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Methodologies for Estimating Shoreline Cleanup Costs

Dagmar Schmidt Etkin
Environmental Research Consulting
Winchester, Massachusetts, USA
etkin@environmental-research.com

Abstract

Shoreline cleanup operations often constitute the most labor-intensive and costly phase of a large-scale oil spill response operation. The characteristics of the impacted shoreline and the spilled oil, as well as the length of shoreline involved and the standards of target cleanliness all influence the amount of labor required and resultant costs. The estimation of shoreline response costs can assist in response planning and in the optimization of allocation of resources for shoreline response and restoration.

This paper describes and compares methodologies for estimating shoreline cleanup costs for hypothetical spill scenarios based on projected shoreline oiling from oil spill trajectory modeling and on the factors that influence costs. The estimation techniques are based on algorithms derived from statistical analyses of historical oil spill cost data in the Environmental Research Consulting databases, from modeling of labor requirements for different shoreline types and oil types, and from other research studies. The paper further discusses the serious limitations of these cost estimation techniques and suggests strategies for improving modeling of shoreline response costs.

1. Introduction

Once oil hits a shoreline, cleanup operations become significantly more complicated, expensive, and time-consuming. It is often wrought with socio-political implications due to the fact that the oil can be *seen* on the shoreline and many coastal areas have important economic and cultural values (Etkin, 1998a,b). In addition, shoreline and intertidal ecosystems are complex and susceptible to serious impacts both from oiling and response operations.

Strategies for removing oil from impacted shorelines should strike a balance between environmental impact and benefit. In many cases, the best approach is to "do nothing." The rate of natural cleaning on a beach depends largely on the amount of wave action and the degree to which the beach is exposed. Stronger wave action physically breaks down the oil more quickly. More exposed beaches encounter greater wave action particularly in winter storms.

Aggressive shoreline cleanup operations can cause more environmental damage than if the oil were left alone (Foster, et al., 1990; Jahns, et al., 1991; Michel, et al., 1991; Michel and Hayes, 1993). Using heavy equipment and having many personnel on a beach can drive the oil deeper into the substrate and damage the physical integrity of the beach. The activity can also do harm to sensitive ecosystems, but, all too often, aesthetic considerations and public pressure to "do something" override long-term environmental considerations in the decision-making process. The resulting manual shoreline cleanup is labor-intensive, slow, and expensive. Ultimately, the results can be disappointing.

2. General Issues for Shoreline Cleanup Costs

When a major oil spill impacts a shoreline, as much as 80-90% of the cleanup costs associated with the overall response operations will be attributable to shoreline cleanup (Etkin, 1998a,b).

As is the case with overall spill response costs (Etkin, 1999; 2000; 2001), shoreline cleanup costs vary tremendously depending on a large number of interrelated factors. Shoreline cleanup operation costs include: labor costs, equipment costs, disposal costs, materials costs (e.g., disposable sorbents or chemicals), and logistical costs.

Each of these cost components is, in turn, highly dependent on the type of shoreline involved, the degree of oiling, the oil type, and the length of shoreline. The time required to complete the cleanup operation depends on the type and length of shoreline, the degree of oiling, the methodology used, the labor and equipment available, the efficiency of the labor and methodology, funds available, and unpredictable factors of weather and logistics.

Shoreline cleanup costs are not only the most expensive part of a response operation, they are probably also the most unpredictable due to the very political nature of the results. The question of "how clean is clean?" plays an important role in determining costs. The standards of "cleanliness" and degree of oil removal balanced with stakeholder concerns and practicality can determine the scope of a shoreline cleanup response operation. The degree to which stakeholders and response officials are willing to allow responders to rely on "natural cleansing" or less-aggressive but potentially more environmentally beneficial treatment options, as determined by a net environmental benefit analysis, can have a significant impact on costs.

3. Estimating Shoreline Cleanup Costs: Basic Methodologies

Four basic approaches to estimating shoreline cleanup costs for projected shoreline oiling for hypothetical spill scenarios based on oil spill trajectory modeling are:

a. Estimate the length of shoreline oiled and estimate the oil removal cost per unit length shoreline oiled (e.g., \$/km);
b. Estimate the area of shoreline oiled and estimate the oil removal cost per unit area shoreline oiled (e.g., \$/m^2);
c. Estimate the amount of oil on the shoreline and estimate the oil removal cost per unit of oil on the shoreline (e.g., \$/tonne); or
d. Estimate the oil removal cost based on historical data on shoreline oiling.

Calculating the cost factor (removal cost per unit shoreline or unit spilled on the shoreline) can be done on the basis of historical spill cost data or by calculating the amount of the work involved in removing the oil and then estimating the cost of the work units. In either case, the cost factors will depend on the oil type, the general type of shoreline, and the methodology used for removal (Figure 1). The oil type and shoreline type determine the options for manual and mechanical oil removal and cleanup (see Owens, 1998; Michel, Benggio, and Byron, 1998). In real spill situations, the actual degree of oiling and the nature in which the oil penetrates the shoreline substrate as well as the most effective and efficient strategies for shoreline cleanup operations are, of course, dependent on the very specific characteristics of a particular shoreline. The general descriptions of shoreline types as well as the general categories of shoreline types as shown in Figure 1 are based on the type of information that is currently available from oil spill trajectory modeling.

4. Basic Limitations in Estimation Approaches

It is important to note that any cost estimation technique for a hypothetical spill is inexact. Firstly, estimation of shoreline response costs for such hypothetical spill scenarios are based on projected shoreline oiling, presented as length of shoreline oiled, area of shoreline oiled, or, in some cases, as amount of oil on the shoreline. Estimation of shoreline response costs then is based on deriving a fairly accurate estimate of shoreline oiling, which, of course, depends on a variety of factors, such as wind direction and speed, currents, tides, and coastal morphology. The highly probabilistic nature of the process of oil spread is inherent in trajectory modeling. The output of oil spill trajectory models, such as those developed by Applied Science Associates (SIMAP) and the National Oceanic and Atmospheric Administration (TAP II) presents a range of possible outcomes for shoreline oiling each spill scenario. Selecting the most probable or "average" outcome or even the "worst case" outcome for shoreline oiling is inexact and brings inaccuracies into the cost estimation.

A second source of error is in estimating the amount of oil on the shoreline or the length or area oiled for use in the response cost estimation models when the output by the trajectory model is in one unit or another, e.g., estimating shoreline area oiled from shoreline length requires estimating the width of the beach. Obviously no shoreline is exactly straight and exactly a certain uniform width.

The third source of error in estimating response costs is in extrapolating the current hypothetical situation to historical oil spill situations. Each and every oil spill is unique in terms of the fate and effects of the oil and in the challenges presented by the oil removal operations both offshore and on the shoreline. Shoreline response strategies are influenced by factors beyond those inherent in the oil and the shoreline, such as politics and local standards and values. The *costs* for these operations can vary tremendously as well. Even with the same general strategies, equipment, and work crews, costs can vary based on a variety of factors, including local salary scales, equipment rental costs, logistical costs, oily waste disposal costs, and spill monitoring costs. All of this variation is included in the historical data upon which much of the estimation modeling is based.

Another source of error in shoreline response cost modeling is the need to make generalized estimates of "work" for each response operation. The estimates are based on removing a certain amount of oil off of a certain length of shoreline in a certain number of worker-days. Certainly the variation in the shoreline structure, logistics, weather, and worker efficiency creates a great deal of variation in the actual time spent and work involved. Shoreline cleanup is not accomplished by a machine removing a uniform thickness of oil off of a perfectly straight beach with no penetration under ideal weather conditions.

With these very real limitations in mind, given the task of determining general ranges of costs for shoreline response for hypothetical spill scenarios, estimation of the shoreline response costs were attempted using the information available from trajectory models, historical oil spill cleanup cost data, and various modeling

5. Historical Spill Data on Shoreline Cleanup Costs

Historical data provide "hindsight" overviews of the costs associated with shoreline cleanup response operations. Unfortunately, despite the many thousands of oil spill response operations that have taken place over the last three or four decades, reliable and reasonably complete information on costs are seriously lacking, though there is some information available. A number of studies have looked at shoreline cleanup costs based on the information available as shown in Figures 2 and 3.

Shoreline cleanup costs per unit spilled or per unit of shoreline length oiled may also vary with the size of the spill, as shown in the work by Ross (1985, 1991) (see Figure 4). Ross showed that cleanup costs rose with shoreline length oiled, so that:

$$y = 7{,}959\ x^{0.673}$$

Where y = cleanup cost per kilometer oiled shoreline
And x = kilometers of oiled shoreline

Ross's work was based on a number of spills that occurred before the 1989 Exxon Valdez spill and later including that spill, renowned for its astronomical costs.

An analysis of over 200 oil spill cleanup cost case studies, showed that overall *per-unit* cleanup cost is positively correlated with the length of shoreline oiled, both internationally and in the US (Etkin, 2000) (Figures 5 and 6). Etkin (2000) developed a number of algorithms based on oil spill factors including oil type, shoreline length oiled, response strategy, spill size, and location based on her cleanup cost database from which the overall response cost was estimated. While the response cost would be based on a number of factors, a general formulae for estimating overall cleanup cost based on length of shoreline oiled was derived as follows:

International (including US): $y = 39.421\ x + 4{,}956$
Where x = length of shoreline oiled (km)

And y = overall cleanup cost per tonne

US only: $y = 87.59\ x + 9{,}469$
Where x = length of shoreline oiled (km)
And y = overall cleanup cost per tonne

Estimates made from these two formulae need to be adjusted to reflect the fact that the estimates derived represent *overall* cleanup costs, not just shoreline cleanup. Reducing the estimates by a factor of 10-40%, based on observations in the review of historical cases that 60-90% of cleanup costs (e.g., Franken, 1994; Etkin 1998a,b) in complex oil spill response operations are attributable to shoreline cleanup, may help in deriving a more realistic shoreline cleanup cost factor based on this historical data. The

Ross formulae are based on estimated shoreline cleanup costs alone and have already taken the reduction factor into account.

Both the Ross (1991) and Etkin estimates involve general estimates for shoreline lengths and gallons spilled respectively, as do the other estimates shown in Figure 2. The cleanup methodology used can also have a significant impact on cost.

For example, Purnell's analysis (Purnell 1999) shows that different shoreline cleanup technologies employed in response to the *Sea Empress* spill in the UK resulted in vastly different per-tonne costs in different locations, and the methods themselves involved vastly different costs as well. The costs for the technologies used to remove oil from the more heavily oiled lengths of shoreline (e.g., scraping, surf washing, and manual removal) resulted in generally lower costs than the methods used for more lightly oiled locations (e.g., pebble washing, in-situ pit washing, flushing/trenching, and rock wiping) (Figure 7).

There is more labor involved in thoroughly removing smaller amounts of oil than in gross removal of oil from heavily oiled sections of impacted shoreline. Presumably, once gross removal has been accomplished, the more thorough (and expensive) removal technologies would be employed in the same locations, complicating per-shoreline length or per-gallon estimates.

6. Estimating Costs By Estimating Work Involved in Shoreline Cleanup

Shoreline cleanup is generally recognized to be the most labor-intensive part of any response operation. Labor costs are usually the most expensive part of shoreline cleanup. Estimating the work required to remove the oil from an oiled shoreline is key to estimating the overall shoreline cleanup costs, but, clearly, this is a complex task.

Olsen and Hamilton (1991) presented the following observations based on the *Exxon Valdez* oil spill shoreline cleanup operations:

- The work required to remove surface oil varied directly with the area, percentage covering, and thickness of deposit;
- The work required to remove subsurface oil also varied with the depth of penetration and permeability of the soil;
- The work required varied with beach topography; both very shallow (not very wide) and very rugged beaches were harder to clean;
- The presence of a "strand line" – a line of debris washed up on shore – added to the work required;
- Work varied with beach composition; for example, gravel or pebble beaches were harder to clean than rocky ones;
- The easiest beaches to clean were those that had a moderate slope and were covered with cobbles (rocks of several inches in diameter), because high-pressure hot-washing could be used with minimal damage.
- Areas of heavy oil contamination accounted for less than 30% of the mileage of shoreline impacted, but accounted for 2/3 of the workload [this is contrary to the observations of Purnell, 1999].

Based on the experiences of the *Exxon Valdez* shoreline cleanup crews, Olsen and Hamilton (1991) developed the following model to calculate the work involved in cleaning a beach. The model is a good way to view the complexity of shoreline cleanup projects from a work perspective.

$$SEBWU = (L/100) \times E_f \times W_f \times P_f \times T_f \times C_f \times D_f$$

Where: SEBWU = standardized equivalent beach work units

L = length (in meters or yards)

E_f = estimated factor for degree of contamination

W_f = estimated factor for width of the beach

P_f = estimated factor for depth of oil penetration

T_f = estimated factor for thickness of the oil deposit

C_f = estimated factor for percentage of coverage

D_f = estimated factor for amount of debris on beach

Another method for predicting shoreline cleanup costs without relying on historical data would be to estimate the work involved in terms of "worker-days" and multiply by known costs per worker per day. Olsen and Hamilton's model per se does not, however, include any methodology for estimating the number of workers and time required and any estimates of worker-hours has to be based on first-hand experience and "eye-balling" each situation.

Michel and Cotsapas (1997) contacted various cleanup contractors for an estimate of the number of worker-days that would theoretically be required to clean up oiled shoreline in hypothetical spills in the Gulf of Mexico. Using their data, they calculated that 0.06 worker-days would be required for each square meter of oiled shoreline.

Shikida (1999) studied records of manual shoreline cleanup from the *Nakhodka* spill in Japan. Shikida's analysis revealed that the amount of oil removed manually from an oiled shoreline in a day correlates with the cumulative amount of oil removed up to that particular day and the number of people engaged in cleaning up on that day, so that:

$$s = 0.012e - 0.0000349c + 34.612$$

Where, s = the amount of oil (in tonnes) removed in a day

e = the number of people engaged in cleanup operations on that day

c = cumulative amount of oil (in tonnes) removed up to that day.

From this formula, it is possible to estimate the amount of "worker-days" required to remove a particular quantity of oil on an impacted shoreline. On the first day of shoreline impact (when no oil has yet been removed): $e = 83.33(s - 34.612)$.

The solution would then give the number of workers required to remove the oil in one day, or the number of worker-days required. For example, if there were 100 tonnes of oil on the shoreline, an estimated 5,450 workers would be required to remove the oil in one day or 5,450 worker-days would be required to remove the oil. With 100 workers, the oil removal operation could be completed in approximately 54 days, while with 1,000 workers the job could, theoretically, be completed in 5.5 days.

7. Estimation of Shoreline Cleanup Costs For Hypothetical Scenarios

Hypothetical scenarios for oil spills from tankers carrying No. 2 fuel and crude oil were created for a site at Carquinez Strait, San Francisco Bay, California, USA, [38º03.7'N/122º13.5'W]. The scenarios were based on spills of 10,000 US gallons (34 tonnes) up to the worst-case discharges of 100,000 DWT product tankers and 300,000

DWT very large crude carriers (VLCCs) -- 25 million gallons (85,034 tonnes) to 80 million gallons (272,108 tonnes), respectively (see Figure 8).

The shoreline impact for the spill scenarios was estimated using the National Oceanic and Atmospheric Administration (NOAA) Trajectory Analysis Planner II (TAP II) (Barker and Galt, 2000). The TAP II model yielded estimates of the amount of oil on the shoreline as well as maps of lengths of oiled shoreline. Shoreline area covered was estimated by assuming a continuous 10-meter-wide beach. The predicted shoreline impacts for the hypothetical spill scenarios are summarized in Figures 9-10.

7.1 Cost Estimation Based on Shoreline Area Coverage

Shoreline cleanup costs estimates were calculated based on the estimate of 0.06 worker-days per square meter of shoreline area oiled (based on Michel and Cotsapas 1994) and high and low cost estimates for shoreline cleanup of US$1,200 per worker-day to US$1,500 per worker-day, values supplied by Massachusetts Maritime Academy, Marine Spill Response Corporation, and National Response Corporation, as average shoreline cleanup worker costs, including oily waste disposal fees, which often represents a considerable portion of the response cost. The cost estimates made by this methodology are shown in Figures 11-12. These costs are generally applicable to US spill scenarios and cannot necessarily be applied directly to shoreline cleanup situations in other nations where labor costs might be different.

7.2. Cost Estimation Based on Shoreline Length

Cost estimations for shoreline cleanup for the spill scenarios were made on the basis of oiled shoreline length based on the Ross (1990) formula, as described above, and the oiled shoreline lengths from the TAP II model. The results are shown in Figures 13-14.

7.3. Shoreline Cleanup Cost Estimates Based On Tonnes of Oil on Shoreline

Cleanup costs were estimated by extrapolating the amount of oil on the shoreline from the TAP II model and using the modified worker-day formula based on Shikida (1999) as described above and shoreline cleanup costs of US$1,200 to US$1,500 per worker-day. The results are shown in Figures 15-16.

A second set of estimates, based on amount of oil on the shoreline and low and high estimates of per-tonne cleanup costs from historical data, is shown in Figures 17-18.

7.4. Shoreline Cleanup Cost Estimates Based On Historical Data

Cleanup costs for shorelines were also estimated by using the Etkin formula (2000) for per-tonne cleanup costs based on shoreline length oiled (based on historical data). The results gave estimates of the *entire* cleanup operation. Shoreline oil removal costs (and disposal) were assumed to be 60-90% of these overall costs, giving the low and high estimates, respectively. The results are shown in Figures 19-20.

8. Summary

A summary of the cost estimates made for all the scenarios based on each of the four estimation techniques is shown in Figures 21-22. The cost estimations for each scenario were made in four different ways:

a) *Based on oil shoreline area:* The shoreline area (in m^2) for each scenario as predicted by TAP II was multiplied by $74/$m^2$ for the low cost value and $92/$m^2$ for the high cost value, as determined by historical data. A second estimate was made based on the formula derived from Shikida (1999):

$$e = 83.33(s - 34.612),$$

Where e = the number of workers,
And s = the amount of oil (in tonnes) removed in a day.

b) *Based on oiled shoreline length:* The shoreline length was obtained from the TAP II model. This figure was inserted into the formula from Ross (1991):

$$y = 7{,}959\ x^{0.673}$$

Where y = cleanup cost per kilometer oiled shoreline
And x = kilometers of oiled shoreline

to obtain the total shoreline cleanup cost for the scenario.

c) *Based on tonnes of oil on shoreline:* The number of tonnes of oil impacting the shoreline was estimated from the TAP II model. The tonne amount was then multiplied by factors of $8,446/tonne and $96,526/tonne (from high and low historical data in Figures 17 and 18 to obtain low and high estimates for shoreline cleanup.

d) *Based on total tonnes spilled and shoreline length oiled:* The shoreline cleanup cost per gallon was estimated by taking the shoreline length oiled obtained from TAP II maps, then taking the shoreline length and applying the formula derived from historical data:

$$y = 87.59\ x + 9{,}469$$

Where x = length of shoreline oiled (km)
And y = overall cleanup cost per tonne

to obtain the $/tonne factor. Then multiplying this by total number of tonnes spilled in the scenario. This number, which represents the *total* estimated cleanup costs can then be multiplied by a factor of 0.60-0.90 to represent the shoreline cleanup alone.

The estimated costs obtained by the different methodologies vary considerably from one another. Firstly, the estimates are based on historical data or "rules of thumb" applied by contractors based on experience. The variability reflects the fact that the historical data itself is influenced by complex factors that impact the cleanup costs. Different models have relied on different data sets with the largest historical data set being that used in the Etkin (2000) model. The methods that have been used to model overall trends in shoreline cleanup costs have had to "average" variability in shoreline morphology, logistical issues, time of year, weather, cleanup methodologies, and cleanliness standards.

The costs estimated by the various cost estimation techniques are indicators of the possible costs that would be incurred in a very thorough manual and mechanical shoreline response strategy rather than in one that relies heavily on natural recovery techniques. Oil and oiled sand and debris are removed to the extent possible.

The lower cost values associated with the amount of oil on shoreline/historical data modeling as well as those of the Ross (1991) formula (shoreline length oiled) are probably based on cases in which lower standards of shoreline cleaning were applied than would likely be tolerated in the US and other locations under most circumstances.

The extremely complex nature of shoreline cleanup operations for a worst case discharge will be reflected in cleanup costs beyond that which can be accounted for in simple calculations of worker days, etc. In fact, Michel and Cotsapas (1997) make the point that disposal and equipment decontamination costs can be extremely high, as witnessed in the *Morris J. Berman* response operations. Factoring in these costs can add considerably to the shoreline cleanup costs and the overall costs of a cleanup operation. The estimations associated with the Etkin (2000) historical model show very high values for the worst-case spill scenarios. Since they are derived from *total cleanup costs* from a large number of historical data points, these cost estimates are more inclusive of some of the other costs associated with cleanup (such as disposal costs, labor logistics, and equipment decontamination). These additional costs are not accounted for in the other simpler models.

Actual shoreline cleaning costs will be largely dependent on cleanliness standards and the actual extent of oiling, as well as the cleanup methodologies employed. The majority of contingency plans do not detail shoreline cleanup strategies beyond describing the general techniques recommended for different shoreline types. Shoreline cleanup is rarely factored into contingency plans because it is generally not crucial to the early activation of a response. Shoreline cleanup operations can take place days, weeks, or months after the initiation of a spill response.

In practice, the predicted costs can be "adjusted" to take into account variations in spill situations. For example, if the shoreline area oiled is not considered to be a location for a relatively high standard of oil removal and can usually be left to natural recovery, the cost figures can be reduced substantially at least for particular sections of shoreline. If winter storms might increase natural recovery efforts as well as preclude immediate response due to logistical problems, the costs could be reduced as well. On the other hand, if the situation calls for very stringent standards due to the timing and location of the spill even higher costs might be expected. For example, the *Morris J. Berman* barge spill in San Juan, Puerto Rico, in which oil landed on tourist beaches at the beginning of the tourist season resulted in shoreline cleanup costs that exceeded $213,600 per kilometer of oiled shoreline.

Contingency plans stress keeping the oil *off* the shoreline by protective booming, mechanical containment and recovery, and, increasingly, effective dispersant use. The predicted costs can be further adjusted to reflect the effectiveness of offshore removal operations. The TAP II model does not take into account any offshore removal of oil. With mechanical containment and recovery operations, up to 15% (in some cases, even more) of the oil may be removed offshore, thus reducing the amount of oil that might impact the shoreline. Cleanup costs can be reduced likewise. The use of dispersants as a first-order response strategy will often significantly reduce shoreline oiling, which would have a significant impact on shoreline response costs.

The wide variability of results using the different methodologies points to the need for a considerably more rigorous model for predicting shoreline cleanup costs for hypothetical spill scenarios used in response planning. A rigorous estimation technique should best be based on an extensive study of the work effort involved in the cleanup of different types of shorelines impacted with different types of oil, applying different standards of ultimate cleanliness. This will then be coupled with local labor rates, and additional information on local disposal costs. Historical spill data could be used to derive work effort information as well as disposal and other related costs. This project is currently underway at Environmental Research Consulting.

9. Conclusion

Vessel and facility response plans are required to address "worst case discharges". What would actually happen in such a situation not clear. The US, for example, has never experienced a tanker spill larger than 42,860 tonnes (the *Mandoil II* tanker spill off Oregon in 1968). In fact, the largest recorded tanker spill in the world since 1960 (and probably before that as well since tankers were smaller at that time) was the *Castillo de Bellver* spill of 267,000 tonnes off South Africa in 1983. The 272,000-tonne worst-case discharge scenarios represent hypothetical events that have never occurred in reality in the US or elsewhere for that matter, with the exception of the accumulated 1991 Gulf War spillage, the Nowruz well blowout in the Persian Gulf in 1983, and the Ixtoc I well blowout in Mexico in 1979-1980. The cleanup of this amount of oil with major shoreline impact cost could be astronomical, particularly in the US, which has among the most expensive average spill cleanup. The manner in which this magnitude of costs would be handled by insurers, compensation funds, and liability regimes is a complex issue.

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Figure 1: Predicted General Shoreline Impact By Shoreline Type and Oil Type		
Shoreline Type	**Oil Type**	
	No. 2 Fuel	**Crude**
"Rocky"[1]	• Oil flows into lower intertidal zone where often wet; oil does not adhere to rock. • Oil stays on surface in upper intertidal.	• Oil stays in upper intertidal zone and adheres to rock. • Oil stays on surface.
"Wetland/ mudflat"[2]	• Oil refloats and transported landward with rising tide • Oil concentrates in upper tidal zone	• Most oil refloats and transported landward with rising tide • Oil concentrates in upper tidal zone • Some oil may become buried
"Beach"[3]	• Oil can penetrate in mixed-sediment and pebble/cobble beaches. • Oil refloats and can be transported	• Oil carried up beach and deposited in upper intertidal zone.

[1]"Rocky" includes bedrock shorelines or shorelines with larger boulders and rocks.
[2]"Wetland/mudflat" includes mudflats and salt marshes,
[3]"Beach" includes mean sandy beaches, mixed-sediment, or pebble/cobble beaches.
Based on Owens 1998; Michel, Benggio, and Byron 1998; NOAA 1992

Figure 2: Summary Per-Unit Shoreline Cleanup Cost Factor Estimates From Various Studies (all costs converted to 2000 US $)

Reference	Cost Factor	Study Parameters
Moller, Parker, and Nichols, 1987	$7,704- $12,198 per tonne on shoreline	Based on 26 international spills
Ross, 1991	$37,453-$939,258 per km oiled shoreline (depending on shoreline length – see Figure 4)	Based on 11 US and Canadian spills, including *Exxon Valdez*
US Department of Energy, 1993	$1,137-$15,293 per tonne on shoreline	Based on 7 US spills
Franken, 1994	$168,921-$337,841 per tonne on shoreline	Based on limited number of US spills, including *Exxon Valdez*
White and Nichols, 1983	$609 per tonne on shoreline	Based on international study
British OSCA, 1993	$8,144 -$33,181 per tonne on shoreline	Based on UK spills
Jaques, 1995	$73,677 per km oiled shoreline	Based on Norwegian spills
Nitve, Moe, and Hedrenius, 1992	$312,590-$624,537 per km oiled shoreline	Based on Norwegian spills
UK MPCU, 1996	$34,712 per km oiled shoreline $1,297-$2,069 per tonne on shoreline	Based on *Sea Empress* spill in UK Dispersants used in some locations
US Minerals Management, 1992	$5,505-$8,500 per tonne on shoreline	Based on US spills (see Fig. 3 for specific locations)
Farrow, et al., 1990	$2,335-$3,381 per tonne on shoreline	Based on US MMS studies
Harper, Godon, and Allen, 1995	$90,710 per tonne on shoreline best estimate: $65,457-$74,204 per tonne	Based on study of 11 US spills, not including *Exxon Valdez*
Etkin, 1998a	$65,445 per tonne *recovered* on shoreline	Based on 5 US spills, not including *Exxon Valdez*
Purnell, 1999	$571-$1,206,576 per tonne on shoreline (depending on methodology used; see Figure 7)	Based on *Sea Empress* spill
Etkin, 1995	$213,647 per km oiled shoreline	Based on *Morris J. Berman* spill
Etkin, 1998a	$7,822-$9,990 per tonne on shoreline	Based on *Alvenus, Burmah Agate*
Etkin, 1998b	$4,778-$5,918 per tonne on shoreline	Based on *Kuzzbass* spill (mudflat)

Figure 3: Predicted Shoreline Cleanup Costs (Per-Tonne Reaching Shoreline) (2000 US $)

OCS[1] Program Area	Moderate Cost	High Cost
Mid-South Atlantic	$4,265/tonne	$6,588/tonne
Eastern Gulf of Mexico	$5,212/tonne	$8,045/tonne
Central Gulf of Mexico	$6,205/tonne	$9,565/tonne
Western Gulf of Mexico	$2,377/tonne	$3,677/tonne
Southern California	$3,282/tonne	$5,059/tonne
Gulf of Alaska	$4,715/tonne	$7,285/tonne
Cook Inlet	$5,973/tonne	$9,221/tonne
Navarin Basin	$6,422/tonne	$9,918/tonne
St. Matthew Hall	$6,739/tonne	$10,404/tonne
Norton Basin	$6,739/tonne	$10,404/tonne
St. George Basin	$6,920/tonne	$10,678/tonne
Hope Basin	$7,417/tonne	$11,444/tonne
Chukchi Sea	$4,175/tonne	$7,285/tonne
Beaufort Sea	$6,108/tonne	$9,429/tonne

[1]OCS = outer continental shelf

Source: US Minerals Management Service 1992

Figure 4: Shoreline Oiled vs. Shoreline Cleanup Cost Per Kilometer (Based on Ross, 1991 Data)

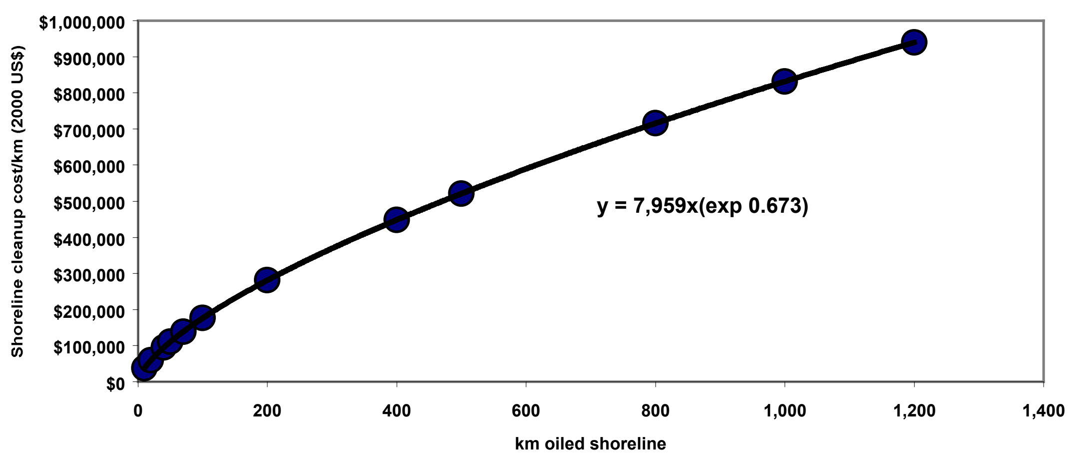

Figure 5: Overall Oil Spill Cleanup Cost/Tonne By Shoreline Length Oiled International Data (Based on Etkin, 2000)

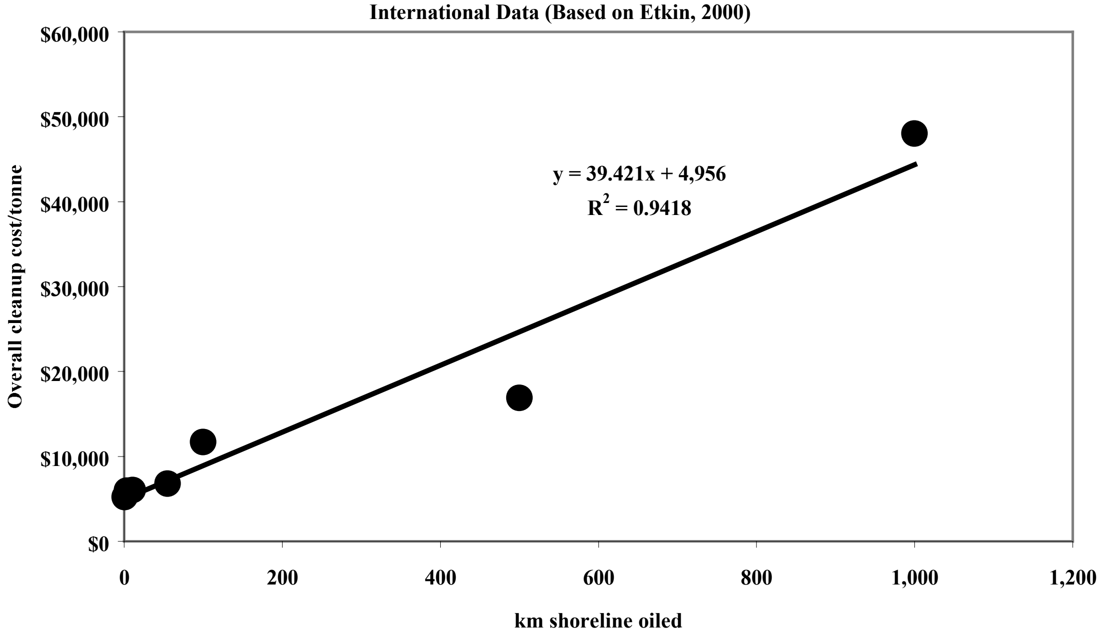

Figure 6: Overall Oil Spill Cleanup Cost/Tonne By Shoreline Length Oiled (US Spills Only) (Based on Etkin, 2000)

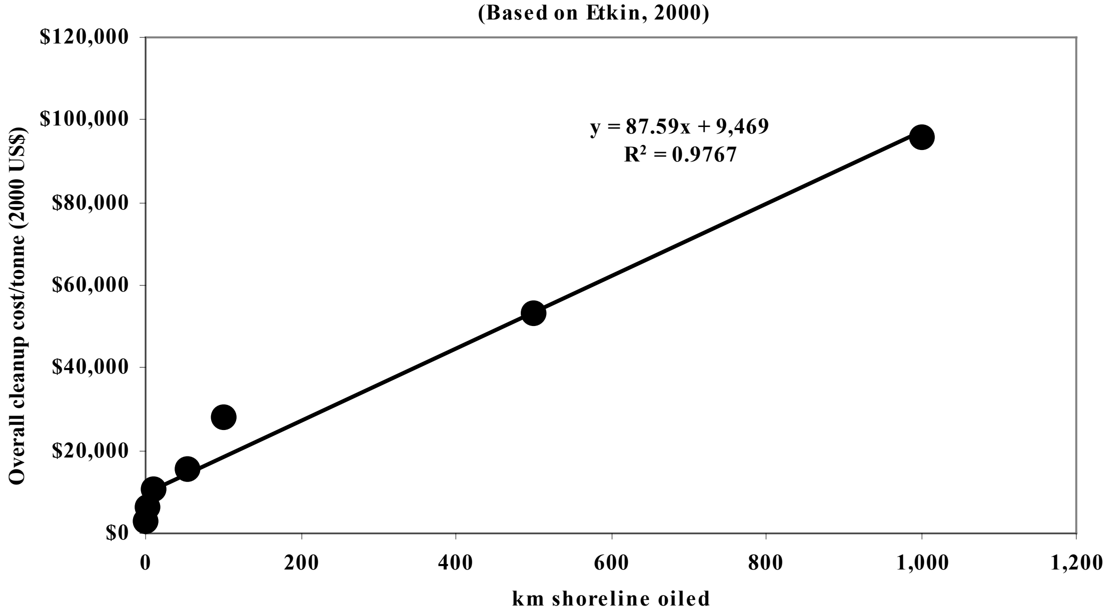

Figure 7: Per-Tonne Shoreline Cleanup Costs By Cleanup Methodology (Based on Purnell 1999)

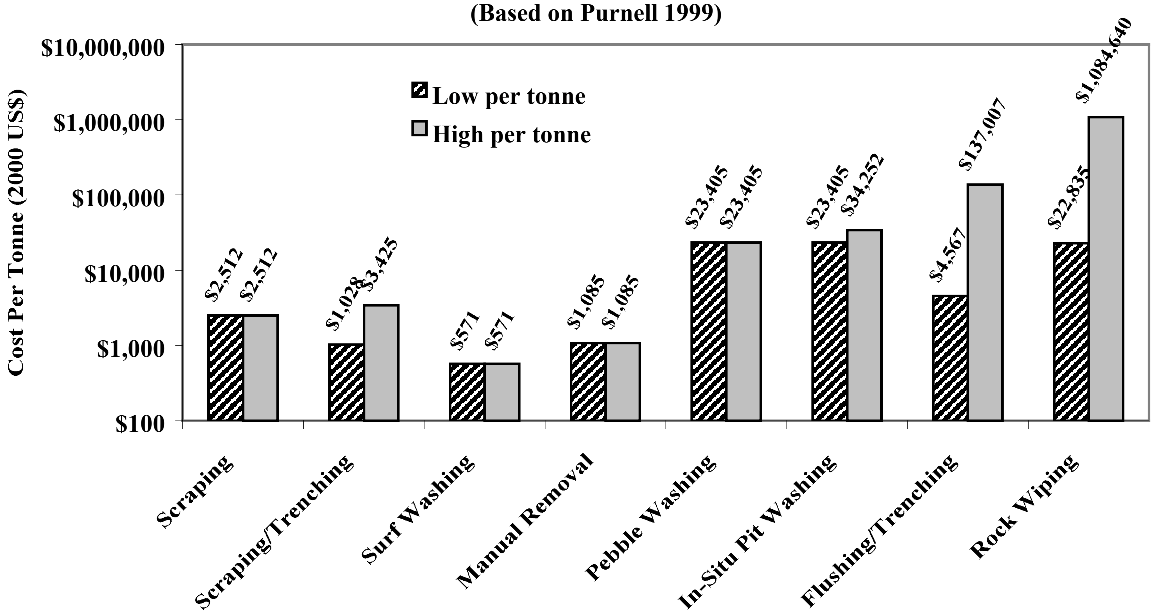

Figure 8: Hypothetical Oil Spill Scenarios		
	Crude Carrier (300,000 DWT)	**Product Carrier (100,000 DWT)**
Maximum[1]	80,000,000 gallons (272,109 tonnes)	25,000,000 gallons (85,034 tonnes)
	40,000,000 gallons (136,054 tonnes)	10,000,000 gallons (34,014 tonnes)
	10,000,000 gallons (34,014 tonnes)	5,000,000 gallons (17,007 tonnes)
	5,000,000 gallons (17,007 tonnes)	1,000,000 gallons (34,000 tonnes)
	500,000 gallons (1,700 tonnes)	500,000 gallons (1,700 tonnes)
	100,000 gallons (340 tonnes)	100,000 gallons (340 tonnes)
Minimum[2]	10,000 gallons (34 tonnes)	10,000 gallons (34 tonnes)

[1]The maximum spill sizes relate to an assumed total loss of cargo from a casualty with either a 300,000 Ton DWT VLCC or a 100,000 Ton DWT product tanker.
[2]The minimum spill sizes are chosen to represent the lower end of typical tank vessel collision or grounding spills that could be reasonably modeled for shoreline impact.

Figure 9: Estimated Shoreline Impact Carquinez Strait, San Francisco Bay Crude Oil Scenarios			
Spill Size	**Shoreline Area[1] (m^2)**	**Amount on Shore[2] (Tonnes)**	**Length[3] (km)**
10,000 gallons (34 tonnes)	660,000	34	66.0
100,000 gallons (340 tonnes)	980,000	340	98.0
500,000 gallons (1,700 tonnes)	104,000	1,700	103.9
5,000,000 gallons (17,000 tonnes)	1,160,000	17,000	116.0
10,000,000 gallons (34,000 tonnes)	1,300,000	34,000	130.0
40,000,000 gallons (136,000 tonnes)	1,440,000	136,000	144.0
80,000,000 gallons (272,100 tonnes)	1,600,000	272,000	160.0
[1]From TAP II model maps assuming 10-meter beach width. [2]From TAP II model. [3]From TAP II model maps.			

Figure 10: Estimated Shoreline Impact Carquinez Strait, San Francisco Bay No. 2 Fuel Oil Scenarios			
Spill Size	**Shoreline Area[1] (m^2)**	**Amount on Shore[2] (Tonnes)**	**Length[3] (km)**
10,000 gallons (34 tonnes)	260,000	34	26
100,000 gallons (340 tonnes)	440,000	340	44
500,000 gallons (1,700 tonnes)	840,000	1,700	84
1,000,000 gallons (3,400 tonnes)	960,000	3,380	96
5,000,000 gallons (17,000tonnes)	1,180,000	16,880	118
10,000,000 gallons (34,000 tonnes)	1,240,000	33,760	124
25,000,000 gallons (85,000 tonnes)	1,340,000	84,400	134
[1]From TAP II model maps assuming 10-meter beach width. [2]From TAP II model. [3]From TAP II model maps.			

Figure 11: Estimated Shoreline Cleanup Costs Based on Oiled Shoreline Area Carquinez Strait, San Francisco Bay Crude Oil Spill Scenarios		
Spill Amount	**Low Cost (2000 US $)**	**High Cost (2000 US $)**
10,000 gallons (34 tonnes)	$48,756,000	$60,944,000
100,000 gallons (340 tonnes)	$72,395,000	$90,493,000
500,000 gallons (1,700 tonnes)	$76,827,000	$96,034,000
5,000,000 gallons (17,007 tonnes)	$88,692,000	$107,114,000
10,000,000 gallons (34,014 tonnes)	$96,034,000	$120,042,000
40,000,000 gallons (136,054 tonnes)	$106,376,000	$132,970,000
80,000,000 gallons (272,109 tonnes)	$118,195,000	$147,744,000
Based on total shoreline areas oiled >100 microns from TAP II models and worker-days per shoreline area derived from Michel and Cotsapas (1997).		

Figure 12: Estimated Shoreline Cleanup Costs Based on Oiled Shoreline Area Carquinez Strait, San Francisco Bay No. 2 Fuel Spill Scenarios		
Spill Amount	**Low Cost (2000 US $)**	**High Cost (2000 US $)**
10,000 gallons (34 tonnes)	$19,207,000	$24,008,000
100,000 gallons (340 tonnes)	$32,504,000	$40,630,000
500,000 gallons (1,700 tonnes)	$62,052,000	$77,566,000
1,000,000 gallons (3,400 tonnes)	$70,917,000	$88,646,000
5,000,000 gallons (17,000tonnes)	$87,169,000	$108,961,000
10,000,000 gallons (34,000 tonnes)	$91,601,000	$114,502,000
25,000,000 gallons (85,000 tonnes)	$98,988,000	$123,736,000
Based on total shoreline areas oiled >100 microns from TAP II models and worker-days per shoreline area derived from Michel and Cotsapas (1997).		

Figure 13: Estimated Shoreline Cleanup Costs Based on Shoreline Lengths Carquinez Strait, San Francisco Bay Crude Oil Spill Scenarios	
Amount of Oil Spilled	**Cost (2000 US $)**
10,000 gallons (34 tonnes)	$8,803,000
100,000 gallons (340 tonnes)	$17,064,000
500,000 gallons (1,700 tonnes)	$18,834,000
5,000,000 gallons (17,000 tonnes)	$22,633,000
10,000,000 gallons (34,000 tonnes)	$27,386,000
40,000,000 gallons (136,000 tonnes)	$32,495,000
80,000,000 gallons (272,000 tonnes)	$38,730,000
Based on shoreline lengths oiled from TAP models maps and Ross formula.	

Figure 14: Estimated Shoreline Cleanup Costs Based on Shoreline Length Carquinez Strait, San Francisco Bay No. 2 Fuel Spill Scenarios	
Amount of Oil Spilled	**Cost (2000 US $)**
10,000 gallons (34 tonnes)	$1,862,000
100,000 gallons (340 tonnes)	$4,485,000
500,000 gallons (1,700 tonnes)	$13,185,000
1,000,000 gallons (3,400 tonnes)	$16,505,000
5,000,000 gallons (17,000 tonnes)	$23,267,000
10,000,000 gallons (34,000 tonnes)	$25,320,000
25,000,000 gallons (85,000 tonnes)	$28,818,000
Based on shoreline lengths oiled from TAP models maps and Ross formula.	

Figure 15: Estimated Shoreline Cleanup Costs Based on Shoreline Amount Shikada (1999) Formula Carquinez Strait, San Francisco Bay Crude Oil Spill Scenarios		
Amount of Oil Spilled	**Low CleanupCost (2000 US$)**	**High CleanupCost (2000 US$)**
10,000 gal. (34 tonnes)	$100,000	$125,000
100,000 gal. (340 tonnes)	$30,499,000	$38,123,000
500,000 gal. (1,700 tonnes)	$166,493,000	$208,117,000
5,000,000 gal. (17,000 tonnes)	$1,697,132,000	$2,121,415,000
10,000,000 gal. (34,000 tonnes)	$3,397,764,000	$4,247,205,000
40,000,000 gal. (136,000 tonnes)	$13,601,396,000	$17,001,745,000
80,000,000 gal. (272,000 tonnes)	$27,206,312,000	$34,007,890,000
Estimates based on total amount of oil on shoreline as estimated by TAP model and worker-day estimations of Shikada (1999) and $1,200-$1,500 worker-days.		

Figure 16: Estimated Shoreline Cleanup Costs Based on Shoreline Amount Shikada (1999) Formula Carquinez Strait, San Francisco Bay No. 2 Fuel Spill Scenarios		
Amount of Oil Spilled	**Low CleanupCost (2000 US$)**	**High CleanupCost (2000 US$)**
10,000 gal. (34 tonnes)	$100,000	$125,000
100,000 gal. (340 tonnes)	$30,499,000	$38,123,000
500,000 gal. (1,700 tonnes)	$165,293,000	$206,617,000
1,000,000 gal. (3,400 tonnes)	$334,087,000	$417,608,000
5,000,000 gal. (17,000 tonnes)	$1,684,333,000	$2,105,416,000
10,000,000 gal. (34,000 tonnes)	$3,372,265,000	$4,215,331,000
25,000,000 gal. (85,000 tonnes)	$8,433,063,000	$10,541,331,000
Estimates based on total amount of oil on shoreline as estimated by TAP model and worker-day estimations of Shikada (1999) and $1,200-$1,500 worker-days.		

Figure 17: Estimated Shoreline Cleanup Costs Based on Shoreline Amount and Historical Cost Data San Francisco Bay Crude Oil Spill Scenarios		
Amount of Oil Spilled	**Low Cost (2000 US $)**	**High Cost (2000 US $)**
10,000 gal. (34 tonnes)	$287,000	$3,283,000
100,000 gal. (340 tonnes)	$2,873,000	$32,832,000
500,000 gal. (1,700 tonnes)	$14,364,000	$164,160,000
5,000,000 gal. (17,000 tonnes)	$143,640,000	$1,641,600,000
10,000,000 gal. (34,000 tonnes)	$287,280,000	$3,283,200,000
40,000,000 gal. (136,000 tonnes)	$1,149,120,000	$13,132,800,000
80,000,000 gal. (272,000 tonnes)	$2,298,240,000	$26,265,600,000
Estimates based on total oil on shoreline as estimated by TAP model and high and low per-tonne estimates in historical data ($8,446/tonne - $96,526/tonne).		

Figure 18: Estimated Shoreline Cleanup Costs Based on Amount of Oil on Shoreline and Historical Cost Data San Francisco Bay No. 2 Fuel Spill Scenarios		
Amount of Oil Spilled	**Low Cost (2000 US $)**	**High Cost (2000 US $)**
10,000 gal. (34 tonnes)	$285,000	$3,259,000
100,000 gal. (340 tonnes)	$2,871,000	$32,807,000
500,000 gal. (1,700 tonnes)	$14,256,000	$162,929,000
1,000,000 gal. (3,400 tonnes)	$28,513,000	$325,858,000
5,000,000 gal. (17,000 tonnes)	$142,563,000	$1,629,288,000
10,000,000 gal. (34,000 tonnes)	$285,125,000	$3,258,576,000
25,000,000 gal. (85,000 tonnes)	$712,814,000	$8,146,440,000
Estimates based on total oil on shoreline as estimated by TAP model and high and low per-tonne estimates in historical data ($8,446/tonne - $96,526/tonne).		

Fig. 19: Estimated Shoreline Cleanup Costs Based on Historical Data Model Carquinez Strait, San Francisco Bay Crude Oil Spill Scenarios		
Amount of Oil Spilled	**Low Cost (2000 US $)**	**High Cost (2000 US $)**
10,000 gal. (34 tonnes)	$311,000	$467,000
100,000 gal. (340 tonnes)	$3,684,000	$5,526,000
500,000 gal. (1,700 tonnes)	$18,952,000	$28,427,000
5,000,000 gal. (17,000 tonnes)	$200,301,000	$300,452,000
10,000,000 gal. (34,000 tonnes)	$425,624,000	$638,437,000
40,000,000 gal. (136,000 tonnes)	$1,802,585,000	$2,703,878,000
80,000,000 gal. (272,000 tonnes)	$3,832,956,000	$5,749,434,000
Estimates based on amount spilled, and low and high per-tonne cleanup costs based on Etkin (2000) model of per-tonne cleanup costs relative to shoreline length oiled.		

Figure 20: Estimated Shoreline Cleanup Costs Based on Historical Data Model Carquinez Strait, San Francisco Bay No. 2 Fuel Spill Scenarios		
Amount of Oil Spilled	**Low Cost (2000 US $)**	**High Cost (2000 US $)**
10,000 gal. (34 tonnes)	$240,000	$360,000
100,000 gal. (340 tonnes)	$2,720,000	$4,081,000
500,000 gal. (1,700 tonnes)	$17,168,000	$25,753,000
1,000,000 gal. (3,400 tonnes)	$36,494,000	$54,741,000
5,000,000 gal. (17,007 tonnes)	$202,027,000	$303,040,000
10,000,000 gal. (34,014 tonnes)	$414,983,000	$622,474,000
25,000,000 gal. (85,035 tonnes)	$1,082,036,000	$1,623,055,000
Estimates based on amount spilled, and low and high per-tonne cleanup costs based on Etkin (2000) model of per-tonne cleanup costs relative to shoreline length oiled.		

Figure 21: Estimated Total Shoreline Cleanup Costs San Francisco Bay Crude Oil Scenarios

Spill Size	Total Cost Estimates (2000 US $)				
	Based on Oiled Shoreline Area	Based on Oiled Shoreline Lengths	Based on Onshore Oil and Shikada (1999) Formula	Based on Onshore Oil and Historical Data	Based on Historical Data Model (Etkin 2000)
34 tonnes	L $48,756,000 H $60,944,000	$8,803,000	L $100,000 H $125,000	L $287,280 H $3,283,200	L $311,000 H $467,000
340 tonnes	L $72,395,000 H $90,493,000	$17,064,000	L $30,499,000 H $38,123,000	L $2,872,800 H $32,832,000	L $3,684,000 H $5,526,000
1,700 tonnes	L $76,827,000 H $96,034,000	$18,834,000	L $166,493,000 H $208,117,000	L $14,364,000 H $164,160,000	L $18,952,000 H $28,427,000
17,000 tonnes	L $88,692,000 H $107,114,000	$22,633,000	L $1,697,132,000 H $2,121,415,000	L $143,640,000 H $1,641,600,000	L $200,301,000 H $300,452,000
34,000 tonnes	L $96,034,000 H $129,942,000	$27,386,000	L $3,397,764,000 H $4,247,205,000	L $287,280,000 H $3,283,200,000	L $425,624,000 H $638,437,000
136,000 tonnes	L $106,376,000 H $132,970,000	$32,495,000	L $13,601,396,000 H $17,001,745,000	L $1,149,120,000 H $13,132,800,000	L $1,802,585,000 H $2,703,878,000
272,000 tonnes	L $118,195,000 H $147,744,000	$38,730,000	L $27,206,312,000 H $34,007,890,000	L $2,298,240,000 H $26,265,600,000	L $3,832,956,000 H $5,749,434,000

Figure 22: Estimated Total Shoreline Cleanup Costs San Francisco Bay No. 2 Fuel Oil Scenarios

Spill Size	Total Cost Estimates (2000 US $)				
	Based on Oiled Shoreline Area	**Based on Oiled Shoreline Lengths**	**Based on Onshore Oil and Shikada (1999) Formula**	**Based on Onshore Oil and Historical Data**	**Based on Historical Data Model (Etkin 2000)**
34 tonnes	L $19,207,000 H $24,008,000	$1,862,000	L $100,000 H $125,000	L $285,000 H $3,259,000	L $240,000 H $360,000
340 tonnes	L $32,504,000 H $40,630,000	$4,485,000	L $30,499,000 H $38,123,000	L $2,871,000 H $32,807,000	L $2,720,000 H $4,081,000
1,700 tonnes	L $62,052,000 H $77,566,000	$13,185,000	L $165,293,000 H $206,617,000	L $14,256,000 H $162,929,000	L $17,168,000 H $25,753,000
17,000 tonnes	L $70,917,000 H $88,646,000	$16,505,000	L $334,087,000 H $417,608,000	L $28,512,000 H $325,858,000	L $36,494,000 H $54,741,000
34,000 tonnes	L $87,169,000 H $108,961,000	$23,267,000	L $1,684,333,000 H $2,105,416,000	L $142,563,000 H $1,629,288,000	L $202,027,000 H $303,040,000
136,000 tonnes	L $91,601,000 H $114,502,000	$25,320,000	L $3,372,265,000 H $4,215,331,000	L $285,125,000 H $3,258,576,000	L $414,983,000 H $622,474,000
272,000 tonnes	L $98,988,000 H $123,736,000	$28,818,000	L $8,433,063,000 H $10,541,331,000	L $712,814,000 H $8,146,440,000	L $1,082,036,000 H $1,623,055,000