wildlife and Fisheries' trawl and dead juvenile crabs were found in a crab pot. A few dead forage fish were observed shortly after the spill.

The trustees employed a site-specific modeling approach to assess the aquatic fauna impacts. The employed model includes algorithms from the "Natural Resource Damage Assessment Model for Coastal and Marine Habitats" (version 2.4, 1996) and new algorithms and data to account for habitats and fauna specific to the Lake Barre incident. The model estimates the aquatic injury that resulted from death due to exposure to concentrations of low-molecular-weight PAHs in the water column. The model also estimates the resulting loss in growth of the organisms predicted to have died from exposure to PAHs. Based on the model, approximately 7465 kg of fish, decapods, and other invertebrates were lost—due to direct mortality and lost growth—as a result of the discharge. The mortality number does not account for a reduction in aquatic faunal production that resulted from a reduction in marsh service flows supporting aquatic fauna; thus, there is no double counting of the aquatic faunal injuries.

Bird Injury Assessment

Bird species were also impacted by the discharge of oil. Mottled ducks, snowy egrets, great egrets, Louisiana herons, sandpipers, rails, gulls, and terns were observed oiled. While only two dead birds were recovered, the trustees believed additional birds were killed as a result of direct exposure to oil. The toxicity of petroleum oils to birds is summarized by Leighton (1995).

The trustees assessed bird losses using the same model that was employed to assess aquatic fauna impacts. In this case, bird species composition and abundance data for species present in and around Lake Barre during the spring was based on the standard model database. In the model, birds that came in contact with the discharged oil were assumed to have died. The model estimates that 333 birds, primarily seabirds and waders, died as a result of exposure to oil. The average weight per bird was assumed to be 1 kg, thus, the injury was estimated as 333 kg of lost bird biomass. This bird loss does not account for a reduction in bird production that resulted from a reduction in marsh service flows supporting bird species, so there is no double counting of the bird impacts.

Since the aquatic fauna and bird impacts were not quantified as the flow of lost resources and services from a particular habitat, these injuries did not fit directly into the habitat equivalency model. However, by converting the biomass losses into a flow of habitat that would have produced the biomass, through primary production, the trustees quantified the aquatic fauna and bird biomass losses as habitat service hectare-year losses, consistent with the HEA model.

The trustees converted the biomass losses to an equivalent amount of salt-marsh hectare-years that would have provided the aquatic fauna and bird biomass through primary production since salt-marsh creation and/or enhancement were selected as the preferred type of project for compensatory restoration of all the injury categories (see next section). First, the trustees converted aquatic fauna and bird biomass to equivalent salt-marsh plant production using trophic level transfers that take account of the inefficient energy exchange between trophic levels. Ecological efficiency from marsh plants to detritivores was estimated to be 4%; the trophic transfer to fish and invertebrates that feed on detritivores was estimated to be 20%; and for birds and mammals, the efficiency from fish or invertebrate prey was estimated to be 2% (see French and others 1996). The combined aquatic fauna and bird biomass losses translated to 2,378,231 kg of plant biomass. Kirby (1971 as reported by Odum and others 1972), estimated salt-marsh primary production to be 2800 g dry weight/m^2/yr. In another study, Kirby and Gosselink (1976) report salt-marsh production in Louisiana to range from 750 to 2600 g dry weight/m^2/yr; they emphasize that the true net production is probably much closer to the high end of the range. White and others (1978) estimate salt-marsh production in Louisiana to be up to 2895 g dry weight/m^2/yr. Based on Kirby (1971) and assuming dry weight is 15% of wet weight, primary production is estimated to be 186,679 kg wet weight/ha/yr. Therefore, 12.7 ha of salt marsh (2,378,231 kg/186,679 kg/ha/yr) would provide 2,378,231 kg of primary production during the course of one year and 12.7 ha-years is the flow of lost habitat resources and services.

Texaco did not accept the trustees' modeling method and formulated another approach for assessing aquatic fauna and bird impacts. Texaco's approach to aquatic fauna impacts was based on measured water column contaminant concentrations at the incident site, wildlife expected to be present at the site, and literature toxicity values. Bird mortality was based on recovered birds and a standard adjustment factor that considers that not all dead birds are recovered. From these analyses, Texaco calculated less impact than what was computed by the trustees. However, Texaco was willing to agree to a restoration requirement for the bird and aquatic fauna injuries without agreement on the injury estimates. To reach agreement, rather than focus on the calculation of injury, the CAG focused on the implications for restoration.

The trustees calculated the amount of salt marsh that would be needed to offset the aquatic fauna and bird injuries. Assuming that a restored salt marsh provides services for 25 years, with constant erosion beginning after marsh maturity (three years), and that the provided services are as productive as the services that were lost, 1.3 ha of compensatory marsh would generate 12.7 ha-years of services and therefore offset the 12.7 ha-year loss. Based on this analysis, 1.3 ha of salt-marsh restoration would be enough to offset the aquatic fauna and bird injuries. Texaco offered 1.6 ha of marsh creation as compensation. The trustees accepted this offer for aquatic fauna and bird compensation. The equivalent discounted service hectare-years to be provided, corresponding to 1.6 ha of marsh, that the CAG agreed to were 13.7.

To summarize the injuries, the interim losses for marsh injury totaled 30.6 discounted service ha-years; the salt-marsh restoration to compensate for interim aquatic fauna and bird injuries had to total 13.7 discounted service ha-years.

Restoration

The trustees determined that salt-marsh creation and/or enhancement was the appropriate type of restoration to compensate for the marsh, aquatic fauna, and bird injuries. Salt-marsh restoration was preferred for the salt-marsh injuries since salt marsh provides direct in-kind restoration. Salt marshes provide critical spawning and nursery areas for many species of juvenile fish and shellfish; they export detritus—an energy source for the aquatic food web—into the estuary, and they improve water quality by filtering sediments of other pollutants from the water column. Salt marshes also provide many bird services, including nesting, cover, and foraging habitat, for a number of bird species. The Damage Assessment and Restoration Plan for Lake Barre, Louisiana (see Natural Resource Trustees 1999) has further discussion of the choice of salt marsh as the preferred restoration alternative.

Selected Restoration Project

The selected restoration project for the Lake Barre incident is planting salt marsh vegetation on East Timbalier Island. Under the existing CWPPRA (Coastal Wetlands Planning, Protection, and Restoration Act) program, dredged material was deposited on the island in order to prolong its life-span. The new land formed by the dredge and fill operation was unvegetated at completion of the project; there were no funds to plant marsh vegetation. The compensatory project for the Lake Barre incident is to plant a portion of the bare ground created on East Timbalier Island with salt-marsh vegetation.

East Timbalier Island is a state-owned and managed barrier island that lies at the mouth of Timbalier Bay; the island is bordered by Timbalier Bay to the north, the Gulf of Mexico to the south, Little Pass to the west, and Raccoon Pass/Penrod Slip to the east (Figure 1). The island is comprised of vegetative communities typically found on Louisiana barrier islands including beach, low dunes, barrier grasslands, salt flats, and salt marshes. Smooth cordgrass (*Spartina alterniflora*) is the dominant species in low-elevation salt marshes; marsh-hay cordgrass (*Spartina patens*) and seashore saltgrass (*Distichlis spicata*) are present at higher elevations. East Timbalier Island is currently experiencing high rates of subsidence and shoreline erosion due to an inadequate supply of sediments, high rates of relative sea level rise, and the impacts from wind-driven sea level change (McBride and Byrnes 1997).

The restoration project to compensate for the natural resource injuries in Lake Barre consists of planting salt marsh vegetation on newly deposited dredge materials on East Timbalier Island. Marsh vegetation (smooth cordgrass and marshhay cordgrass) will be installed in strips, each strip consisting of multiple rows of plants. Strips will be oriented parallel to the east–west shoreline and will be separated by unplanted areas. The first strip will be planted along the northern (bay) edge of the marsh platform to protect the platform against erosion. The remaining strips on the interior of the platform will consist of marshhay cordgrass.

The enhancement project of planting in strips has three basic functions. First, the planted strips will mature more rapidly than natural colonization on the platform, thereby providing marsh and faunal services in the strips faster than otherwise would be the case. Second, the planted strips will enhance colonization of the gap areas by marsh plants. Third, the presence of plants on the platform will reduce erosion and so the overall life-span of the marsh platform will be extended. The reduction in erosion due to planting will occur in both the planted strip areas and in the gap areas that are under the influence of vegetative spreading.

The salt-marsh services to flow from the restoration project will be the same type and quality as the resources and services that were injured. The salt-marsh project directly restores the salt-marsh injuries. The salt marsh also supports aquatic fauna and bird species of the kind that were impacted by the oil discharge. Because the project occurs in the same watershed where the injuries occurred and will provide the same resource and service opportunities, the resources and services of the project will be of comparable value as those that were lost. Thus, it is appropriate to quantify the restoration benefit as discounted service hectare-years to directly offset the discounted service hectare-year losses. In other words, the use of habitat equivalency is appropriate for determining the scale of compensatory restoration.

Restoration Scaling

The purpose of restoration scaling is to determine the amount of marsh planting that will provide the flow of services that were lost due to the oil discharge. This section describes how the service flows from the planting project are calculated within the HEA model and ultimately how much planting is needed to offset the interim service losses.

The model or framework for calculating service benefits is based on the project of planting the bare platform—modeled as a rectangle 198 ms wide and 4435 ms long—in strips of two types of marsh plants with gaps in between the strips. The model has two separate components. The first component is for planted strips. The second component is for the nearby gap areas where planted strips will contribute to colonization of the marsh platform. In both planted strips and gap areas, the service benefit is calculated as the discounted service hectare-years (DSHYs) of services generated on the platform with planting minus the DSHYs of services that would have been generated on the platform if no planting were to take place and only natural colonization were to occur. The calculation of compensation for faunal injuries (aquatic fauna and birds) and marsh injuries is done separately to account for differences in the project's provision of bird and aquatic faunal biomass and marsh services. The planted marsh provides faunal services sooner than the full array of marsh services and the created marsh is more productive at providing faunal services than all the marsh services. Faunal services from a marsh depend on above-ground biomass and created marshes achieve the function of natural marshes with respect to above-ground biomass [see Broome and others (1986) for an example].

Planted Strips

In the planted strips, the model uses a set of input parameters to generate DSHYs with and without planting; the net benefit of planting is the difference between the two. The service hectare-years (SHYs) of marsh services either with or without planting in any year depend on two factors: (1) the percent service in the planted area in that year (SHYs per hectare); and (2) the hectares that remain (dependent on erosion). Multiplication of these two numbers gives total SHYs in that year. Note that restoration for the faunal and marsh injuries is calculated separately, so a subscript k is added to the relative services, with k equal to faunal for faunal injuries and k equal to marsh for marsh injuries. Using a real discount rate, these yearly SHYs are then translated into the present value DSHYs.

The formula for DSHYs of benefit in a planted strip is:

$$\mathrm{DSHY}_k = \sum_{t=0}^{t=L^p} \beta^t * S^p_{t,k} * A^p_t - \sum_{t=0}^{t=L^{nc}} \beta^t * S^{nc}_{t,k} * A^{nc}_t \tag{1}$$

where $t = 0$ is the base year when damages are calculated, L^i is the project life-span with the superscript i

Table 2. Parameters to quantify benefits of marsh restoration

	Restoration for			
	Birds and aquatic fauna resources and services		Marsh services	
	Planting	No planting	Planting	No planting
Relative services (%)	100	100	50	50
Time to maturity (yr)	3	12	5	20
Functional form	Linear	Linear	Linear	Linear
Base year	1997	1997	1997	1997
Beginning of project	2000	2000	2000	2000
Discount rate (%)	3	3	3	3

indicating either planting ($i = p$) or under natural colonization ($i = nc$), S_t^i is the relative services at time t for $i = p, nc$, A_t^i is the proportion of the area remaining at t for $i = p, nc$, and $\beta^t = (1 + d)^{-t}$ is the discount factor (note that here, t is an exponent).

The percent services component for faunal services and marsh services in each year is based on the input parameters in Table 2. For full marsh services, the time to maturity without planting was derived from a study by Hester and Mendelsson (1992) on the vegetation dynamics of a restored marsh on Timbalier Island. The colonization rate for unplanted, unfertilized plots in the Hester and Mendelsson paper was extended into the future by assuming a linear rate of growth. Based on this rate of growth, it was inferred that unplanted plots would reach maturity at 20 years. The relative services for the unplanted marsh platform are based on standard values for this parameter, derived from studies of the services provided by marsh creation projects. The planted areas are also expected to provide 50% of the services of natural marsh. The planted areas are expected to mature in five years.

For faunal services, which are dependent on aboveground biomass, the time to maturity in planted areas was determined to be three years and the service provision relative to natural marshes was determined to be 100% (Broome and others 1986). An unvegetated platform (no planting) would be more valuable to shorebirds than a vegetated platform; however, <0.1% of the faunal biomass injury is shorebird biomass. The restoration parameters associated with planting reflect the benefits of planting to finfish, shellfish, seabirds, and waders, the resources most heavily impacted by the oil spill. In the absence of planting, faunal maturity was set equal to three fifths of the full service maturity of 20 years (i.e., in the same ratio as the maturity of the faunal component to the maturity of the full marsh services with planting).

The model for quantifying service benefits incorporates an erosion factor via the proportion of the area remaining term, A_t^i in equation 1 above. This factor represents the combined effects of bayside and gulfside erosion. Bayside erosion is expected to begin at year 1, while gulfside erosion begins only after breach of the revetment and dune system that was installed as part of the CWPPRA project. For bayside and gulfside erosion, the erosion is modeled as taking place at a constant rate along the marsh platform.

The model uses the percentage of the platform remaining to represent erosion. Let E_g^i be the erosion rate (in meters per year) from the gulf side, E_b^i be the erosion rate from the bayside (for $i = p, nc$), and B be the date of breech of the revetment and dune. Then the term A_t^i in equation 1 is given by

$$A_t^i = [198 - E_g^i * \max(0, t - B) - E_b^i * t]/198 \quad (2)$$

The erosion rates are not specified directly in the model. Rather, a project life-span under a natural colonization scenario is specified with both bayside and gulfside erosion, and with only gulfside erosion. Suppose that the lifespan without any bayside erosion ($E_b^i = 0$) is $\hat{L}$ years. Then, the gulfside erosion rate under natural colonization is the solution $\hat{E}_g^{nc}$ to

$$0 = 198 - E_g^{nc} * (\hat{L} - B)$$

Given this gulfside erosion rate, the bayside erosion rate under natural colonization is obtained as the solution to

$$0 = 198 - \hat{E}_g^{nc} * (L^{nc} - B) - E_b^{nc} * L^{nc}$$

The erosion rates with planting are then determined as a proportion of the erosion rates under natural colonization.

The input parameters proposed for calculating the bayside and gulfside erosion rates are identified in Table 3 and apply to both the full marsh services and to the faunal services. The date of breach was based on

Table 3. Parameters for calculating erosion rates

Year of breach of revetment and dune	Year 6
Project life-span under natural colonization with both bayside and gulfside erosion (yr)	20
Project life-span under natural colonization in the absence of bayside erosion (yr)	25
Reduction in the gulfside erosion rate if the platform is planted (%)	10
Reduction in the bayside erosion rate if the platform is planted (%)	95

analyses by Picciola and Associates (1998). The study predicted revetment failure during a storm event with a recurrence frequency of six years. So, on average, breach will occur three years after the project starts. Dune failure was expected three years after revetment failure. The year of breach of the revetment is unchanged by planting. The project life-span without planting of 20 years was based on design features and engineering studies for the marsh platform creation project. The project life-span without planting and without bayside erosion is 25 years.

Under these parameters, the bayside erosion rate is 2.6 m/yr and the gulfside erosion rate is 10.4 m/yr. The implied gulfside and bayside erosion rates fall within the range discussed in McBride and Byrnes (1997).

When the platform is planted, the gulfside erosion rate is assumed to be 90% of the no-planting value, or 9.4 m/yr, and the bayside erosion rate is assumed to be 5% of its no-planting value, or 0.13 m/yr. These parameters imply a project life of 26.7 years if the platform is planted. The seven-year extended life-span with planting is the same as that used by the trustees' scaling of benefits for another project on a barrier island. The project life-span with planting is denoted by L^p. The state-owned island will provide services beyond 27 years if it has not been lost to erosion.

Gap Areas

The gap areas benefit from plants spreading from the planted strip. For the first planted strip along the bay side of the platform, only one gap area benefits; for interior strips, two gap areas benefit, one on each side of the strip. The rate of spread of the strip in meters per year is different depending on the species of cordgrass planted (either smooth cordgrass or marshhay cordgrass). The colonizing front marches out from the planted strip each year. The model assumes that: (1) the relative services provided by the colonizing front grow over time in the same way as in the planted strips, but with a one-year lag; (2) the relative services from the colonizing front are added to the level of relative services under natural colonization; (3) the maximum of the sum of the two effects is the relative services of created marsh at maturity; and (4) after a given interval in the gap has been reached by the advancing front of plants from the planted strip, seed source is assumed to be an insignificant source of colonization relative to vegetative spread, and so services are assumed to grow over time at the same rate as in the strip areas.

Let f^i be the rate of vegetative spread in meters per year, with $i = s$ for smooth cordgrass and $i = m$ for marshhay cordgrass. The maximum distance into the gap areas where the model computes a credit for planting is at a distance $f^i * (L^p - 1)$ from the edge of a strip planted with species i. The model partitions the gap area between the edge of the planted row and into $(L^p - 1)$ intervals, each one being f^i meters long. Index these intervals by j, such that $j = 1$ is the first interval next to the strip. Assuming that planting takes place at $t = 0$ and that an entire interval is colonized in one year, interval j is first colonized at year $t = j$. Let t_j be the date at which gap interval j is reached by the colonizing front. For future use, form an index function $\delta(t \geq t_j)$, which takes the value 1 if its argument is true and the value 0 if not.

It is assumed that the maximal relative services are the same under planting and natural colonization. Let this common level of maximal services be $S^{\max}$, and let M^p be the number of years until the planted strips reach maturity and provide maximal services. The relative services, on a per-hectare basis, at interval j in year t are

$$S_t^j = \min\{S^{\max}, [1 - \delta(t \geq t_j)] * S_t^{nc} + \delta(t \geq t_j) * [S_{t_j}^{nc} + (S^{\max}/M^p) * (t + 1 - t_j)]\} \quad (3)$$

For example, take the case of the full set of marsh services. The planted strips have a five-year maturity period to reach 50% relative services with a linear maturity curve. Under natural colonization, maximal services are 50%, the maturity curve is linear, and maturity occurs after 20 years (or at a rate of 2.5% per year). Then, in year 0, the planted strips provide 10% relative services. The next year, the planted strip provides 20% relative services, while the first interval provides 12.5% services, 10% due to the colonizing front, and 2.5% due to natural colonization. In year 2, the first interval provides 22.5% services (12.5 + 10), while the second interval provides 15% services [10 + 2 * (2.5%)]. This process continues, with maximal services from the strip effect plus natural colonization capped at 50% services.

Each linear meter planted in the strip generates services in the gap area, the total area of which is $1 * (L^p - 1) * f^i$ square meters. The services associated with a meter of planted strip generated in each interval of the gap is given by equation 3, multiplied by the length of the interval, f^i, divided by 10,000 square meters per hectare.

The full amount of services generated in the gap areas per meter of strip planted with species i is

$$S_{t,i} = (1/10{,}000) \sum_{j=1}^{j=L^p-1} f^i * S_t^j, \qquad (i = m,s) \quad (4)$$

where S_t^j is given in equation 3.

The only input parameters required for calculating the gap benefits are the rates of colonization by vegetative spread. For the first strip (assumed to be smooth cordgrass), the rate of spread is expected to be 0.76 m/yr. For the interior strips (assumed to be marshhay cordgrass), the rate of spread is expected to be 0.46 m/yr. These rates are site-specific expectations based on experiences with other salt-marsh plantings in the area.

The erosion factor applied in the gap area is a weighted average of the erosion rates for the planted strips with and without planting. The weights are derived from the fraction of the gap area colonized at that date. No additional input parameters are needed. The percent area remaining in the gap area at date t is

$$A_{t,i} = W_{t,i} * A_t^p + [1 - W_{t,i}] * A_t^{nc} \qquad (5)$$

where the weight is

$$W_{t,i} = [f^i * (L^p - 1) - t * f^i]/[f^i * (L^p - 1)]$$

The gap credit is the present value of gap services with planting minus the present value of gap services under natural colonization. Keeping in mind that the restoration for the faunal and marsh injuries is calculated separately, we now add a subscript k to the relative services, with k = faunal for faunal injuries and k = marsh for marsh injuries. The gap credit per meter of row planted with species i is

$$\text{DSHY}_{i,k} = \sum_{t=0}^{t=L^p} \beta^t * S_{t,i,k} * A_t - (1/10{,}000) \sum_{t=0}^{t=L^{nc}} \beta^t * f^i * (L^p - 1) * S_{t,k}^{nc} * A_t^{nc} \qquad (6)$$

Scale of Restoration

In scaling the amount of planting that is needed, the full credit per meter is the sum of the strip credit and the gap credit. The model ties the gap areas to the planted rows and computes the credit for each meter of strip planted. The model then accumulates credits for each meter of strip planted until the sum of the marsh loss and the amount of benefit generated for compensating faunal injuries is reached.

The planted row credit per linear meter of row planted is the credit per hectare in equation 1 divided by 10,000 m^2/ha, times the width of the planted strip (in meters). To this strip credit is added the amount of gap credit in equation 6.

It is assumed that the first strip planted is smooth cordgrass planted along the bay side of the platform and that the compensation for the faunal injuries occurs in this strip. This strip is specified to be 10.7 m wide in the planting design, while the interior strips are 9.1 m wide. Let W^i be the width in meters of strips planted with species i. Then, C_k^i, the credit per meter of strip planted with species i in order to compensate for injuries k, is given by

$$C_k^i = (W^i/10{,}000) * \text{DSHY}_{i,k}^{\text{strip}} + \text{DSHY}_{i,k}^{\text{gap}}$$

Let P be the length of the platform, D^f be the faunal injury restoration requirement, and D^m be the marsh losses. The scaling of the faunal restoration (in meters of planted strip) is the solution R^*_{faunal} to the equation

$$R^*_{\text{faunal}} = \begin{cases} D^f/C^s_{\text{faunal}} \text{ if } D^f/C^s_{\text{faunal}} < P \\ P + [(D^f - P * C^s_{\text{faunal}})/C^m_{\text{faunal}}] \text{ otherwise} \end{cases}$$

Then, the total meters of strip planting needed to compensate for both the faunal and the marsh injuries is determined as the solution R^*_{total} to the equation

$$R^*_{\text{total}} = \begin{cases} D^m/C^s_{\text{marsh}} \text{ if } D^m/C^s_{\text{marsh}} \le P - R^*_{\text{faunal}} \ge 0 \\ P + \{[D^m - (P - R^*_{\text{faunal}}) * C^s_{\text{marsh}}]/C^m_{\text{marsh}}\} \text{ otherwise} \end{cases}$$

The meters of strips to plant for the marsh injuries is the difference between R^*_{total} and R^*_{faunal}.

The quantification of the restoration benefit from salt-marsh vegetation enabled the trustees to determine the amount of planted strip necessary to offset the faunal and marsh impacts. To provide the necessary faunal restoration, 1422 m of strip must be planted, which equals 1.5 ha; 6086 m of strip must be planted to compensate for the marsh injuries, which equals another 6.0 ha. The area to be planted in strips totals 7.5 ha. The total area enhanced—either planted in strips or more rapidly colonized because of the strips—was calculated to be 23.4 ha.

The results of the habitat equivalency analysis were the basis for Texaco's restoration liability in the natural resource damage settlement, which was finalized in the fall of 1999. The consent decree outlining the settlement requires Texaco or its contractors to plant 7.5 ha on East Timbalier Island as salt marsh. The additional 15.9 ha that will be enhanced result from the planting.

To ensure that the services required to compensate for the injuries actually are provided by the project, the consent decree also specifies performance criteria that the restoration project must meet and a monitoring schedule for evaluating project performance. Monitoring will be conducted annually for three years to provide an assessment of project progress and to allow for implementation of corrective actions early in the project, if necessary. Project performance will be assessed 60 days following the conclusion of all planting and three years after the completion of the 60-day assessment. The 60-day event will assess plant survival in the planted areas. The monitoring event three years after the 60-day event will assess percent vegetative cover in the planted areas and gap areas. Monitoring between these two performance events will be conducted annually to determine if any corrective actions are needed in order to meet percent cover requirements by the three-year event.

Project performance will be assessed by comparing monitoring results with performance standards. Performance criteria were developed for percent survival at the 60-day event in planted areas and for percent cover at the three-year event in planted and gap areas. The performance criteria consider the results from similar marsh restoration projects on Timbalier and East Timbalier islands. If the performance criteria are met at the three-year monitoring event, the trustees believe that the project will be established and no further monitoring will be required. If the performance criteria have not been met after three years, corrective action and up to two additional years of monitoring may be required.

Project implementation occurred in June 2000. All the hectares of *Spartina alterniflora* were planted. Planting of *Spartina patens* was suspended because of drought conditions on East Timbalier Island. At the 60-day survival monitoring event in August 2000, the trustees determined that the *S. alterniflora* met the survival requirements while the *S. patens* did not. A corrective action is required for the failure of the *S. patens* plantings; at the time of writing, that action had not been specified.

Summary

Habitat equivalency is a framework for determining the scale of restoration necessary to compensate the public for natural resource injuries. Under the framework, interim losses are quantified as lost habitat resources and services, and the scale of restoration is that which provides equivalency between the lost and restored resources and services.

The HEA model framework was used to determine the scale of restoration as compensation for the discharge of oil into Lake Barre, Louisiana. Impacts of the oil on resources and services were quantified from the time of the discharge until their recovery to the baseline condition; salt marsh, aquatic fauna, and birds were the focus of the assessment. For the selected restoration project, which was the planting of dredge material to salt marsh, the trustees, in cooperation with Texaco, quantified the resource and service benefits. To compensate the public for the marsh, aquatic fauna, and bird interim losses, it is necessary to plant 7.5 ha of salt marsh. Those planted hectares will benefit another 15.9 ha through vegetative spreading. Altogether, the project will enhance 23.4 ha of dredge platform as compensation for the natural resource injuries. Monitoring is being conducted to ensure that the project is successful and the public is compensated for the resource impacts associated with the oil spill.

It may initially seem implausible that planting 7.5 ha of salt marsh would compensate for the effects of an oil spill involving more than 6500 barrels of oil in about 1750 ha of marsh. However, it should be recalled that more than 96% of the affected area only suffered limited service losses with full recovery occurring after four months, and the restoration ultimately will include more than just planting 7.5 ha of salt marsh. The planting will spread vegetation to an additional 15.9 ha. Furthermore, the planting and vegetation spread will stabilize the marsh platform and extend its lifetime providing additional resource services. The habitat equivalency analysis described here demonstrates how, using site specific data and other existing information and experience, all of these factors can be quantitatively taken into account in scaling a restoration action to compensate for the natural resource injuries.

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