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RISK ANALYSIS AND PREVENTION

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1.1 INTRODUCTION

Understanding oil spill risk is at the heart of the entire study of oil spills because it encompasses both the likelihood of spills occurring and the nature of those spills, as well as the complex factors that determine the fate and effects of oil in the environments into which it spills. Risk mitigation—reducing risk—is the purpose of spill prevention measures and spill response. Studies of oil behavior, toxicity, ecosystem effects, and organism impacts are related to the consequences side of risk. Studies of spill rates, causes, and prevention strategies are related to the probability side of risk.

1.2 EXECUTIVE SUMMARY

Risk is the probability that an event will occur multiplied by consequences of the event. With regard to oil spills, risk is a combination of the probability that a spill will occur and the consequences or impacts of that spill. Because oil spills can have such different environmental and socioeconomic impacts based on the specific circumstances of each incident, it is important to consider the *type* of spill event that occurs with regard to oil type, volume, source, location, and season and the *impacts* that that kind of spill is likely to have in a given location and season based on the spillage volume and type of oil.

Spill risk analysis involves studying both the probability of occurrence and the impacts that may occur. Event tree analysis or fault tree analysis (FTA) is often used to evaluate the sequences of events that contribute to a spill occurring. In the event that a spill does occur, the spill volume, oil type, geographic location, resources at risk, and spill response effectiveness will determine the degree of impact. State-of-the-art modeling techniques and qualitative evaluations on impacts incorporating knowledge about oil behavior, toxicity, persistence, and adherence along with knowledge on the sensitivities of species, habitats, and shoreline types can provide data on the consequences side of the risk equation. Socioeconomic impacts and the cost of spill response should also be factored into any analysis.

There are many practical applications for spill risk assessments, including contingency planning for response and preparedness, protection of sensitive resources, risk allocation for insurance or taxation, response trade-off evaluation, cost–benefit analyses of oil exploration, production, storage, or transport; developing spill prevention measures; and evaluating alternative courses of action for oil exploration, production, storage, or transport. A scientifically

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based risk assessment removes much of the subjectivity in the process.

Evaluating and developing spill prevention measures is arguably the most important application of risk assessments. With significant reductions in spill rates over the last two decades, there have clearly been positive effects of spill prevention programs and measures, such as double hulls on tankers and legislation such as the Oil Pollution Act of 1990 (OPA 90). A greater appreciation and understanding of the consequences of spills, including environmental and socioeconomic impacts and costs, has also contributed immensely to regulatory and voluntary changes that have led to the reduction of spills despite increased usage of oil.

1.3 OIL SPILL RISK ANALYSIS

While “zero risk” of oil spills is apparently the aspiration of the majority of the general public, the concept is nearly an oxymoron. The complete elimination of oil spills is a laudable goal but near impossibility, at least with current practices and available technologies.

The complete elimination or mitigation of oil spill impacts is also a near impossibility given the facts of oil behavior and the challenges of spill response. Despite arduous efforts and favorable circumstances during the response to a spill, there is still bound to be some degree of impact from a spill.

But between “zero risk” and “extreme risk,” there is a broad spectrum that needs to be carefully assessed to develop reasonable and effective spill prevention, preparedness, and response programs and strategies. “Oil spill risk analysis” encompasses the study of all of the factors that affect risk in terms of both probability and consequences. Such analyses allow policy makers to determine the best ways to assign resources to prevention measures to have the greatest effect on reducing spillage, identify the most sensitive resources at risk, and invest in the most effect ways to mitigate spill impacts.

1.3.1 Defining “Oil Spill Risk”

Colloquial usage of the term “risk” often implies only the chance or likelihood that an event will occur, but this is not its complete technical meaning. By its classical definition, “risk” is the probability that an event will occur multiplied by the consequences of that event:

$$\text{Risk}_{\text{event a}} = \text{Probability}_{\text{event a}} \times \text{Consequences}_{\text{event a}}$$

There can be low-probability or exceedingly rare events that have high consequences (e.g., a meteor hitting the earth), as there can be high-probability or very common events that have very low consequences (e.g., spilling a glass of water), as well as all sorts of probabilities and consequences on that spectrum. Often, risk is characterized in a risk matrix, as shown in Figure 1.1. The red-shaded box (high probability–high impact) represents the greatest risk in this highly simplified risk matrix. The orange, yellow, light-green, and dark-green boxes indicate increasingly lower risk.

With regard to oil spills, risk is a combination of the probability that a spill will occur and the consequences or impacts of that spill. Because oil spills can have such different environmental and socioeconomic impacts based on the specific circumstances of each incident, it is important to consider the *type* of spill event that occurs with regard to oil type, volume, source, location, and season and the *impacts* that that kind of spill is likely to have in a given location and season based on the spillage volume and type of oil.

The circumstances of a spill—the source of the spill (e.g., tank ship, pipeline, or tanker truck), the cause of the spill (e.g., vessel collision or pipeline corrosion), the oil type involved (e.g., crude oil or diesel fuel), the amount spilled, location of the spill (political regime, habitat type, and geography), and the season in which the spill occurs (e.g., weather, bird migrations and nesting, tourism, and commercial

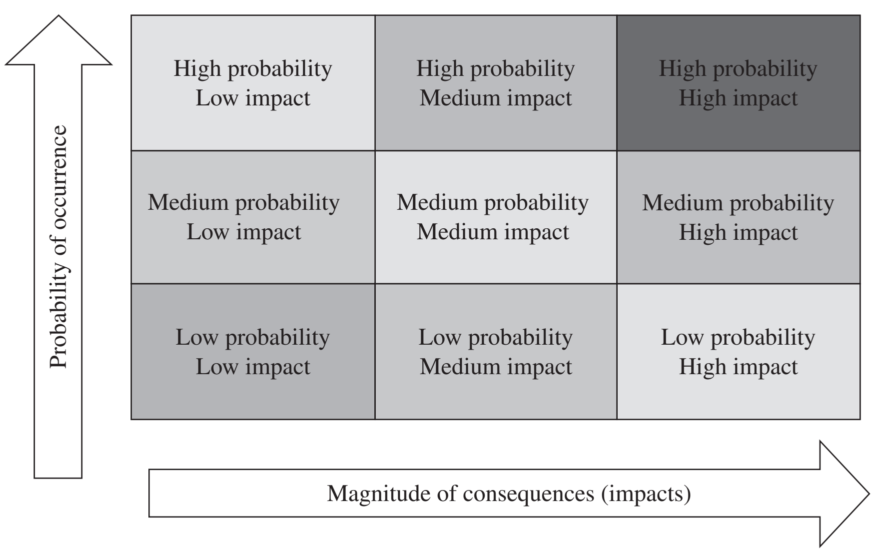

FIGURE 1.1 Basic risk matrix.

fishing)—are all to some extent interrelated with regard to spill scenario probability and all have an effect on the impacts. The source of the spill can be the determinant of the oil type spilled. For example, a tanker truck is much more likely to carry a load of diesel fuel or gasoline than crude oil.

The source also dictates the amount of oil spilled in that the cargo or carrying capacity of the source determines the maximum that can be spilled. A large tank ship might spill as much as 270,000 tonnes of oil, whereas a tank barge will carry a much smaller load, perhaps a maximum of 6500 tonnes. A cargo vessel's bunker capacity is also determined by its size and type. The amount of oil that will spill from a pipeline is determined by the pipeline diameter, the length between shutoff controls, and the pressure of flow. The cause of the spill will also have a determining effect on the spill volume. A vessel grounding or collision has the potential for causing a much larger spill than might be expected from operator error during a fuel transfer operation. A pipeline rupture and explosion will cause a much larger release than a pinhole-sized hole caused by corrosion. The source type will also to some extent limit the type of location. For example, a large tank ship will not have a spill in a small inland river because it cannot travel in such waters. A tanker truck will not have a spill in offshore marine waters.

1.3.2 Factors That Determine the Probability of Spill Occurrence

The probability of occurrence of a particular spill scenario depends on a large number of factors: source type, cause, location, and season or other measure of timing. There may be a number of serial probabilities at play in determining the likelihood of a particular type of incident. An example analysis of factors involved in determining the likelihood of tanker spills due to grounding and collisions follows.

1.3.2.1 Probability Event Trees from Historical Data and Engineering Studies A common way to represent a series of probabilities is as an "event tree." An example is shown for tankers in Figure 1.2. Probabilities for the event tree are shown in Table 1.1. Calculated probabilities for spills from large-sized double-hulled tankers are shown in Table 1.2 and from the same-sized tanker with a single hull in Table 1.3. A comparison between the single-hulled and double-hulled tanker for the probabilities of spillage with accidents is shown in Table 1.4. A side-impact collision involving a single-hulled large tanker is 3.4 times more likely to result in a spill than one involving a double-hulled tanker. Likewise, side- and bottom-impact collision or a hard grounding is 4.4 and 5.1 times more likely to result in spillage, respectively.

These probabilities apply to an individual tanker operating for a year. To determine the probability of each type of spill occurring in a particular location or for a particular tanker fleet, it is necessary to multiply these probabilities with the number of vessels involved. There are different probabilities associated with each accident type and vessel type and size. For the tanker incidents, the probabilities of accidents and spillage were determined by examining historical data [1], as well as naval engineering studies of impacts and oil outflow [2,3].

1.3.2.2 Analysis of Other Data to Determine Probabilities: Weather and Seismic Data For predicting spill probabilities for hypothetical situations for which there are no

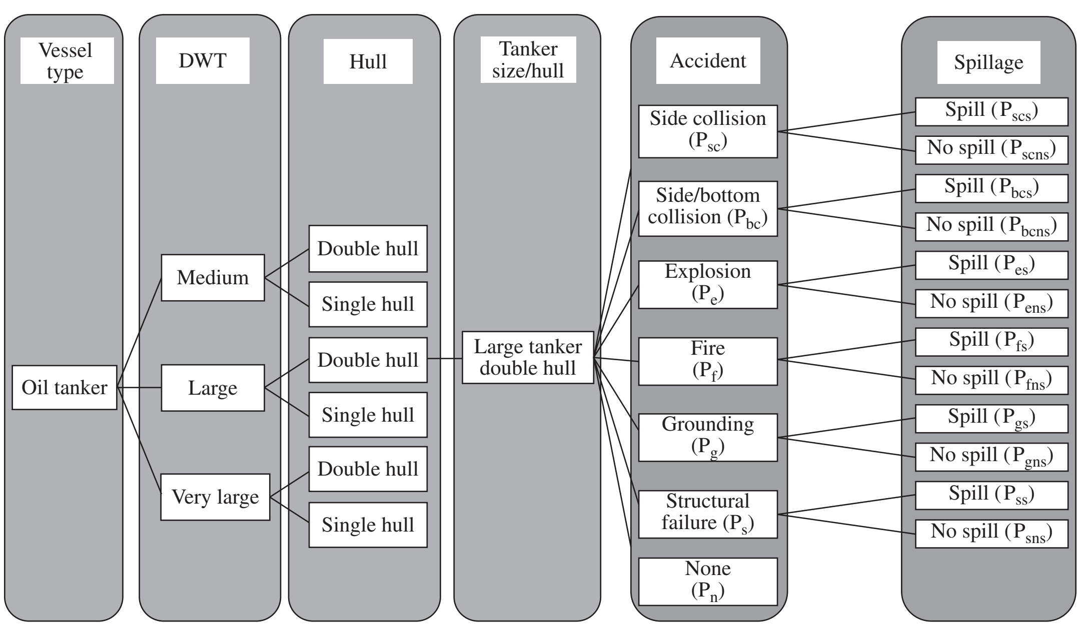

FIGURE 1.2 Event tree for tanker spills.

TABLE 1.1 Event tree probabilities for tanker spills

	Probability by tanker size and hull[a]						
	Medium[b]		Large[c]		Very large[d]		
Event	Single hull	Double hull	Single hull	Double hull	Single hull	Double hull	Source
Accident[e]	2.0E-02		2.0E-02		2.0E-02		[37]
No accident	9.8E-01		9.8E-01		9.8E-01		
Side collision	2.4E-05		4.5E-05		4.5E-05		[2,37]
Spill	6.8E-01	1.5E-01	6.5E-01	1.9E-01	8.1E-01	1.9E-01	[16]
No spill	3.2E-01	8.5E-01	3.2E-01	8.5E-01	1.9E-01	8.1E-01	
S/B collision[f]	5.7E-05		1.1E-04		1.1E-04		[2,37]
Spill	8.1E-01	1.7E-01	7.9E-01	1.8E-01	8.8E-01	2.0E-01	[3]
No spill	1.9E-01	8.3E-01	2.1E-01	8.2E-01	1.2E-01	8.0E-01	
Explosion	2.4E-04		2.3E-04		2.3E-04		[37]
Spill	4.0E-01	4.0E-01	4.0E-01	4.0E-01	4.0E-01	4.0E-01	[5]
No spill	6.0E-01	6.0E-01	6.0E-01	6.0E-01	6.0E-01	6.0E-01	
Fire	1.6E-04		2.3E-04		2.3E-04		[37]
Spill	4.0E-01	4.0E-01	4.0E-01	4.0E-01	4.0E-01	4.0E-01	[5]
No spill	6.0E-01	6.0E-01	6.0E-01	6.0E-01	6.0E-01	6.0E-01	
Grounding[g]	1.6E-04		1.1E-04		1.1E-04		[37]
Spill	9.1E-01	1.8E-01	9.2E-01	1.8E-01	9.3E-01	2.0E-01	[3]
No spill	9.0E-02	7.2E-01	8.0E-02	7.2E-01	7.0E-02	8.0E-01	
Structural failure	2.0E-04		1.5E-04		1.5E-04		[37]
Spill	4.0E-01	4.0E-01	4.0E-01	4.0E-01	4.0E-01	4.0E-01	[5]
No spill	6.0E-01	6.0E-01	6.0E-01	6.0E-01	6.0E-01	6.0E-01	

[a]Probability per tanker year of operation for accident rates. Spillage rates per accident based on probability of spillage given incident.
[b]Handysize (20,000–34,999DWT) and Handymax (35,000–60,000 DWT).
[c]Panamax (60,000–79,999 DWT); Aframax (80,000–119,999 DWT).
[d]Very large crude carriers: 200,000–319,999 DWT; ultra-large crude carriers greater than 320,000 DWT.
[e]Per vessel trip.
[f]Side and bottom impact in collision.
[g]Assumes hard grounding rather than soft-bottom grounding.

TABLE 1.2 Probabilities of spillage for accidents of large-sized double-hull tanker

	Probability (per tanker year)		
Accident event	Accident	Spill	Accident × spill
Collision with side impact	4.50E-05	1.90E-01	8.55E-06
Collision with side/bottom impact	1.05E-04	1.80E-01	1.89E-05
Explosion	2.30E-04	4.00E-01	9.20E-05
Fire	2.30E-04	4.00E-01	9.20E-05
Hard grounding	1.10E-04	1.80E-01	1.98E-05
Structural failure (non-accident)	1.50E-04	4.00E-01	6.00E-05

Probability per tanker year of operation for accident rates.

TABLE 1.3 Probabilities of spillage for accidents of large-sized single-hull tanker

	Probability (per tanker year)		
Accident event	Accident	Spill	Accident + spill
Collision with side impact	4.50E-05	6.50E-01	2.93E-05
Collision with side/bottom impact	1.05E-04	7.90E-01	8.30E-05
Explosion	2.30E-04	4.00E-01	9.20E-05
Fire	2.30E-04	4.00E-01	9.20E-05
Hard grounding	1.10E-04	9.20E-01	1.01E-04
Structural failure (non-accident)	1.50E-04	4.00E-01	6.00E-05

reliable historical spill or accident data, other approaches may be required. For example, for determining the probability of a weather event of a certain magnitude that might

TABLE 1.4 Comparison of spillage in large-sized single- vs. double-hull tanker

	Probability of spill (per tanker year)		
Accident event	Single hull (SH)	Double hull (DH)	P(SH)/P(DH)
Collision side impact	2.93E-05	8.55E-06	3.4
Collision side/ bottom impact	8.30E-05	1.89E-05	4.4
Explosion	9.20E-05	9.20E-05	1.0
Fire	9.20E-05	9.20E-05	1.0
Hard grounding	1.01E-04	1.98E-05	5.1
Structural failure (non-accident)	6.00E-05	6.00E-05	1.0

cause spillage based on engineering studies, historical weather data can be applied.

Table 1.5 gives an example of hurricane data that were applied to determine the likelihood of the toppling of an oil-containing offshore wind turbine generator (WTG) to cause spillage. The analysis indicates that in the last 154 years, there have been 10 hurricanes that have impacted Massachusetts. Five were Category 1 hurricanes on the Saffir–Simpson Hurricane Scale, two were Category 2, and three were Category 3. There have been no Category 4 or 5 hurricanes in Massachusetts in 154 years. Over the next 30 years, there are likely to be two hurricanes that impact the waters of Massachusetts, potentially including Nantucket Sound (wind farm location). If a hurricane did occur, there is a 46% chance that it would be Category 1, 19% chance that it would be Category 2, and 27% chance that there would be a major hurricane of Category 3. It was concluded that it would be extremely unlikely (0.2 hurricanes) with the damage potential (Category 4 or greater) to topple a WTG in 30 years.

Another potential cause of spillage with the WTGs might be due to seismic activity. Between 1990 and 2001, there were 284 earthquakes recorded in the northeastern United States and eastern Canada. The distribution of magnitudes is shown in Figure 1.3. Nearly 94% of the earthquakes had magnitudes below 3.5, which are generally inconsequential for structural damage. There were three events of 4.7–4.8 magnitude. These earthquakes caused little damage. The probability that there would be an earthquake of at least 4.75 magnitude in the immediate area or within 50 km of the project is 0.002 in 5 years, 0.003 in 10 years, and 0.015 in 30 years. The probability of a major earthquake of 7.0 or greater is less than 0.001 in 30 years, based on U.S. Geological Survey earthquake probability models.

Tsunamis occur with undersea earthquakes of at least 7.5 (Richter scale). The recent massively destructive tsunami in Southern Asia followed a 10.0 earthquake. Tsunamis are most common in the Pacific Ocean, but have occurred in the North Atlantic, including one that followed the 1775 Lisbon earthquake. This tsunami was seven meters high in the Caribbean Sea. The probability that there would be an earthquake severe enough to cause a tsunami in Nantucket Sound over the course of 30 years is, for all practical purposes, zero. Tsunamis also rarely occur after extraterrestrial collisions from asteroids or meteors or as a result of massive underwater landslides, which are often related to or caused by earthquakes. The probability of this occurring in Nantucket Sound or near enough to impact coastal waters (CW) in 30 years is also exceedingly small [4].

1.3.2.3 Fault Tree Analysis FTA is another frequently applied technique to determine the probability of a spill occurring under various circumstances. FTA for spills involves analyzing sequences of events that may (or may not) lead up to a system failure (in this case a spill) and

TABLE 1.5 Potential hurricanes in Massachusetts

Hurricane category Saffir–Simpson scale	Winds (km/h)	Annual probability	Potential hurricanes in time period			
			1 year	5 years	10 years	30 years
Category 1	119–153	0.032	0.032	0.162	0.325	0.974
Category 2	154–177	0.013	0.013	0.065	0.130	0.390
Category 3	178–209	0.019	0.019	0.097	0.195	0.584
Category 4	210–249	0.006	0.006	0.032	0.065	0.195
All categories	—	0.070	0.070	0.356	0.715	2.143

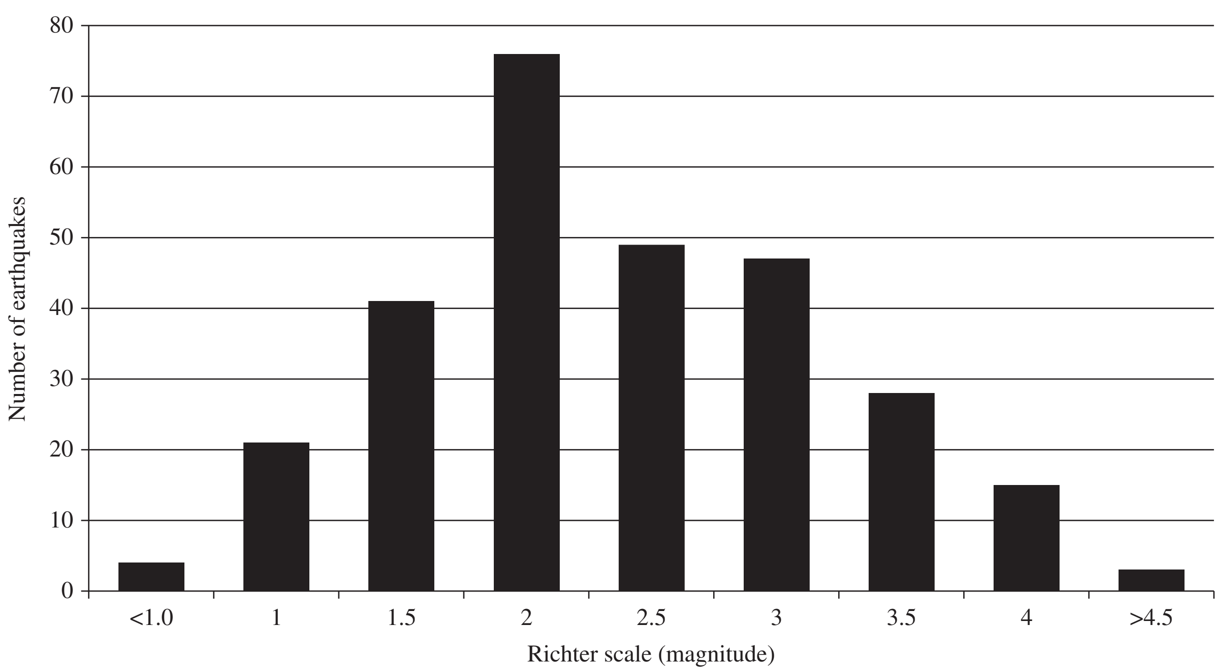

FIGURE 1.3 Number of earthquakes in Eastern US 1990–2001 [13,23]. Lamont Doherty Seismic Network, Columbia University, New York, NY.

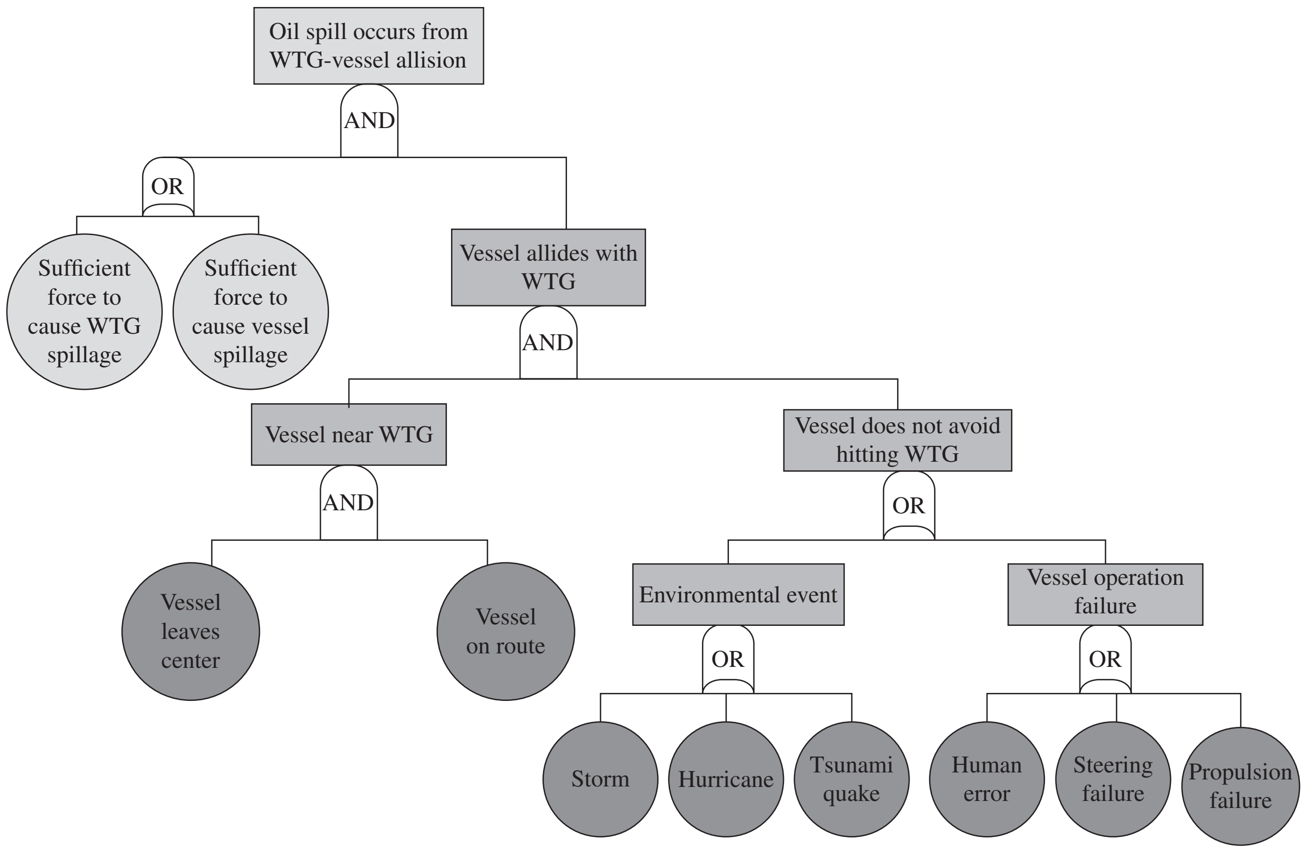

FIGURE 1.4 Fault tree diagram for vessel-WTG Allision analysis [13,23].

TABLE 1.6 Probability of occurrence per vessel trip applied to fault tree analysis [5]

	Fault tree basic events per vessel trip							
	Wind turbine generator vicinity		Environmental event			Vessel failure		
Vessel type	Vessel deviation from course	Vessel in route	Storm	Hurricane	Earthquake Tsunami	Human error	Steering failure	Propulsion failure
A	0.028	1.0	0	0.004731	0.000003	0.00034	0	0
B	0.028	1.0	0	0.000114	0	0.00032	0	0
C	0.028	1.0	0	0.000437	0	0.00032	0	0
D	0.028	1.0	0	0.000038	0	0.00032	0	0
E	0.028	1.0	0	0	0.000017	0.00031	0.00002	0.00003
F	0.042	1.0	0	0	0.000022	0.00047	0.00002	0.00002
G	0.042	1.0	0.0004	0	0.000034	0.00047	0.00002	0.00002
H	0.042	1.0	0.0007	0	0.000020	0.00069	0.00003	0.00003
I	0.042	1.0	0	0.000798	0	0.00044	0.00002	0.00002

A, cruise/dry cargo ships; B, tankers; C, tow/tugboats; D, tank barge; E, ferries; F, commercial fishing vessels; G, charter fishing vessels; H, touring vessels; I, dry cargo barge.

assigning probabilities to each event. Figure 1.4 shows a "fault tree diagram" for an analysis of vessel allisions with WTGs at the wind farm.

Each event (circle) has a probability associated with it (Table 1.6). The blue portions deal with the probability of an allision (i.e., impact of a moving object on a stationary object). The green parts relate to the probability of an oil spill resulting from the allision. The logic behind this diagram is that an oil spill would occur from a WTG allision only if a vessel allides with the WTG and there is sufficient force to cause spillage from either the vessel or the WTG. The probability of an allision depends on the vessel being in the vicinity of a WTG (WTGs are located proximal to the shipping lane) and the vessel not avoiding hitting the WTG because of an environmental event or a vessel operation failure. The environmental event and vessel failure scenarios each depend on at least one of three things happening. The probabilities of each independent event are multiplied together to get the probabilities of the sets of circumstances that would lead to a spill. This type of analysis can be applied to a large variety of spill circumstances in which there is some knowledge of the probabilities of occurrence of the relevant sub-events.

The value of conducting a comprehensive location- or situation-specific spill probability analysis for contingency planning and risk management is that it provides an evaluation of the range of possible spill scenarios and the probabilities that they will occur. This will allow for appropriate measures to be taken to address spills that occur, focusing on preparation for spills with the highest likelihood for first-tier responses but also allowing for more complex responses for more rare, but potentially more consequential, spills. The next part of the risk analysis involves analyzing impacts of the various spill scenarios to better determine the complete *risk* (probability × impacts) of each type of spill scenario to focus particular attention on the highest risk (high probability/high impact) spills for prevention measures and for response planning, recognizing that sometimes smaller spills can cause higher impacts than larger ones if they are in an inopportune location.

Each spill risk analysis requires consideration of the best customized approach to analyzing the probability of spillage, as well as the distributions of spill volumes and scenarios that might occur. Careful consideration needs to be given to the purpose of the analysis, the degree of risk "tolerance" for the end-user, and the specific ways in which spills might conceivably occur based on the location, potential sources, and time frame.

1.3.3 Probability Distributions of Spill Volume

Determining the probability of a spill occurring is only the first step in assessing risk. The next step is to determine the nature of the spill, including the volume of spillage. Thus, for the tanker spills described earlier, the probabilities only indicate the likelihood of a spill occurring. These probabilities do not indicate whether these are large spills or very small spills.

Each spill that occurs will have a certain volume. This spillage volume is dependent on a number of factors: source size (oil capacity), source condition (e.g., corrosion and engineering), incident cause, and nature of spill cause (e.g., force of impact, and effectiveness and speed of source control, among others).

There is a probability associated with each spill volume, that is, the likelihood that the spill that occurs will be in this volume or volume range. In general, there is a much higher probability of a small spill than a very large spill, as in Figure 1.5 and Table 1.7, which shows an analysis of nearly 75,000 spills in U.S. waters over the course of the 10-year period 1990–1999.

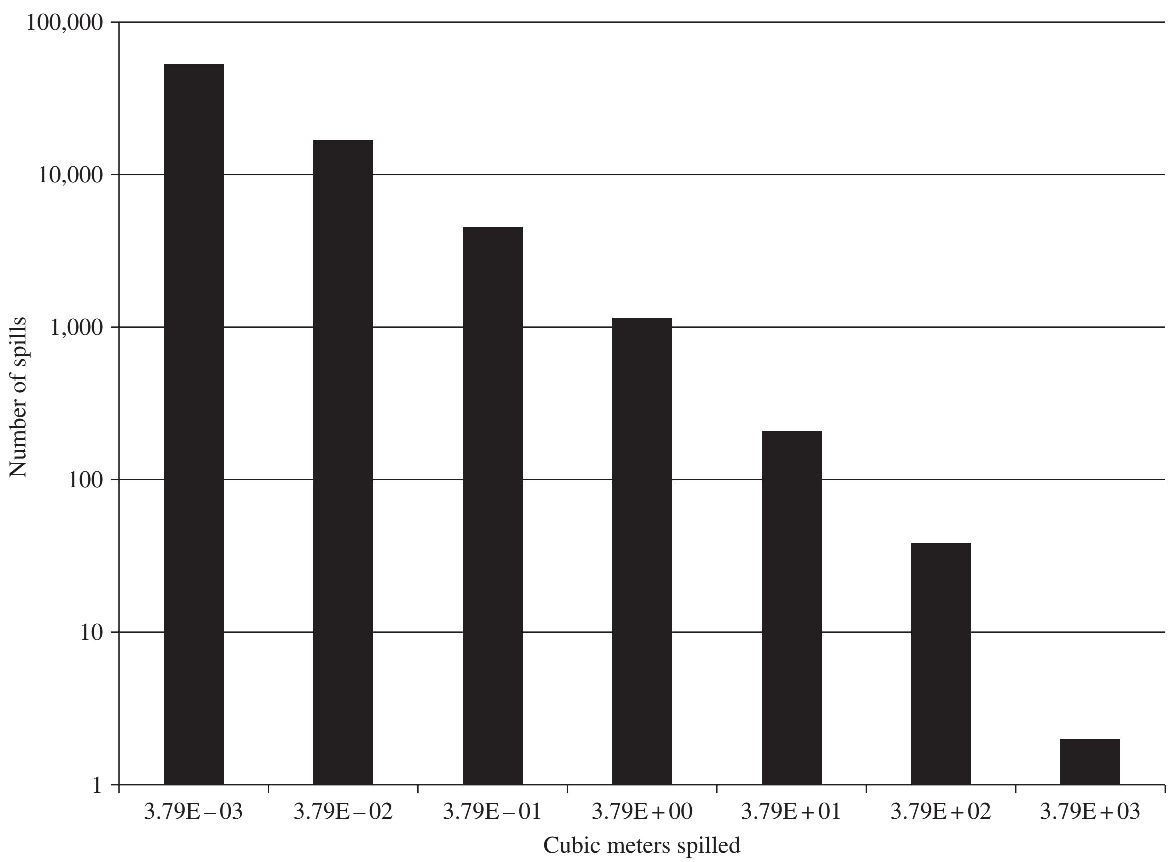

FIGURE 1.5 Oil spills in US waters (1990–1999) (Source: ERC).

1.3.3.1 Probability Distribution Functions The range of spill volume probabilities is often analyzed and presented as a probability distribution function (PDF). A PDF shows the cumulative percentages of spill volumes and the percentile of each spill volume. The *n*th percentile spill is that spill volume larger than *n*% of spills for that source and type and is smaller than 100 – *n*% of spills. For example, the 90th percentile spill is larger than 90% of spills and only smaller than 10% of spills. These percentages can be used as probabilities for determining the likelihood of a spill being a particular volume when an incident occurs.

The PDF for spill volumes will vary by source type, cause, and other factors. An example of a PDF showing the 90th percentile spills for tanker spills caused by impact accidents (collisions, allisions, and groundings) and non-accident structural failures is shown in Figure 1.6 and Table 1.8.

TABLE 1.7 Oil spills in U.S. marine waters (1990–1999) by volume

Spill volume (m^3)	Number of spills	Percent total incidents (%)	Cumulative percentage (%)
0.0038	52,378	69.945	69.945
0.038	16,626	22.202	92.147
0.38	4,491	5.997	98.144
3.8	1,142	1.525	99.669
38.0	208	0.278	99.947
380	38	0.051	99.997
3,800	2	0.003	100.000

Combining the probability of an accident occurring with the probabilities of spill volumes associated with the type of volume for the hypothetical double- or single-hulled tanker results in the probabilities for a large spill (38,000 m^3 or about the volume of the 1989 Exxon Valdez tanker spill), as shown in Tables 1.9 and 1.10.

For a particular large double-hulled tanker, there is thus a 1.07×10^{-5} probability that there will be a large spill of 38,000 m^3 due to any cause. For a single-hulled large tanker, that probability is 1.67×10^{-5}. Based on these data, there is a 36% reduction in probability with the double hull.

1.3.3.2 Incorporating Potential Spillage into Risk Analysis Analyses of historical data on spills provide a synopsis of what actually happened in the past but do not necessarily provide an accurate picture of what could happen in the future. For contingency planning purposes, potential spillage, especially with respect to worst-case discharges (WCDs), often needs to be evaluated. The theoretical WCD from a source is the total release of all of the oil content of the source (e.g., all of the oil in a fully loaded tanker or storage tank). Obviously, the volume of spillage for the WCD will depend on the carrying capacity of the source.

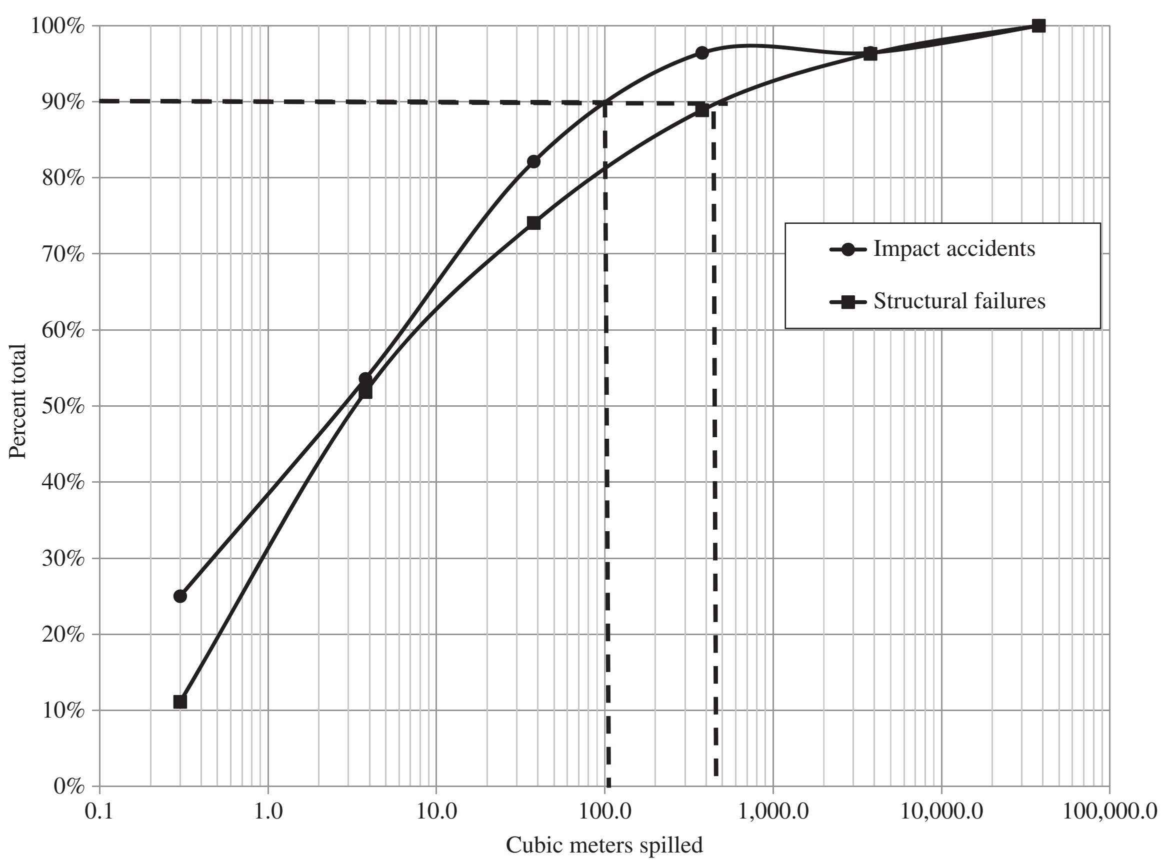

FIGURE 1.6 Probability distribution function of US tanker spills.

In each spill incident, there is the potential for all of the oil to be released from the source up to its total carrying capacity. An analysis of potential spillage for U.S. tanker spills is shown in Figure 1.7, which shows the distribution of actual volumes from historical spills and the volume that each of those spills would have been had each of the spills been WCDs. There is a distribution of volumes because there was a distribution of volumes of carrying capacity (or actual cargo load) in the tankers that were involved in the spill incidents.

1.3.4 Determining the Probable Locations and Timing of Spills

The spill location will be an important factor in determining the impacts of a spill, as will be described in Section 1.3.6. Predicting the locations of likely spill events is another important part of spill risk analysis. Just as there are distributions of probabilities of spills from different sources and spills of different volumes, there are also distributions of spill locations in space and time. Based on spill histories and patterns of weather, traffic, transport, and other relevant factors, a distribution of spills in space and time may also be established.

An example of analysis for a spatial spill distribution is shown in Figures 1.8 and 1.9 [5]. Figure 1.8 depicts the spatial distribution of vessels in traffic lanes with locations of highest collision probability.

Figure 1.9 indicates the approximate locations of vessel traffic lanes shown in relation to two vessel–vessel collision risk areas considered, WTGs allision risk area, and electric service panel allision risk area that were analyzed for the vessel collision and allision study for the Cape Wind offshore wind project in Nantucket Sound, Massachusetts, USA.

Marine and river traffic lanes and ports are obvious locations to analyze for vessel incidents. For stationary sources, such as pipelines and facilities, the infrastructure of the system needs to be analyzed for determining the likely location of spill incidents.

1.3.5 Factors That Determine the Consequences/Impacts of a Spill

The impacts and consequences of a spill form the other side of the risk equation. Spilled oil can have a broad range of environmental and socioeconomic impacts, along with legal and political ramifications. While each spill is a unique event in terms of consequences and impacts, there are a number of factors that will generally affect the outcome of a spill:

- Oil type
- Spill location with respect to proximity to sensitive resources

TABLE 1.8 Probabilities of spill volume for U.S. tanker spills (1985–2000)

	Impact accidents		Non-accident structural failure	
Spill volume (m^3)	Percent	Cumulative percentage (%)	Percent	Cumulative (%)
0.38	25.0	25.0	11.1	11.1
3.8	28.6	53.6	40.7	51.9
38.0	28.6	82.1	22.2	74.1
380	14.3	96.4	14.8	88.9
3800	0.0	96.4	7.4	96.3
38,000	3.6	100.0	3.7	100.0

TABLE 1.9 Probabilities of large spills for accidents of large double-hull tankers

	Probability (per tanker year)			
Accident event	Accident	Spill	Accident × spill	Large spill (38,000 m^3)
Collision with side impact	4.50E-05	1.90E	8.55E-06	3.1E-07
Collision with side/bottom impact	1.05E-04	1.80E	1.89E-05	6.8E-07
Explosion	2.30E-04	4.00E	9.20E-05	3.4E-06
Fire	2.30E-04	4.00E	9.20E-05	3.4E-06
Hard grounding	1.10E-04	1.80E	1.98E-05	7.1E-07
Structural failure (non-accident)	1.50E-04	4.00E	6.00E-05	2.2E-06

TABLE 1.10 Probabilities of large spills for accidents of large single-hull tankers

	Probability (per tanker year)			
Accident event	Accident	Spill	Accident × spill	Large spill (38,000 m^3)
Collision with side impact	4.50E-05	6.50E	2.93E-05	1.1E-06
Collision with side/bottom impact	1.05E-04	7.90E	8.30E-05	3.0E-06
Explosion	2.30E-04	4.00E	9.20E-05	3.4E-06
Fire	2.30E-04	4.00E	9.20E-05	3.4E-06
Hard grounding	1.10E-04	9.20E	1.01E-04	3.6E-06
Structural failure (non-accident)	1.50E-04	4.00E	6.00E-05	2.2E-06

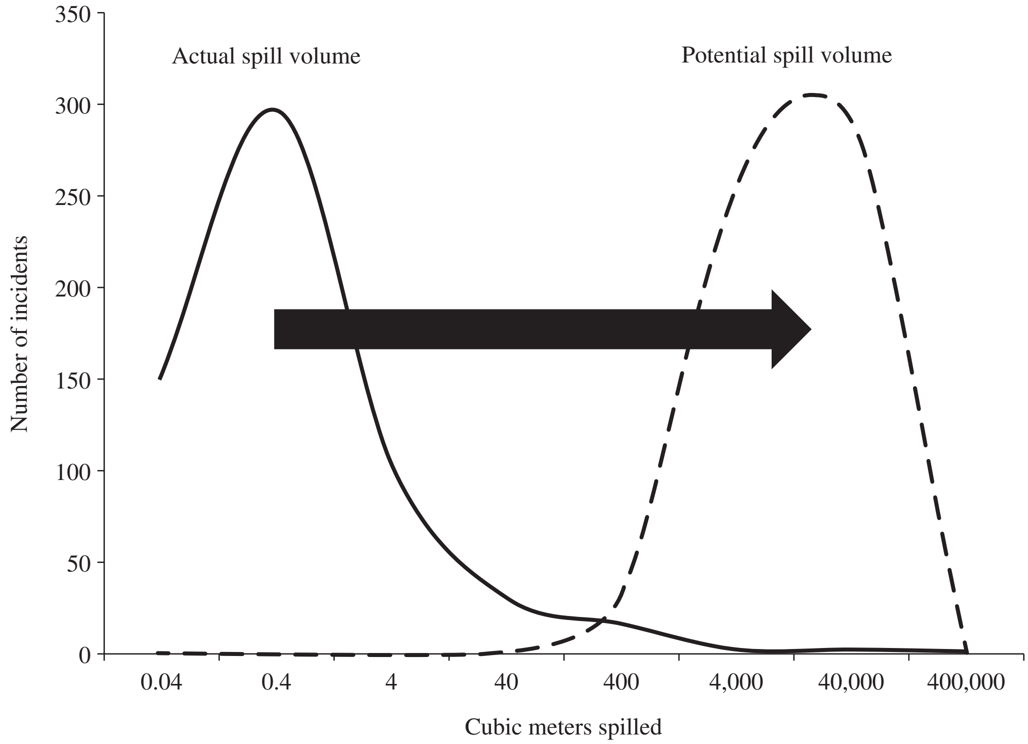

FIGURE 1.7 Actual versus potential spill volume for US tanker spills [5,8].

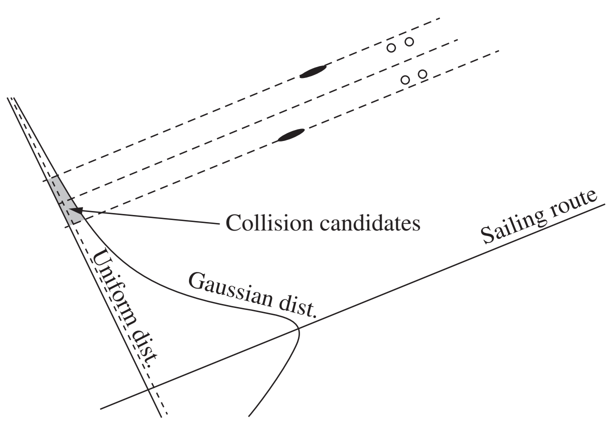

FIGURE 1.8 Geometrical ship distribution in traffic lane [2].

- Environmental conditions (e.g., currents, tides, winds, waves, and weather)
- Sensitive resources (e.g., habitats, flora and fauna, and socioeconomic resources) in vicinity
- Impact mitigation through effective response
- Impacts from response itself

1.3.5.1 Oil Type Different oil types (Table 1.11) vary in their potential for environmental and socioeconomic impacts due to differences in their persistence, toxicity, and coating/mechanical injury effects.

Though each petroleum-based oil has its unique characteristics, for the purpose of modeling and damage or impact estimation, it is useful to put the various oils into one of four basic categories. These categories are generally not only based on the density (specific gravity) of the oils but also incorporate the concentrations of aromatics, which tend to be more toxic and evaporate more easily, versus concentrations of heavier components, which are less toxic but are highly persistent in the environment. Ultimately, these are the factors that will determine short- and long-term impacts on natural and socioeconomic resources.

Volatile distillates include refined petroleum products that are highly toxic but evaporate relatively rapidly, such as gasoline, jet fuel, kerosene, crude condensate, and No. 1 fuel oil. In the United States, this category is called "Group I Oil," which consists of hydrocarbon fractions at least 50% of which, by volume, distill at a temperature of 340°C and at least 95% of which, by volume, distill at a temperature of 370°C. In general, these oils exhibit the following behavior:

- Highly volatile (evaporate completely within 1–2 days);
- Contain high concentrations of toxic soluble compounds;
- Capable of causing localized, severe impacts to surface and subsurface resources and contaminating drinking water; and
- Generally nearly impossible to clean up with conventional response tools.

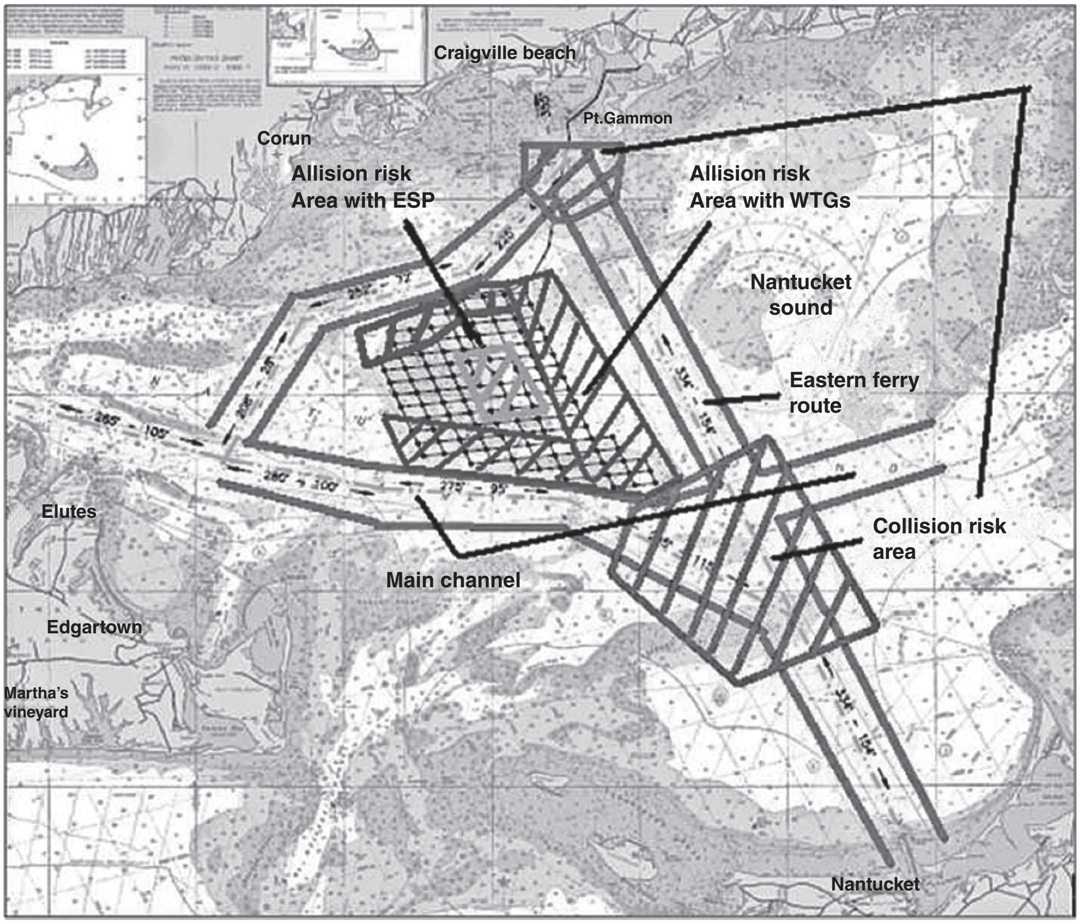

FIGURE 1.9 Vessel collision locations for cape winds facility [15].

TABLE 1.11 Modified oil type persistence classifications

Persistence category[a]	Oil types[b]	Examples in category
Nonpersistent	Volatile distillates	Jet fuel, kerosene, gasoline[c]
Low persistent	Light fuels	Diesel fuel, No. 2 fuel, home-heating oil, marine diesel
Medium persistent	Lube oils	Lubricating oils
	Crude oil	Medium crude oils[d]
Heavy persistent	Heavy oils	Heavy fuel oil; bunker oils Bunker A, Bunker B, and Bunker C; intermediate fuel oil; No. 4 fuel; No. 5 fuel; No. 6 fuel; transmix; residual oils/fuel; waste oil

[a]There is no standard method to determine oil persistence. For example, diesel fuel is sometimes classified as "persistent" and sometimes classified as "non-persistent" [3].
[b]These categories have been used by the EPA in its assessment of impacts of spills from inland facilities regulated by the agency [10].
[c]Gasoline can be separated out as a separate category if desired.
[d]Heavy crude oils have many of the same characteristics as heavy oils, and light crudes tend to be more like light fuels.

The light fuels category incorporates crude oils and refined petroleum products that are not only quite toxic but also contain some persistent components. These oils do not evaporate as readily as volatile distillates. The category includes No. 2 fuel, diesel fuel, light crude oil, gas oil, hydraulic oil, and catalytic feedstock. In the United States, this category is called "Group II Oil," including crude oil and products that have a specific gravity less than 0.85 (American Petroleum Institute (API°) >35.0). These oils have the following characteristics:

- Moderately toxic and will leave a residue of up to one-third of the spill amount after a few days;
- Contain moderate concentrations of toxic soluble compounds;
- Capable of oiling surface and subsurface resources with long-term contamination potential;
- Generally possible to clean up with effective response tools.

The medium oils category includes crude oils and refined petroleum products that are moderately toxic and moderately persistent, such as most crude oils, lube oil, and intermediate fuel oil. This category would also include synthetic crudes. In the United States, these oils are considered "Group III Oils," having a specific gravity between 0.85 and less than 0.95 (API° ≤35.0 and >17.5). In general, these oils exhibit the following behavior:

- About one-third will evaporate within 24 h;
- Oil contamination can be severe and long-term;
- Oil impacts to waterfowl and fur-bearing mammals can be severe; and
- Cleanup is most effective if conducted quickly.

The heavy oils category includes crude oil and petroleum products that are very persistent, though less toxic. This group includes heavy fuel oil, Bunker C, No. 5 or No. 6 fuel, and heavy crude oils. This category would also include bitumen blends. In the United States, these oils are classified as Group IV, having a specific gravity between 0.95 to and including 1.0 (API° ≤17.5 and >10.0). In general, these oils exhibit the following behavior:

- Heavy oils with little or no evaporation or dissolution;
- Heavy contamination likely;
- Severe impacts to waterfowl and fur-bearing mammals (coating and ingestion);
- Long-term contamination of sediments possible;
- Weathers very slowly; and
- Shoreline and substrate cleanup is difficult under all conditions.

Oil type is an extremely important factor in determining the costs and impacts of spills. The oil type determines the properties of the oil itself and the way in which the oil will behave once it is spilled into the environment. The characteristics of spilled oil are interrelated and can affect response operations in a number of ways. First, the degree to which the oil evaporates, disperses, and dissolves will affect the amount of oil that is available for removal via mechanical containment and recovery, dispersant application, manual removal, or in situ burning. The degree of weathering as well as the oil's viscosity, density, adhesiveness, and other characteristics will affect the effectiveness of these removal techniques [6].

1.3.5.2 Oil Evaporation Effect on Environmental and Socioeconomic Impacts The most toxic substances in oil (e.g., benzene, toluene, ethylbenzene, and xylene) are also more likely to evaporate and disperse, which reduces the time that they remain concentrated in the aquatic environment. The toxic effects of oil are usually realized in the first hours to days of a spill. Evaporation of the volatile hydrocarbons leaves behind the heavier, more persistent fractions of oil. Evaporation rates are dependent on temperature with higher evaporation in warmer temperatures.

The more oil that evaporates, the less oil there is to clean up and the less oil that persists in the environment to impact natural and socioeconomic resources. At the same time, the presence of volatile components generally means that there will be at least some toxic impacts from the oil, which translates to environmental and socioeconomic damages as well.

1.3.5.3 Oil Density Effect on Environmental and Socioeconomic Impacts Density, the mass per unit volume of the oil, determines its buoyancy in water. Density is commonly expressed in grams per cubic centimeter (g/cm^3).[1] The density of oil increases with weathering (evaporation of volatile hydrocarbon components) and decreasing temperature.

The density of oil affects its buoyancy and the possibility of sinking. Oil will sink if its density is higher than that of the water. It will also sink when it comes in contact with sediment or other particles or debris that makes the mixture heavier than water. Sunken oil presents significant challenges for spill response.

Oil density also affects the rate of natural dispersion with denser oils dispersing more readily. Denser oils also spread faster on the water surface in the early stages of a spill. Denser oils are also more likely to form stable emulsions.[2] Dispersion, spreading, and emulsion formation all affect spill response costs. While natural dispersion will tend to reduce response costs, as there is less to effectively remove, spreading and emulsion formation both tend to increase costs. With oil spreading, it is more difficult to locate and contain oil for mechanical recovery or to effectively burn or chemically disperse the oil.

1.3.5.4 Oil Viscosity Effect on Environmental and Socioeconomic Impacts Viscosity is a measure of the resistance of oil to flowing once in motion. Oil viscosity increases as weathering progresses and with decreasing temperature. Viscosity is one of the most important properties for spill behavior as it affects spreading—the more viscous the oil, the more slowly it spreads—and emulsification—the more viscous the oil, the more stable the emulsion.

Viscosity also affects the effectiveness of certain spill response measures. Highly viscous oils are very difficult to disperse chemically. Natural dispersion is also significantly reduced in highly viscous oils. More viscous oils are difficult to recover with skimmers and pumps and thus tend to increase response costs.

[1] Pure water has a density of 1 g/cm^3; seawater generally has a density of 1.03 g/cm^3.

[2] A water-in-oil emulsion is a stable emulsion of small droplets of water incorporated in oil. Oil spills on water may form stable water-in-oil emulsions that can have very different characteristics than the parent crude oil.

1.3.5.5 Interfacial Tension and Environmental and Socioeconomic Impacts Interfacial tension is a measure of the surface forces that exist between the interfaces of the oil and water and the oil and air. Interfacial tensions (oil and air and oil and water) are insensitive to temperature but are affected by evaporation. Interfacial tension affects the rate and type of spreading on the water surface as well as sheen[3] formation. Interfacial tension also affects emulsion rates and emulsion stability.

Since chemical dispersants work by reducing the oil and water interfacial tension to allow a given mixing energy[4] to produce smaller oil droplets, the degree of interfacial tension in an oil will affect the ability of the oil to be chemically dispersed. Oils with high interfacial tensions are more difficult to disperse with chemical dispersing agents and also disperse less naturally. This will tend to limit the effectiveness of dispersants and require more expensive mechanical methods for cleanup.

At the same time, mechanical recovery with oleophilic skimmers (e.g., rope-mop and belt skimmers) work better on oils with moderate to high interfacial tensions. Increased effectiveness of mechanical recovery will generally reduce response costs. The amount of oil recovered offshore (on the water surface) will be greater reducing the amount of oil on the shoreline where cleanup tends to be more labor-intensive and expensive. If more oil can be recovered on the water surface, the less impact on shorelines.

1.3.5.6 Oil Pour Point Effect on Environmental and Socioeconomic Impacts The "pour point" of a particular oil is the lowest temperature at which the oil will still flow at a given rate. The pour point temperature increases with weathering (evaporation of volatile components). Pour point affects spreading on the water surface. Oils that are at temperatures below their pour points will spread only very slowly and are more difficult to disperse. Viscosity increases dramatically at temperatures below the pour point.

Because oils will resist flowing toward skimmers or down-inclined surfaces in skimmers, there are significant challenges in mechanical oil recovery at these temperatures. The solidification of the oil below its pour point also causes problems in storage and transfer. These factors can increase spill response costs because more work needs to be done manually.

1.3.5.7 Adhesiveness Effect on Environmental and Socioeconomic Impacts The adhesiveness of an oil is the degree to which the oil remains on a surface after contact and draining. This character has an effect on spill impacts by way of the amount of oil that will stick to surfaces, including shoreline substrates and structures (e.g., piers, boats, and seawalls). Higher adhesion increases damage costs and shoreline cleanup costs. At the same time, adhesion can increase the effectiveness of some on-water recovery methods, including the use of oleophilic skimming devices.

1.3.5.8 Emulsification Effect on Environmental and Socioeconomic Impacts A water-in-oil emulsion[5] is a stable emulsion of small droplets of water incorporated in oil. Oil spills on water may form stable water-in-oil emulsions that can have very different characteristics than the parent crude oil. The tendency to form emulsions, the stability[6] of those emulsions, and the water content of stable emulsions are all important characteristics of an oil that can affect impacts as well as response.

Emulsification can significantly affect the impacts of a spill and increase the amount of storage capacity required during response and operations. Emulsified oils can be highly persistent in the environment. Strongly emulsified oils are also highly viscous, often with 10–100 times the viscosity of the parent oil. Oils with relatively high concentrations of asphaltenes are most likely to form stable water-in-oil emulsions. Some heavy oils do not easily form emulsions because the high viscosity of the oil prevents the uptake of water. Some light or medium oils do not form an emulsion immediately, but once evaporation occurs and the asphaltene concentration increases, the emulsification process begins and usually proceeds quickly thereafter.

Emulsions can present challenges for all types of response strategies, increasing costs and logistical concerns, such as increases in storage of collected oil (i.e., larger volume with oil/water mixture).

1.3.5.9 Persistence Effect on Environmental and Socioeconomic Impacts The persistence of the oil in the environment can also significantly affect the impacts of a spill as well as the response strategies and costs. Persistence of petroleum-based oils is a very important consideration in assessing the environmental risk of an oil spill and often affects the resources needed for spill recovery and remediation. The heavier, more persistent fractions of oil are those that adhere to the feathers of birds and fur of mammals, as well as to shoreline and wetland communities. For birds and mammals, this coating can cause hypothermia. For organisms living along shoreline or in wetlands, this can cause smothering. Both smothering and hypothermia can result in mortality, which increases environmental damages.

The persistent portions of oil can also coat other surfaces (e.g., tourist beaches, seawalls, marinas, and boats) causing socioeconomic impacts. The persistence of oil and the

[3]A "sheen" is a very thin layer of oil on the water surface. Rainbow-colored sheens are generally 0.0003 mm thick. Silver sheens are usually about 0.0001 mm thick.

[4]Waves and sea state.

[5]Water-in-oil emulsion is colloquially called "chocolate mousse".

[6]Emulsion stability can be low, which indicates the emulsion is unstable and will break quickly once removed from the mixing environment; moderate, which means the emulsion will break within a few hours; or high, which means the oil forms a very stable emulsion that is unlikely to break even after standing for 24 h.

degree to which the oil adheres to shoreline substrates and penetrates those substrates will affect the type of shoreline response that is required [1,7]. The labor and resources, as well as disposal, required for shoreline responses will vary by shoreline type, oil type, and degree of oiling, which in turn affect the complexity involved in the cleanup [8,9].

1.3.5.10 Toxicity and Environmental and Socioeconomic Impacts The *toxicity* of the oil determines the adverse effects and mortality of fish, wildlife, and invertebrates after short-term exposure (hours to days). Mortality as well as sublethal effects (e.g., reduced fecundity) is relevant to both environmental impacts and socioeconomic impacts in as much as commercial fisheries, subsistence fishing (particularly important in Tribal Nation areas), and recreational fishing are affected. Different organisms have different tolerances of exposure.

1.3.5.11 Mechanical Injury and Environmental and Socioeconomic Impacts Oil can also cause "mechanical injury" based on its adhesive properties. This injury is caused by coating, fouling, or clogging of organisms and their appendages and apertures, such that movements and behaviors are physically inhibited [10].

1.3.6 Spill Impacts: The Effects of Spill Location Type

The impacts of spills of each oil type will be affected by their individual properties, as well as by the environment into which the oil spills. The characteristics of a spill location also determine impacts in the following ways:

- Hydrodynamics (currents, tides, and wave heights) will affect the way in which spilled oil will travel and spread on the water surface;
- Current velocity and wave height will also affect the degree to which booming, both for shoreline protection and for mechanical containment for on-water oil recovery operations, will be effective;
- Prevailing wind patterns will also affect the way in which the oil spreads and its trajectory on the water surface;
- The water and air temperatures in different seasons will affect the behavior of oil with respect to rates of evaporation and dispersion and viscosity;
- Presence or absence of ice will affect the behavior of the oil and strategies for spill response; and
- Types of shoreline substrates and configurations of the coastline will affect the degree of impacts on shoreline resources, as well as determine the nature of shoreline cleanup response strategies [8].

1.3.6.1 Location Type: Oil Behavior and Potential Effectiveness of Spill Response The effectiveness of the response, in turn, determines the degree to which the environmental and socioeconomic impacts of the spill can be mitigated or reduced. It is important to remember that a spill response can only mitigate a percentage of the damages from a spill depending on the type of response employed and the efficacy of the oil removal. In most cases, this will represent a small percentage of the oil spillage. Except under highly unusual circumstances (i.e., sheltered waters with little to no current around a pre-boomed dockside vessel), mechanical containment and recovery will remove 3–10%, and occasionally as much as 25%. Dispersant application and in situ burning will have much higher efficacy, though there are limitations to the use of these strategies that need to be considered in response decisions.

Shoreline areas and land-based substrates most sensitive to oiling include those with long oil residency—fine-grained (silt–mud) flats, marshes, and lagoons—as well as shorelines with the greatest potential for penetration and remobilization—coarse-grained (cobble, cobble–boulder mix) substrates [11]. The degree to which oil adheres to and penetrates into various types of shorelines is determined by complex factors [1,7]. The oil-holding capacity of a particular substrate is related to the following:

- Sediment type (porosity and permeability);
- Oil type (viscosity and adhesiveness); and
- Water and air in the pore spaces of the sediment.

Impacts to different shoreline types are summarized in Table 1.12.

The behavior of spilled oil as it first strands on a shoreline or first spills onto or into a substrate depends on a number of interrelated factors: oil type and characteristics (e.g., viscosity); oil thickness on the substrate; time until impact (i.e., degree of weathering); timing with regard to tides; weather during and after the spill; and nearshore wave energy, in the case of spills into water. The adhesiveness of oil to shoreline substrates, in turn, depends on the properties of the oil,

TABLE 1.12 Shoreline substrate types and spill damage implications

Type name	Damage issues
Rock platform	Low penetration and residency; oil will wash off with wave action
Rock cliff	Low penetration and residency; oil will wash off with wave action
Rock with gravel beach	Some penetration and potential remobilization
Rock sand gravel beach	Some penetration and potential remobilization
Rock with sand beach	Some penetration and potential remobilization
Gravel beach	Higher penetration and potential remobilization
Gravel flat	Higher penetration and potential remobilization
Sand gravel beach	Some penetration and potential remobilization
Sand beach	Lower penetration and potential remobilization
Sand gravel flat	Some penetration and potential remobilization
Sand flat	Lower penetration and potential remobilization
Mud flat	Long residency and difficulties with cleanup
Estuary, marsh, lagoon	Long residency and difficulties with cleanup
Man-made (solid)	Lower penetration
Riprap	Higher penetration and remobilization

especially viscosity [12]. The degree of weathering can have a significant impact on the ability of oil to adhere to a substrate. Weathering can also cause emulsification, which can also change the oil viscosity. The degree of emulsification depends on the chemical composition of the oil. The degree of weathering that occurs is related to oil type and environmental conditions. Lighter oils evaporate more quickly than heavier oils. Temperature, wind, light conditions, and other environmental factors can influence the rate of weathering.

Fresh oils tend to be less adhesive than more weathered oils. Light fuels or volatile organic distillates tend to be relatively nonadhesive. Heavier fuels tend to be more adhesive than lighter oils. Penetration into the substrate will also depend on oil type. All other things being equal (e.g., shoreline porosity), heavier oils will penetrate less than lighter oils. Oil viscosity is positively correlated to oil adhesion on the shoreline. Adhesion is inversely related to penetration—the more adhesive an oil, the lower its penetration potential. Oil thickness on the shoreline is a factor of the amount spilled, spill trajectory, oil properties, steepness of the shoreline slope, tidal conditions at the time of shoreline impact, and the porosity of the surface.

Oil behavior at the shoreline or in a substrate is also highly dependent on the substrate characteristics, particularly porosity and permeability. The substrate structure largely determines the degree of oil penetration [13,14]. Penetration will be less in substrates with very fine granules that are packed closely together and greater in more coarsely grained substrates. If the pores are large and interconnected, the substrates will be more "permeable" and allow deeper penetration and lateral movement of the oil through capillary action.

Bedrock is largely impermeable to oil except when the oil is able to enter crevices or fractures in rock surfaces. Gravel tends to have large interconnected pore spaces that will allow oil to readily penetrate. Sand and mud beaches tend to have tightly packed sediments with small pore spaces that are less permeable to oil, though some lighter oils can penetrate. Some substrates have features that can influence oil retention and penetration that are not related to granule size. Tidal flats often have holes from burrowing animals that will allow oil penetration [15]. Oil adhesion can also be influenced by the presence of vegetation, such as in wetlands or mangroves. Ice is another substrate that can cause variations in oil adhesion and penetration based on its nature (tightly packed, granular, smooth, or rough) [16].

Nearshore wave energy can affect the degree of initial deposition and penetration for spills into water [17]. The effectiveness of wave energy in removing or refloating oil is dependent on the permeability of the shoreline substrate, as well as the oil type and weathering condition with respect to adhesiveness. Wave energy can effectively remove oil from a bedrock shoreline where there is little, if any, penetration. Wave action can also cause the shoreline substrate to redistribute itself, as in the case of gravel or sand. This action can affect the degree of oil retention and refloating. The extent of oiling on the shoreline is also dependent on the tidal stage at the time of oil deposition.

The presence of ice on the water affects spill response in a number of ways. The oil tends to be more viscous, affecting the effectiveness of certain spill response measures. Highly viscous oils are very difficult to disperse chemically. Natural dispersion is also significantly reduced in highly viscous oils. More viscous oils are difficult to recover with skimmers and pumps and thus increase response costs.

At the same time, solid, pack, or broke ice; floes; or brash ice can contain and entrain oil that is spilled on, into, or under the ice. While this sometimes complicates recovery with skimmer and booms, it can also act as a natural containment that isolates spilled oil from the marine environment. Oil spilled under ice will eventually resurface. Recovery can sometimes be safely delayed until winter conditions are more amenable to cleanup operations.

Skimmers used on spills in ice must be able to deal with emulsified, highly weathered oil and oil that is mixed with a good deal of debris, including ice pieces. Sometimes, chemical treatment agents designed to increase viscoelasticity and cohesiveness of oil are added to increase the efficiency of skimmers.

In situ burning is widely touted as the most effective means of removing large volumes of spilled oil on ice and in open water situations. Air pollution and safety issues need to be considered. The use of dispersants in icy water conditions has had mixed results. Issues related to efficacy and potential impacts need to be considered.

Overall, the degree to which an effective spill response can be implemented under the conditions in the spill location may have a significant effect on the impacts and consequences of a spill.

1.3.6.2 Location Type: Oil Trajectory and Fate The trajectory and behavior of the oil will have a large effect on the spill impacts. As discussed in Section 1.3.5, oil type is an important factor in determining the behavior of the oil spilled into water, or on land. In water, surface spreading, evaporation rate, and dissolution or dispersion into the water column are all dependent on oil type, but are also affected by the depth of the oil release (surface or subsurface) and duration and nature of the release (instantaneous, chronic, episodic, or prolonged), water and air temperature, and wind velocity. Wind and current velocity and direction will determine the path or trajectory of the oil, including the probability of the oil impacting sensitive shorelines and other resources. An example of modeling outputs from spill modeling is shown in Figure 1.10.

The model results are then summarized statistically to describe probability and degree of oiling and the time after the spill when each impacted area would be first affected. Exposures to each oil constituent on the water surface, in the water column, and on the shoreline are analyzed over all the simulations to determine the median and worst cases for impacts.

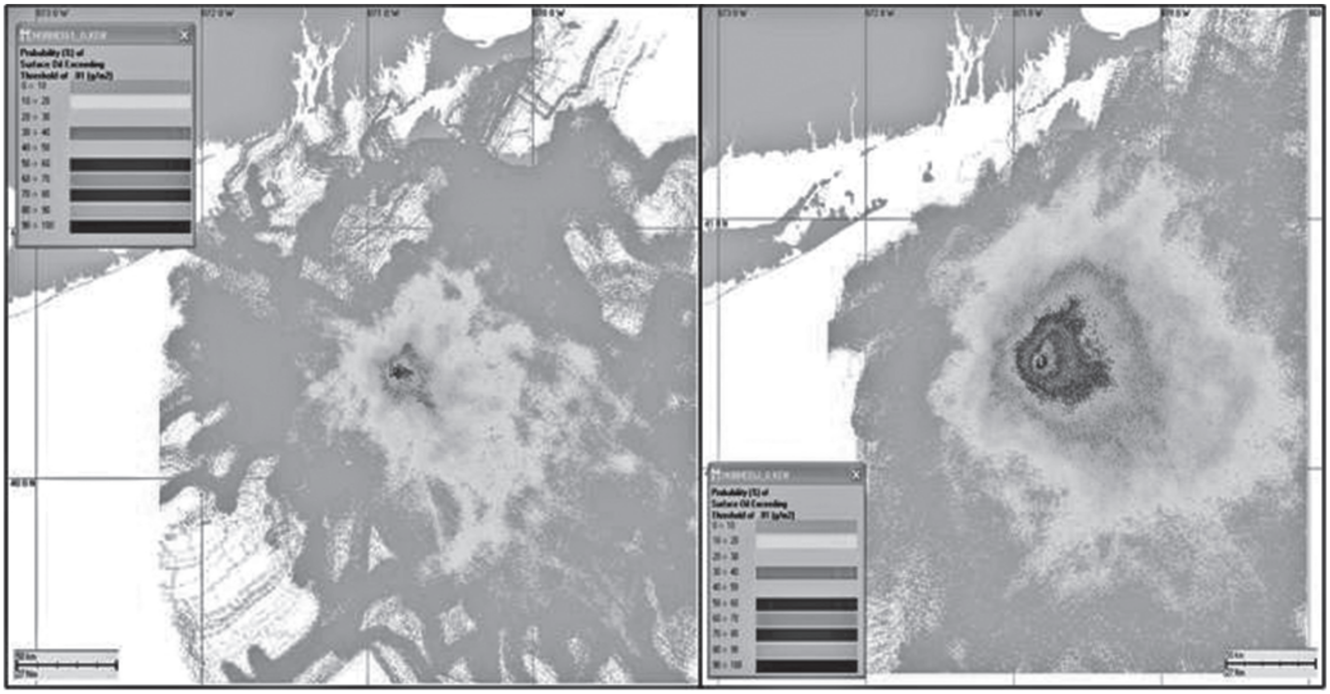

FIGURE 1.10 Hypothetical releases of 17,000 m^3 no. 6 fuel [19].

Probabilistic or stochastic modeling, described in greater detail in Chapter 7, provides a means to estimate the probabilities of impact to various resources at risk [18,19].

1.3.6.3 Location Type: Sensitive Resources at Risk The probability of oil impacting sensitive resources depends on the location of the spill in relation to sensitive ecological and socioeconomic resources and the probability that the oil will be carried towards those resources by dispersion and dissolution into the water column or by currents, tides, and winds.

The sensitivity of various resources to oil impacts varies greatly, depending on oil type, particularly the toxicity, persistence, and adherence properties, and the resources themselves. (This is discussed in greater detail in Chapter 7.) There are seasonal factors that need to be considered as well. Wildlife species are often more vulnerable during certain times in their life cycles, such as fish spawning and bird nesting. Socioeconomic resources also have seasonal sensitivities in some cases as with tourist beaches and commercial and recreational fishing.

Spill risk analysis involves a survey of potentially impacted sources in the area of potential oil impact. Environmental sensitivity index (ESI) mapping has been extremely helpful in allowing planners to assess resources at risk. Examples of ESI Maps for Upper Cook Inlet, Alaska, USA, are shown in Figures 1.11 and 1.12. The key to sensitive resources is shown in Figure 1.13. Note the seasonal differences between the spring and winter resource presence and sensitivity.

Socioeconomic resources at risk can also be incorporated into mapping, as shown in Figures 1.14 and 1.15.

After determining the presence of "resources at risk" in a potential spill area, the actual sensitivity of the resources to the degree of oiling that may occur, as well as the probability that oiling over a sensitivity threshold will occur, needs to be evaluated. If there are sensitive resources in the area of the likely spill impact, but the concentrations of oil are likely to be insignificant or only cause minor damage, the overall risk is low. On the other hand, with some particularly sensitive resources, even relatively small quantities of oil may cause significant impacts. An example of the rankings of species by their LC_{50} to polycyclic aromatic hydrocarbons in crude oils and fuel oils is shown in Figure 1.16. LC_{50} is the concentration at which 50% of the individuals die. The higher the LC_{50} for a species, the less sensitive it is to oil components, which is because it requires a higher concentration of the oil to kill 50% of the individuals.

The degree of impact by different oils will also depend in large part on the degree of contact and the duration of the exposure, particularly with regard to toxicity. The "dose" of oil is a combination of the toxicity of the oil based on its chemical components, the duration of the exposure in time, and the sensitivity of the particular organisms. The volume of spillage and the properties of the oil are important factors in determining dose. An example of an evaluation of species sensitivity to oiling by different oil types for species groups common in Cook Inlet, Alaska, USA, is shown in Table 1.13 [5].

1.3.7 Measuring Oil Spill Impacts

Measuring the impact of oil spills on ecological and socioeconomic resources is a complex science. With such a broad array of potential impacts to sensitive resources—from fish mortality to bird nesting habitat oiling and to disruptions to commercial fishing and tourism—there are many ways to quantify impacts.

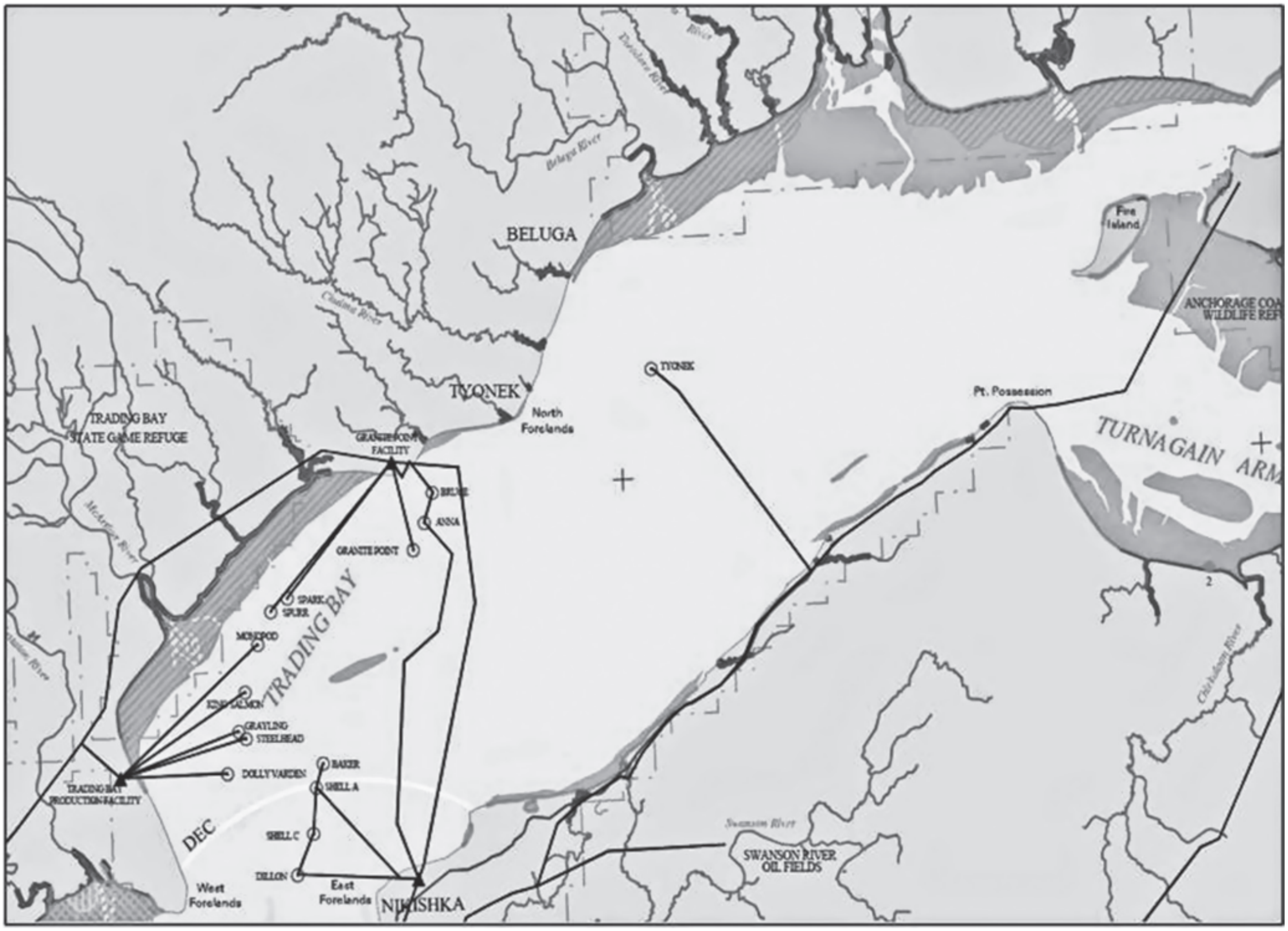

FIGURE 1.11 ESI map of Upper Cook Inlet in winter.

1.3.7.1 Quantifying Ecological Impacts Ecological impacts can be measured with regard to mortality numbers of individuals of different species groups, reductions in ecosystem production, biomass mortality (e.g., kg of fish), changes in the abundance of species, or through a system of natural resource damage assessment (NRDA). NRDA provides a quantification of the cost of restoration of the oiled environment in situ or in another quasi-equivalent location.

Probabilistic oil fates and effects modeling can be used to estimate potential impacts and natural resource damages [20]. The oil fates model uses wind data, current data, and transport and weathering algorithms to calculate mass balance of fuel components in various environmental compartments (water surface, shoreline, water column, atmosphere, sediments, etc.), oil pathway over time (trajectory), surface distribution, shoreline oiling, and concentrations of the fuel components in water and sediments. Exposure of aquatic habitats and organisms to whole oil and toxic components is estimated in the biological model, followed by estimation of resulting acute mortality and ecological losses. Natural resource damages are based on estimated costs to restore equivalent resources and/or ecological services, using Habitat Equivalency Analysis and Resource Equivalency Analysis methods. These methods can be used to provide a cost (in currency) of ecological impacts.

Another approach to assessing ecological impacts is to rank impacts on a more qualitative scale [5]. An example of a 5-point scale that can be used in risk assessments is as follows:

- Very high impact (VH) (5 points): Long-term impacts (over 5 years) anticipated over a large part of the region and potentially outside of the region and/or significant impacts to threatened species or species indicated for special management. Recovery of populations and ecosystems will take over 5 years, and/or threatened or special-management species will be very significantly impacted at the population level.
- High impact (H) (4 points): Moderate-term impacts (2–5 years) anticipated over a large part of the region or very significant (high) impacts to specific areas of the Inlet. Recovery of populations and ecosystems will take 2–5 years.
- Moderate impact (M) (3 points): Moderate-term impacts (2–5 years) anticipated over a smaller part of the region or significant (high) impacts to specific areas

FIGURE 1.12 ESI map of Upper Cook Inlet in spring.

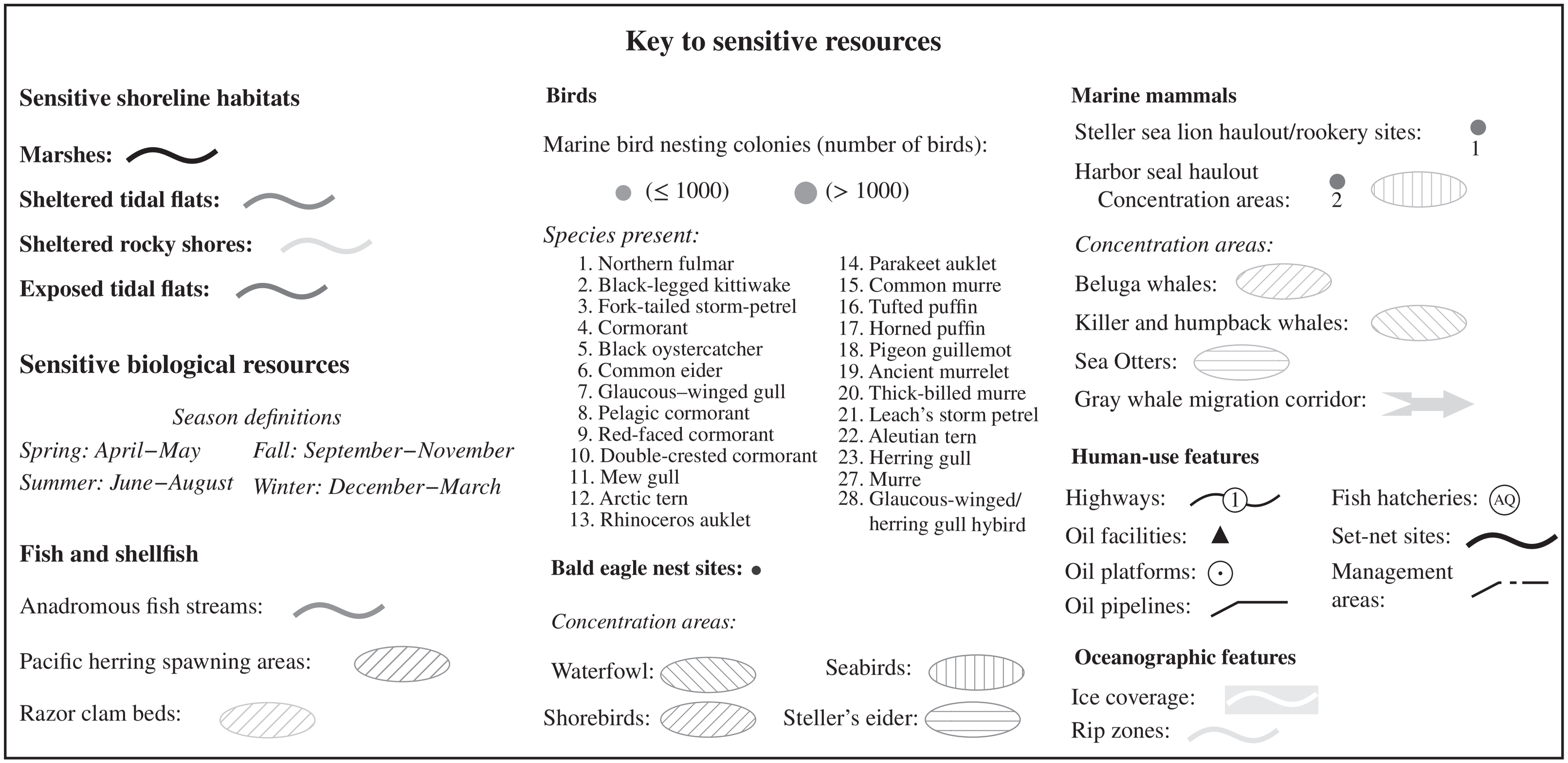

FIGURE 1.13 Key for ESI maps in Figures 1.12 and 1.13.

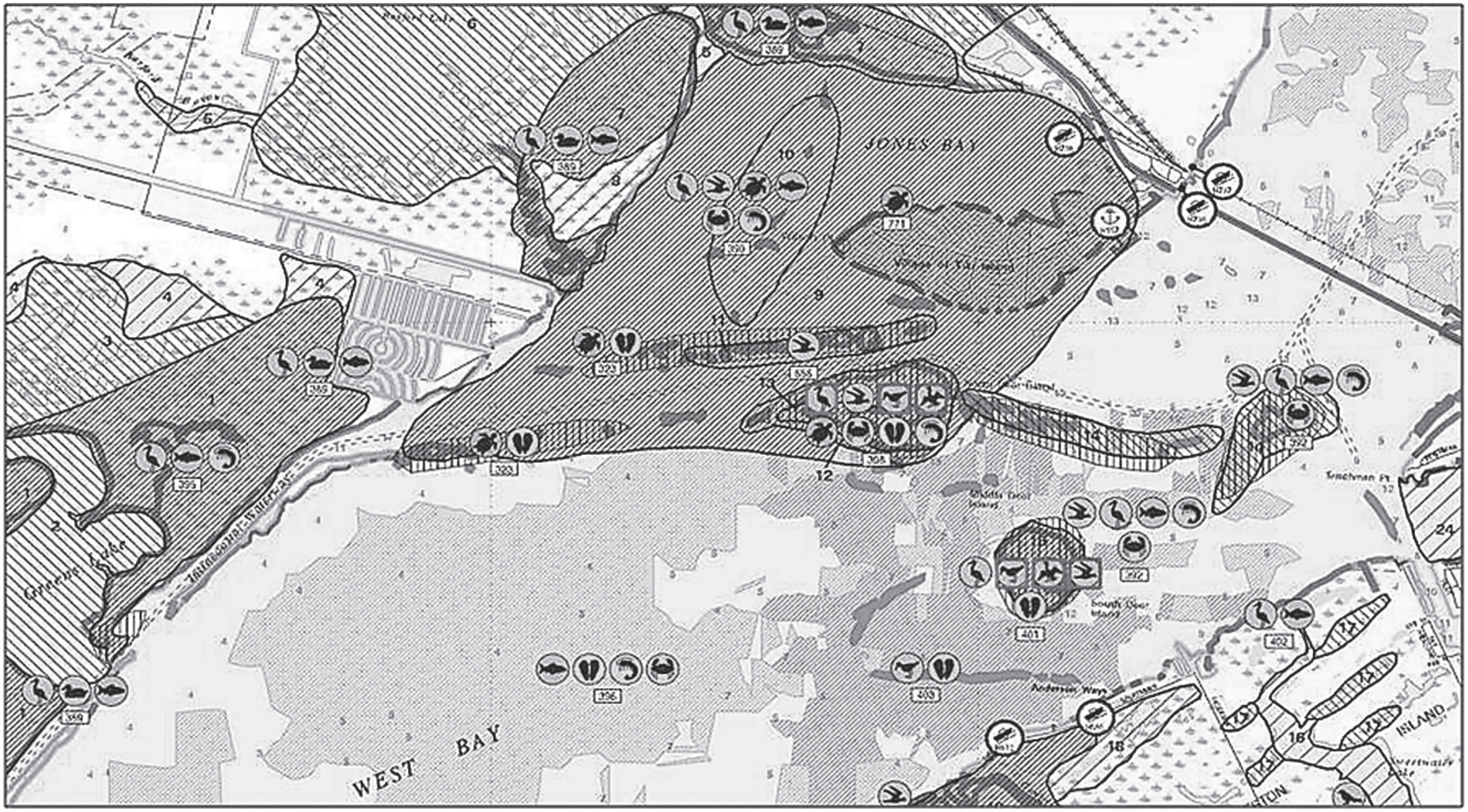

FIGURE 1.14 ESI map from Upper Texas Coast.

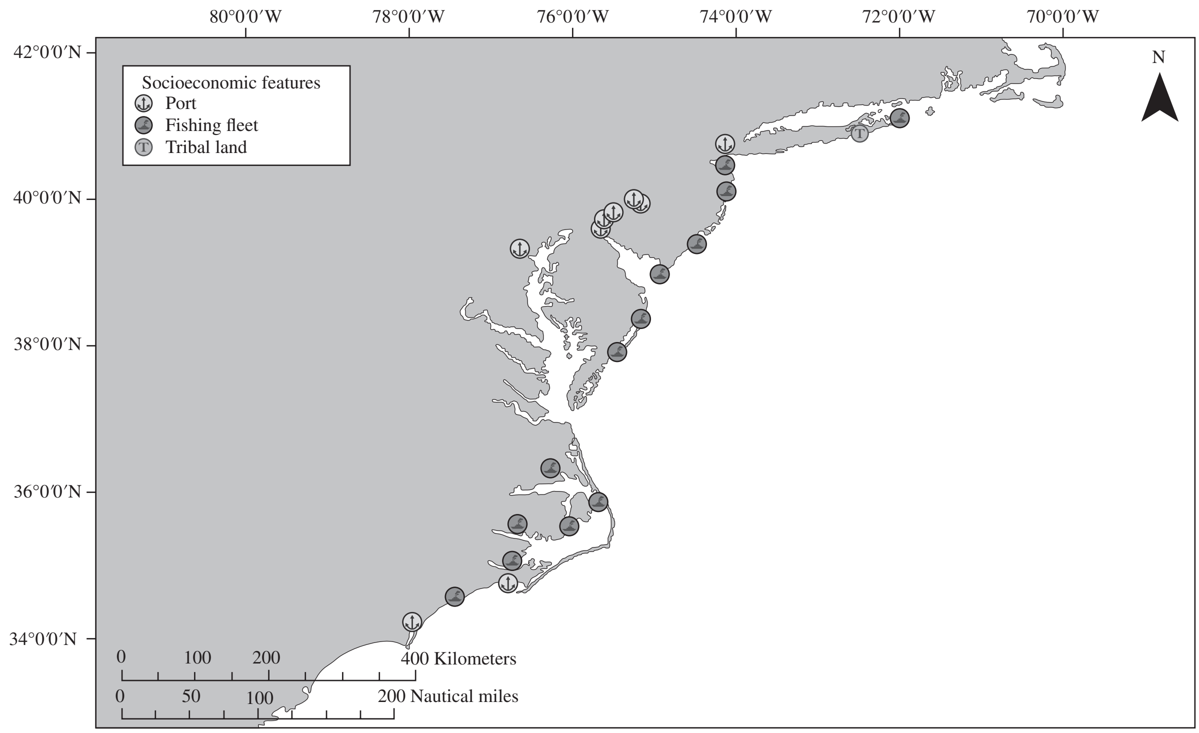

FIGURE 1.15 Sample of socioeconomic resources at risk (North Atlantic, USA).

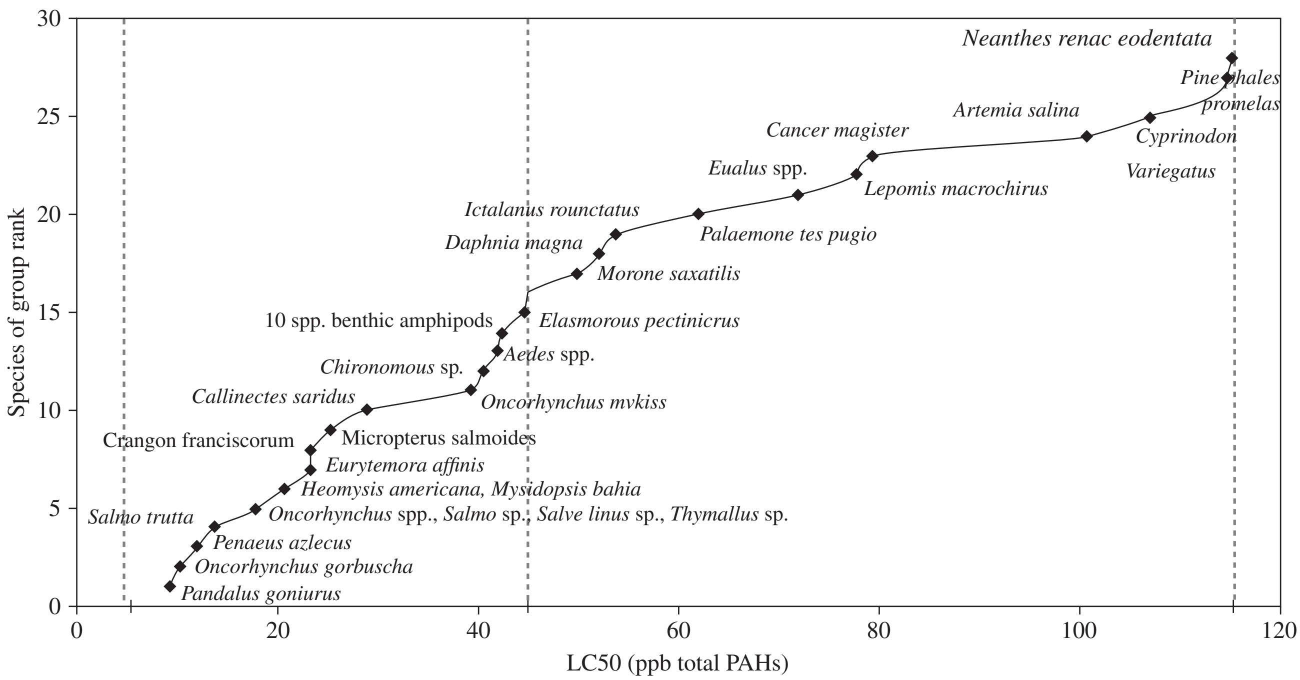

FIGURE 1.16 Species sensitivity rankings to PAHs in crudes and fuel oils. Vertical dashed lines are geometric mean and range for 95% of species [25].

TABLE 1.13 Overall degree of sensitivity to oiling for cook inlet species [38,39]

	Degree of sensitivity to oiling									
	Fish		Shellfish	Birds				Marine mammals		
Oil category	Salmon	Herring	Razor clams	Waterfowl	Seabird	Shorebird	Eider	Otter	Sea lion	Whale
Nonpersistent	**H**	**H**	**L**	**L**	**L**	**L**	**L**	**L**	**L**	**L**
Low persistent	**H**	**H**	**M**	**M**	**M**	**L**	**M**	**M**	**M**	**L**
Medium persistent	**M**	**M**	**H**	**H**	**H**	**M**	**H**	**H**	**H**	**L**
Heavy persistent	**L**	**L**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**L**

H, high sensitivity; L, low sensitivity; M, medium sensitivity.

of the region. Recovery of populations and ecosystems will take 2–5 years.

- Low impact (L) (2 points): Significant shorter-term impacts (under 2 years) to a large part of the region or moderate impacts to specific areas of the Inlet. Recovery of populations and ecosystems will take less than 2 years.
- Very low impact (VL) (1 point): Significant shorter-term impacts (under 2 years) to a smaller part of the region or low impacts to larger areas of the region. Recovery of populations and ecosystems will take less than 2 years.

Determining the rate of ecosystem and population recovery is extremely complex. There are a large number of complex and interrelated factors involved in determining short- and long-term consequences of oil spills. There is considerable and legitimate debate in the scientific community about scientific data on short- and long-term recovery rates and the ways in which the results of many spill impact studies and models should be interpreted and applied. A complete analysis generally requires highly complex modeling and studies. The five-point rating system presented earlier and its application to the spill scenarios are based on generalized data analyses on spill impacts based on studies of hundreds of spill case studies and over 1000 spill impact studies.

In determining environmental impacts of hypothetical spills, cultural values placed on impacted environment need to be considered. These can only truly be understood and appreciated by the myriad of stakeholders in the region of concern. While from an ecosystem and a population-level perspective, recovery rates may be similar to those indicated here, the "acceptability" of any degree of environmental impacts from spills will be a matter for stakeholders to consider.

1.3.7.2 Consensus Ecological Risk Assessment In some risk assessment processes, there is greater concern about some resources than others or the concern about resources differs among the stakeholders. A commonly applied approach in these cases is a consensus-based ecological risk assessment (ERA), in which stakeholders rate, rank, and prioritize resources at risk with respect to their sensitivity [21]. ERA is a process through which one can evaluate the possible ecological consequences of human activities and natural catastrophes. An ERA emphasizes the comparison of exposure to a stressor or stressors (i.e., oil and/or the spill response options) with an ecological effect (e.g., population disruption, changes in ecological community structure or function, and toxicological effects). As much as possible, this comparison is made quantitatively, including estimating the probability that the predicted consequences will occur and of the associated severity and magnitude of the effects. Figure 1.17 shows a strategy employed in a number of ERA in the United States.

1.3.7.3 Quantifying Socioeconomic and Response Cost Impacts Besides the environmental impacts, there are also socioeconomic costs that are on the consequences side of the risk equation. Oil spills can have significant impacts on a variety of socioeconomic resources, such as the following:

- Commercial, subsistence, and recreational fishing by causing mortality and/or tainting of fish stocks and interfering with fishing activities;
- Ports and port traffic by interfering with and delaying port traffic and oiling of port facilities;
- Tourism and recreation by oiling of beaches and other coastal property, as well as parks and recreational areas;
- Tribal cultural activities and lands by oiling of water and coastal resources owned by and used by native tribes; and
- Wildlife viewing, diving, and other activities by oiling natural habitats.

Many of these impacts can be quantified to a great extent based on loss of income based on delays and disruptions to commerce and other direct means of putting a currency value on the impact [20]. Other costs, particularly tribal cultural values, are more difficult to quantify. The impacts can also be qualitatively assessed as in the five-point scale previously described. Most impacts will be relatively short-term with the economic resources regaining their original value within a certain period of time, though others may experience a longer impact time.

There are models that can be used to estimate socioeconomic costs of oil spills based on the location type, resources

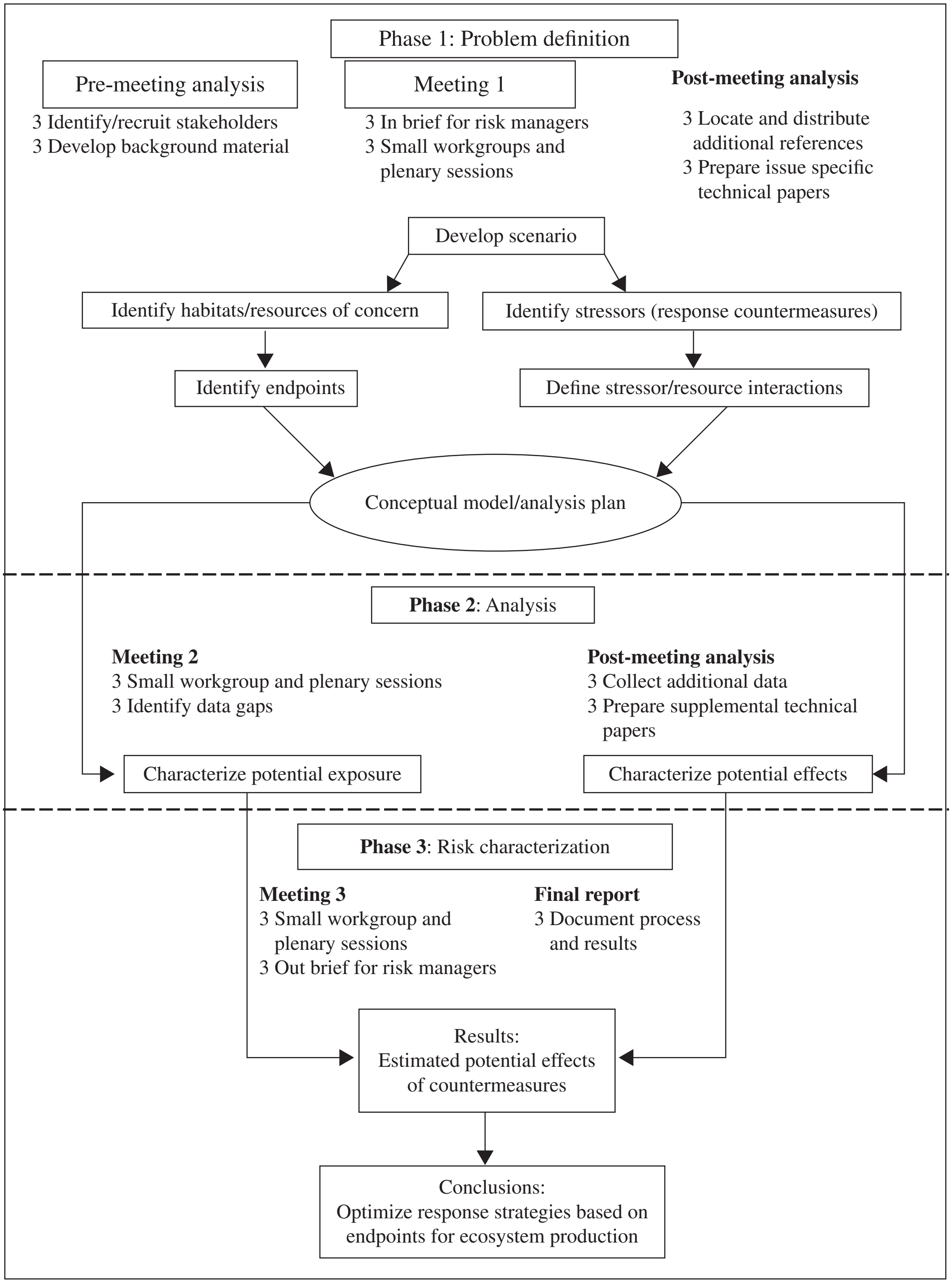

FIGURE 1.17 Consensus ecological risk assessment process [1].

at risk, oil type, and spill volume, including the Basic Oil Spill Cost Estimation Model (BOSCEM) [22,23] and parts of the Oil Spill Response Cost Effectiveness Analytical Tool (OSRCEAT) [24].

A spill incident will also generally require a cleanup response, which can also result in significant costs, depending on the magnitude of the spill, location, oil type, and method of response. Spill response costs include the cost of equipment, personnel, logistical support, waste disposal, monitoring, and government oversight during the various phases of the spill response operations on, and, in some cases, under the water, on land, and on the shoreline. The BOSCEM and OSRCEAT models estimate spill response costs based on location factors, oil type, spill volume, and response measures. More precise estimates can be developed by analyzing oil fate and trajectory outputs from modeling and determining the amount of resources and time required for various types of response strategies [6,25,26]. Shoreline response costs can be estimated from algorithms developed from analyses of past spill responses based on the amount of work and resources required to remove oil from different types of shorelines [8,9].

1.3.7.4 Combining Probability of Impact and Degree of Impact For spills on water, the three main categories of risk factors for ecological and socioeconomic resources at risk are as follows:

- Impacts to water column and resources in water column (e.g., fish and invertebrates);
- Impacts to water surface and surface resources (e.g., diving birds and shipping lanes); and
- Impacts to shoreline and shoreline resources (e.g., bird nesting habitats and tourist beaches).

The impacts from an oil spill would depend greatly on the direction in which the oil slick moves, which would, in turn, depend on wind direction and currents at the time of and after the oil release. Impacts are characterized in risk analyses based on the likelihood of any measurable impact, as well as the degree of impact that would be expected if there is an impact. The measure of the degree of impact is based on the median case for which there is at least some impact. The median case is the "middle case"—half of the cases with significant impacts have less impact than this case, and half have more. For each category of ecological and/or socioeconomic resources at risk, risk is defined as follows:

- The probability of oiling over a certain threshold (i.e., the likelihood that there will be an impact to resources over a certain minimal amount); and
- The degree of oiling (the magnitude or amount of that impact).

The ecological and socioeconomic resources at risk for water column impacts include fish, marine mammals, and invertebrates (e.g., shellfish and small organisms that are food for larger organisms in the food chain). These organisms can be affected by toxic components in the oil. The threshold for water column impact to ecological resources at risk is a dissolved aromatic hydrocarbon concentration of 1 ppb (i.e., 1 part total dissolved aromatics per 1 billion parts water). Dissolved aromatic hydrocarbons are the most toxic part of oil. At this concentration and above, one would expect impacts to water column organisms.

After spilling on the water surface, oil will spread rapidly into a relatively thin layer, which will break up into patches and streams of oil. After some time, the oil spreads out into an extremely thin layer of sheen, which is visible. The threshold level for water surface impacts to socioeconomic resources at risk is 0.01 g/m^2. At this concentration and above, one would expect impacts to socioeconomic resources on the water surface. Sheen and thin layers of oil tend to have lesser ecological impacts. Ecological resources at risk at the water surface include surface-feeding and diving sea birds, sea turtles, and marine mammals. These organisms can be affected by the toxicity of the oil as well as from coating with oil. The threshold for water surface oiling impact to ecological resources at risk is 10 g/m^2. At this concentration and above, one would expect impacts to birds and other animals that spend time on the water surface.

On the shoreline, there are differing sensitivities depending on the shoreline type. Shorelines that are difficult to clean and sensitive to the impacts of spill response operations, such as wetlands, are particularly vulnerable [8,9]. The threshold for shoreline oiling impacts to ecological resources at risk is 100 g/m^2. For socioeconomic impacts, however, a lower threshold of impact should be applied since the visibility of the oil is generally the most important factor in determining socioeconomic impacts. The threshold for impacts to shoreline resources at risk is 1 g/m^2 [19].

In a risk analysis, for each of the subcategories of resources—water column, water surface, and shoreline—the probability that oiling above a certain threshold will occur needs to be established. This can be achieved through probabilistic or stochastic modeling that provides a range of outcomes for a large number of simulations with variations in winds, currents, and, in some cases, exact locations of release (e.g., over the length of a shipping lane). The percentage of simulation modeling cases in which the assigned impact threshold is reached can be considered the probability of impact the area of concern. These percentages can be divided into general categories, as in a 3- or 5-point scale.

Then, the actual degree of oiling (volume of water column, area of water surface, and length or area of shoreline) over the threshold needs to be determined. Again, this can be accomplished through stochastic modeling. For the degree of oiling, however, there will again be a range of outcomes, for example, different lengths of shoreline that might be oiled. In this case, the "worst" case and/or the "median" case might be selected for further analysis. The worst case of shoreline oiling may mean the case in which the most shoreline was oiled, or the most sensitive shorelines were oiled. In some modeling analyses, the shorelines are "weighted" by sensitivity so that impacts to the most sensitive shorelines (wetlands, marshes, or mangroves) would be weighted more heavily than shorelines with lesser sensitivity (e.g., sandy or rocky) [26]. Again, the degree of oiling can be divided into categories of impact, as shown in the risk matrix in Figure 1.18. The five-scale rankings are given scores of 1–5. Risk scores created by multiplying the

Probability of impact	Degree of impact				
	Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Very high (5)	5	10	15	20	25
High (4)	4	8	12	16	20
Medium (3)	3	6	9	12	15
Low (2)	2	4	6	8	10
Very low (1)	1	2	3	4	5

FIGURE 1.18 Risk matrix for probability and degree of impact to resources.

two 5-point scales can then be divided into risk categories, which are as follows:

- Very low risk: 1–5 points
- Low risk: 6–10 points
- Medium risk: 11–15 points
- High risk: 16–20 points
- Very high risk: 21–25 points

These risks then need to be compared with the actual resources at risk. If there is significant shoreline oiling, but there are no important socioeconomic or ecological resources in the area of impact, for example, the risk can then be categorically reduced to a lower level.

1.3.8 Interpreting Risk for Policy-Making

The results of oil spill risk analyses are incorporated into risk assessments, which involve the process of interpreting that risk for practical purposes, such as the following:

- Contingency planning for response and preparedness for most-probable and worst-case spill scenarios;
- Planning for protection of resources at risk;
- Risk allocation for insurance or taxation;
- Evaluation of trade-offs in decision-making;
- Conducting cost–benefit analyses of oil exploration, production, storage, or transport;
- Developing spill prevention measures; and
- Evaluating alternative courses of action for oil exploration, production, storage, or transport.

A scientifically based risk assessment process, including modeling of potential impacts and analysis of probabilities of impacts to sensitive resources, removes much of the subjectivity in the process. One example of the way in which such an analytical approach was applied for spill risk allocation were the analyses conducted for the state of Washington's Joint Legislative Audit and Review Committee (JLARC). JLARC was concerned with studying the risk of spills from various sources in the state so that the tax that was levied on the various parts of the industry to support state spill response programs could be better allocated with respect to the risk presented [10,27,28].

TABLE 1.14 Relative spill risk analysis for spills in Washington State [27]

Source type	Historical spillage analyses		Future (2015) analyses	
	Actual spillage	Worst-Case Discharge (WCD) spillage	Actual spillage	WCD spillage
Tank ships	3.78	75.44	3.03	56.93
Tank barges	1.77	6.40	1.77	6.04
Cargo vessels	10.29	15.42	11.32	32.00
Fishing vessels	1.38	2.01	1.38	3.79
Passenger vessels	0.04	0.34	0.04	0.64
Oil terminals	1.40	0.30	1.05	0.42
Pipelines	78.92	0.09	78.98	0.18
Tank trucks	2.39	0.00	2.39	0.01
Marinas/others	0.06	0.00	0.04	0.00
Total	100.00	100.00	100.00	100.00

Table 1.14 shows the analytical results of that study. The results indicate the percentage of risk (based on risk scoring conducted on probabilities of spills and impacts in different locations across the state). The risk differs by source type, as well as by time frame—past and future. Projected future spillage takes into account changes in patterns of vessel types, fuel used, oil consumption rates, and vessel traffic rates.

Past data indicate that the highest risk is from pipelines. This is because the largest spill in the study time frame was from a pipeline. It is also interesting to note that, based solely on historical data or projected data of actual spillage, tank ships would not be ranked very high with respect to spill risk. If, however, potential WCD scenarios are taken into account, the risk for tankers rises. This is because, while historically there have not been significant tanker spills in the state, there is the potential for a much larger volume of spillage from tankers than from other sources. For the purposes of taxation, the state elected to impose taxes based on past performance. For the purposes of spill response preparedness, however, the need for higher levels of preparedness is dictated by the potential volume of spillage, even if the probability is exceedingly low.

For contingency planning purposes and for development of spill prevention strategies, risk analyses are extremely important. With limited resources and economic constraints, government and industry officials are often concerned with aiming preparedness and prevention strategies at those measures that will bring the greatest benefit. Weighing the likelihood of spill events and the causes that lead up to them, as well as the potential impacts of hypothetical spill scenarios, can help to guide this process.

In the end, conceptualizing “risk” is often difficult. Industry and government officials are often confronted with a public demand for “zero risk” from oil spills, which is most likely a goal that is not realistically attainable.

High-profile spill events, such as the Deepwater Horizon (Macondo MC252 well blowout) incident, have reawakened the petroleum industry, risk managers, and government officials around the world from a state of relative complacency about the need to quantify risk and prepare for responses to high-consequence, very low-probability spill events, as well as to major spills in general. Public and governmental scrutiny over the appropriateness, effectiveness, and timeliness of the response to this spill of unprecedented magnitude has also called for a review of oil exploration and drilling risks, as well as contingency plans at all levels. With the reexamination of contingency plans and response preparedness in the Deepwater Horizon aftermath comes also an unprecedented opportunity to approach the contingency planning process anew with both the lessons learned from the Deepwater Horizon incident and the benefit of state-of-the-art modeling tools and recent research on spill risk.

1.4 OVERVIEW OF OIL SPILL PREVENTION

There are four basic ways to mitigate oil spill risk: reducing the volume of leakage, improving spill response by increasing the removal rate of oil, preventing oil from entering particularly sensitive locations, and, most importantly, preventing spills from occurring or reducing the probability of spills occurring.

1.4.1 Basic Strategies for Spill Prevention

The most effective way to mitigate oil spill risk is to prevent spills from occurring in the first place, or to reduce the likelihood of spill occurring. Spill prevention encompasses a broad array of tactics that aim to stem the release of oil or in some way impede the series of errors or malfunctions that can lead to a spill event. Prevention measures include such strategies as the following:

- Enclosing stored or transported oil in structures (e.g., tanks, pipelines, and vessels) that are less likely to be breached through outside impact or force (e.g., collision and frost heaving) or corrosion or breakage by the use of stronger materials, thicker hulls, or redundant layers (e.g., double hulls and secondary containment);
- Implementing strategies and systems to reduce the likelihood of outside force damage, such as vessel traffic systems to prevent collisions, improved navigational charting to reduce the likelihood of grounding, or marking of underground pipelines to prevent digging damage;
- Improving training of operators to reduce human error in producing, transporting, storing, handling, or using oil;
- Instituting operating procedure that reduces the likelihood of spillage;
- Installing devices to control the flow of oil and prevent overpressured flow as in well blowout preventers;
- Improving maintenance and inspection procedures to detect anomalies in structure, function, and operation that may lead to spillage;
- Relocation or rerouting of oil transport, handling, and storage to locations that are less likely to be the site of events that could lead to spillage; and
- Isolating oil-containing facilities and vessels to prevent sabotage and vandalism that might lead to spillage.

With spill prevention, the *probability* aspect of risk is reduced. The greater the reduction in probability of spillage, the more effective the spill prevention measure will be.

Each of the aforementioned prevention strategies has an impact on the probability of spillage. Other so-called spill prevention measures are really aimed at stemming the flow of an existing oil spill or leak and preventing it from becoming larger. This, in effect, affects the consequences side of the risk equation in that the consequences of a spill are closely related to the volume of spillage. Examples of spill volume reduction measures include such strategies as the following:

- Installing early leak detection systems that will notify operators of spillage or automatically shut the leak off from the system before the leakage becomes larger;
- Conducting salvage and lightering operations on a leaking ship to stabilize the vessel and remove remaining oil;
- Requirements for protective booming around vessels during lightering operations;
- Capping of a well during a blowout; and
- Shutting off a segment of a pipeline system that contains a ruptured pipeline.

Another way to reduce the risk of spills without actually preventing spillage is to affect the location and/or timing of potential spills. This would also act to reduce risk on the consequences side of the equation. Strategies could include such measures as follows:

- Locating or relocating spill handling facilities, vessels, or pipelines to locations that would have less sensitivity to impacts if a spill were to occur (e.g., rerouting pipelines away from high-consequence areas);
- Conducting oil handling or transporting during times or seasons when sensitive populations are not in the area; and
- Preventing construction of oil facilities (e.g., drilling rigs) in highly sensitive locations.

A corollary of this relocation strategy is the deflection of oil through protective booming during a spill response [29]. This strategy diverts oil from highly sensitive locations (e.g., wildlife areas) to areas that are less sensitive to the impacts of oil. Another example is conducting certain potentially risky operations (e.g., lightering) in locations that are not subject to conditions (e.g., high currents) that might allow significant oil to spread in the event of a spill.

1.4.2 Implementation of Spill Prevention Measures

Many of the spill prevention strategies described are part of voluntary industry initiatives and best-practices programs. In many cases, however, regulations have been imposed to reinforce spill prevention and risk mitigation measures for operators and companies in the oil industry (e.g., oil facility spill prevention regulations and double hulls on tank vessels). In other cases, officials have instituted measures that affect the larger system of oil transport, handling, and storage through the use of regulatory permitting and zoning for the location of facilities, improved vessel traffic and navigational systems, escort tug systems, and others [30]. Local, regional, and national spill response preparedness and contingency planning for spills also affects the larger system.

Regulations for spill prevention often involve fines and penalties for spillers and for those operators that do not abide by the regulatory measures. These fines and penalties are intended to act as deterrents in the event that the spills themselves with regard to costs of cleanup and other losses are not in and of themselves deterrents.

Spill prevention and risk mitigation programs require significant resources and costs for both the regulator and potential spillers with regard to capital expenditures on retrofitting and engineering, as well as costs for maintenance, training, monitoring, inspections, litigation, and enforcement.

Spill prevention regulations range from local permitting and zoning (e.g., locations of gas stations and oil storage facilities) to state or provincial regulations (e.g., storage tank inspection programs), to national laws (e.g., OPA 90 in the United States), and to international conventions (e.g., International Convention for the Prevention of Pollution from Ships 1973, as Amended in 1978, known as "MARPOL 73/78").

1.4.3 Effectiveness of Spill Prevention

The actual effectiveness of spill prevention measures depends on a variety of factors, including the degree of enforcement and compliance with the measures whether they are voluntary best practices or regulated. The effectiveness is also ultimately reliant on the extent to which the prevention measure really addresses the root cause of the spillage and the frequency with which spillage would have occurred without any intervention.

1.4.3.1 Overall Spill Reduction There has clearly been a significant reduction in oil spills across the board on an international basis in the last two decades or more [31]. This reduction has occurred despite the fact that there is more oil consumption and thus more oil production, transport, storage, and handling than previously.

While there are anomalies, such as the unprecedented spillage in the 2010 Deepwater Horizon/Macondo MC252 spill in the Gulf of Mexico, overall, there is a lower volume of spillage and fewer larger incidents occurring. There is also a trend toward the reporting of increasingly smaller incidents as part of a general awareness on the part of the public about impacts of spills, including very small incidents. There are a number of factors that have contributed to this spill reduction trend, which are as follows:

- Implementation and enforcement of prevention-related regulations;
- Better engineering and use of prevention equipment and practices;
- Greater awareness of the public on spill risks;
- Increased environmental responsibility of the oil and shipping industries; and
- Awareness of and reaction to the increasing consequences of spills, including higher response standards and costs, damage liability, and fines and penalties for noncompliance.

1.4.3.2 Double Hulls on Tank Vessels Probably, the most often–cited example of a spill prevention measure is the requirement for double hulls on tank vessels (tank ships or tankers and tank barges). Double hulls are mandated by the year 2015 in U.S. waters by the U.S. OPA 90, legislation enacted largely in reaction to the 1989 Exxon Valdez oil spill in Alaska. International convention followed suit by regulations in MARPOL and related national legislation to require double hulls on international fleets by the year 2026. There has been a continuous phase-in of double hulls with new tanker construction so that the fleets are increasingly double-hulled even before the mandated time.

As described in Section 1.4.3.2, double hulls on tank vessels act to both reduce the probability of spillage from impacts (collisions, allusions, and groundings) and reduce the volume of outflow in the event of a spill. For non-tank vessels, there is no reduction in oil outflow in the event of a spill, but there is a reduced probability that oil will be released as the result of damage from an impact casualty [32,33].

OPA 90 specified double hulls based largely on outflow models and engineering studies that indicated that there would be a 30% reduction in spillage for a 40,000 DWT tanker up to 70% for a 240,000 DWT very large crude carrier [2,34]. Analyses of empirical data showed that there were average reductions of spillage of 62% for tank ships and 20% for tank barges. This analysis confirms that double hulls are effective in reducing oil spillage [35].

Another study on international tanker spills estimated that for the time period 2000–2005, there was a 72% reduction in spills from tankers attributable to double hulls [36]. This reduction included a 49% reduction in small spills (between 7.8 and 780 m^3) and an 82% reduction in large spills (780 m^3 or larger).

There are, however, trade-offs with regard to safety on double-hulled tankers. An industry survey conducted by National Research Council indicated anecdotally that there were advantages as well as disadvantages of double hulls, as summarized in Table 1.15 [3].

TABLE 1.15 Advantages and disadvantages of double hulls on tank ships [3]

Function	Advantages	Disadvantages
Cargo operations	• Faster cargo discharge and good cargo outturn • Easier and faster cargo tank cleaning	
Construction		• Higher cost • More steel required • Longer construction time
Inspection and maintenance		• Higher maintenance cost • Need for continuous monitoring and maintenance of ballast tank coatings
Operational safety		• Structural safety concerns over intact stability • Increased stillwater bending moment • Difficult access and ventilation of ballast spaces

1.4.3.3 Oil Pollution Act of 1990 OPA 90, the comprehensive legislation enacted in the United States in large part in reaction to the 1989 Exxon Valdez spill, established stringent requirements for tankers operating in U.S. national waters. While double hulls on tankers were an important part of this legislation, there were other facets that would affect spill rates with regard to pollution liability, compensation, prevention, and spill response.

Perhaps, the most important rules of OPA 90 that effected spill prevention were those related to spiller liability. The regulations in OPA 90 regarding spiller liability are incompatible with the international conventions Civil Liability Convention and International Oil Pollution Compensation Fund Convention and are a major reason for the United States' decision not to become parties to those conventions. OPA 90 set federal limits of spill liability for costs and damages as high as $1200 per gross ton for vessel over 3000 DWT and unlimited liability in the case of gross negligence.

In addition, OPA 90 allowed states to set their own liability limits that could exceed the federal limits, including unlimited liability. Indeed, of the 24 U.S. coastal states, 16 have unlimited liability. This means that the responsible party (i.e., the "spiller") must pay for any and all costs for cleanup and damages, in addition to any fines and penalties that are imposed by federal and/or state authorities.

A radical departure from international protocol is the liability for natural resource damages. These are damages to ecological systems, habitats, and wildlife species that occur as a result of the spillage of oil. A NRDA is conducted by federal and state officials to determine the degree of damage to the environment and the costs of rehabilitating that environment in the same or similar location to reestablish the habitats and species that were affected by direct mortality and/or by impacts to reproduction and life cycles.

This increased liability for costs and damages coupled with generally increasing costs for spill response and a higher public concern about cleanup standards and spill impacts meant that there was greater risk and more at stake for the oil industry and others handling oil. Theoretically, with more at risk, it would be prudent for operators to increase vigilance about spill prevention and for industry to develop systems and practices that would reduce and prevent spillage even if there were no regulatory incentives.

Analyses of tanker spill rates (and spill rates in general) support this hypothesis in that there were reductions in spillage after OPA 90, which preceded the implementation of some of the more direct means of spill prevention, such as double hulls. A study conducted by Homan and Steiner [40] on the impact of OPA 90 on reducing oil spills indicated that increased liability was a statistically significant factor in reducing spillage. The same study also validated the hypothesis that double hulls were an effective means of reducing spills in tankers. The researchers calculated that without OPA 90 there would have been 26 large spills (>38 m^3) in 2004 as opposed to the actual number of five spills. Including much smaller spills, the expected number of spills without OPA 90 would have been over 80% higher than with the legislation (Fig. 1.19).

1.4.3.4 Environmental Protection Agency Spill Prevention, Control, and Countermeasures Program Another study conducted to determine the benefits of the U.S. Environmental Protection Agency's Spill Prevention, Control, and Countermeasures (SPCC) program showed similar results [22]. The SPCC rules affect oil storage and handling facilities that have a total aboveground storage capacity of 5 m^3 or more, store more than 160 m^3 underground, have had a spill of 3.8 m^3 or more, or two spills of more than 0.16 m^3 in a 12-month period. This affects hundreds of thousands of facilities across the United States. SPCC regulations require that facilities adopt a number of strict spill-preventive measures and prepare spill contingency plans.

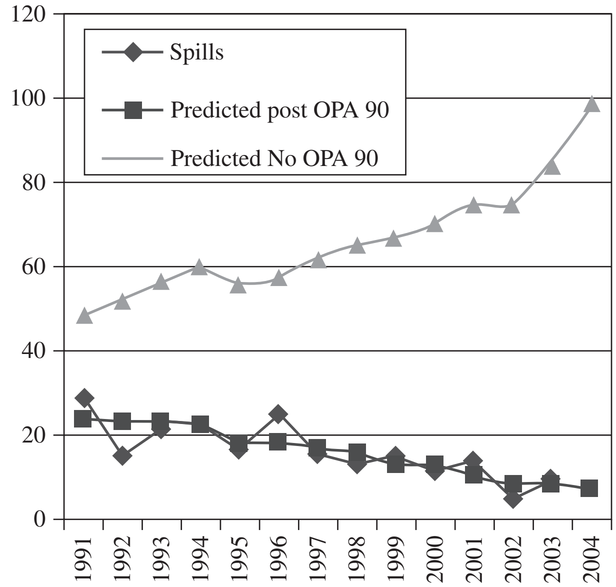

FIGURE 1.19 US spills >3.8 m^3 with and without OPA 90 [34].

An analysis of 25 years of spills (1980–2004) showed that spill rate for incidents over 1.9 m^3 decreased significantly despite a 27% increase in oil consumption in the United States over that time period. The number of spills per oil consumption decreased by 50% over 20 years, as shown in Figure 1.20. The benefits of the regulations in terms of spills prevented are shown in Figure 1.21.

1.4.4 Spill Fines and Penalties as Deterrents

Fines and penalties are major components of many spill-preventive regulations around the world. The purpose of these sanctions is to act as deterrents for future incidents as well as to impose on those who have committed offenses. A sample of oil spill fines and penalties for various nations is shown in Table 1.16.

There are no comprehensive studies that definitively determine whether fines and penalties are indeed effective deterrents for oil spills. Certainly, at least theoretically, the amount of the fine or penalty needs to be high enough to exceed the costs of avoiding the spill, whether that means instituting better training programs for operators, improving safety practices, or installing prevention devices, in order to have an actual deterrent effect.

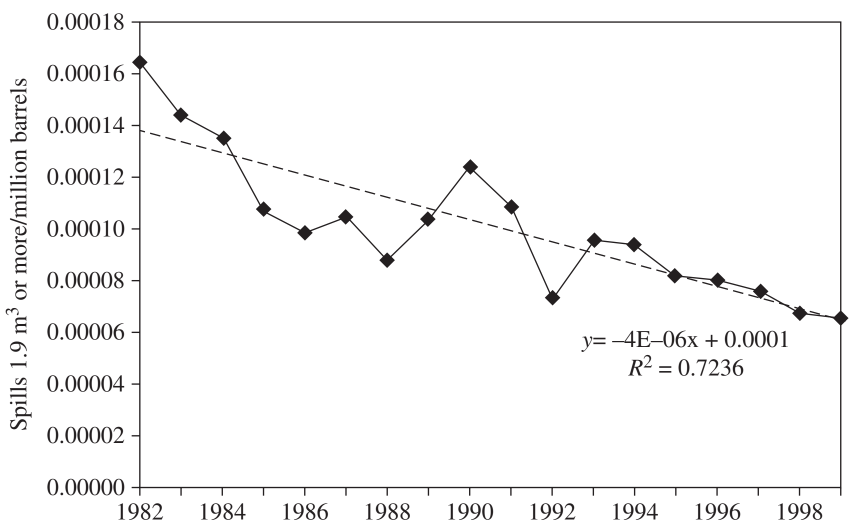

FIGURE 1.20 Number of spills from SPCC facilities per US oil consumption [10].

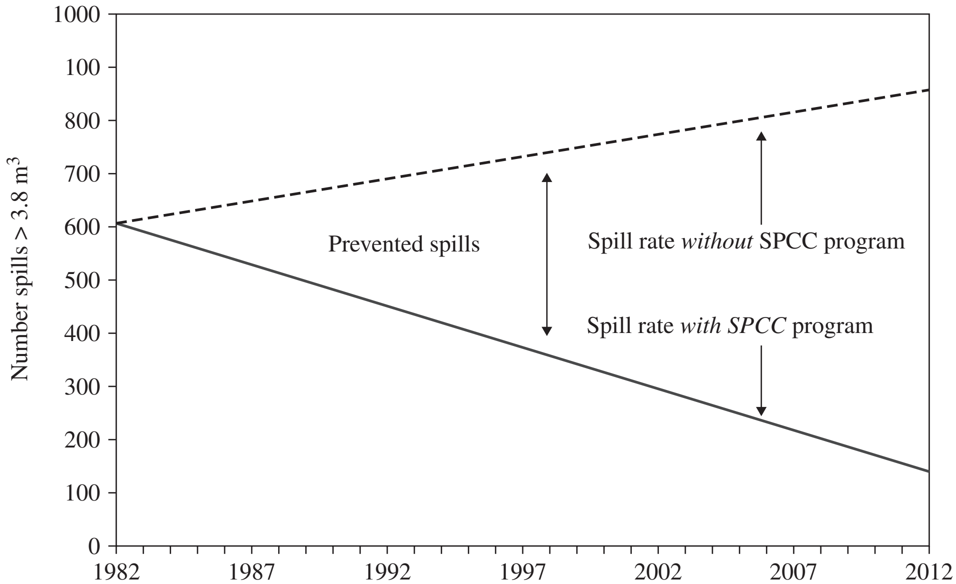

FIGURE 1.21 Facility spillage prevented with SPCC regulations [10].

TABLE 1.16 Sample of marine oil spill fines and penalties

Nation	Marine oil spill law	Fines and penalties
Albania	1991 Law on Environmental Protection	*Illegal discharges (individuals):* 1000–50,000 Leks [US$10–500]; *Illegal discharges (corporations):* 5000–500,000 Leks [US$100–5000]
Australia	Marine Pollution Act of 1987	To Aus$200,000 [US$130,907] *vessel master*
Brazil	No specific law *State and federal fines applicable*	*State:* To 50 million Reals [US$28 million]; *Federal:* Additional fines
Bulgaria	Environmental Protection Act of 1991	*Noncriminal pollution offenses:* 50,000–3,500,000 Leva [US$23,000–1,610,000]; *Repeat offenses:* 100,000–7,000,000 Leva [US$46,000–3,220,000]; *Insignificant violations:* To 50,000 Leva [US$23,000]
Cambodia	Law on Environmental Protection and Natural Resource Management	*Failure to allow vessel/facility inspection:* 500,000–1 million Riel [US$129–257]; *Repeat offenses:* 1–5 million Riel [US$257–1285]; *Pollution and failure to clean up pollution:* 1–10 million Riel [US$257–2570] *and/or* 1–3 months prison
Canada	Canada Shipping Act Migratory Bird Act (MBA) Fishing Act Canadian Environmental Protection Act	*Minor offenses:* To C$250,000 [US$168,175] *and/or* 6 months prison; *Major offenses:* To C$1 million [US$672,700] *and/or* 3 years prison; *Under MBA:* To C$520,000 [US$350,000]
Chile	Navigation Act of 1978	*Pollution violations:* To 1 million Pesos [US$1848]; *Serious dumping violations:* To 5 million Pesos [US$9240]
China	Marine Environmental Protection Law	*Causing pollution:* To 100,000 Yuan [US$11,961]; *Failure to report:* 1000–5000 Yuan [US$120–598]; *Failure to observe rules for dispersants:* 1000–5000 Yuan [US$120–598]; *Oil record book violation or false information:* 1000 Yuan [US$120]
Denmark	Act for the Protection of the Marine Environment	To 2100–5600 Krones [US$297–793] *ship master*
Estonia	Water Act Code of Administrative Offenses Pollution Charge Law Merchant Marine Code	*Discharges (individual):* To 4430 Kroons [US$298]; *Discharges (corporation):* To 114,789 Kroons [US$7729]; *Oil record violations:* 1840–3973 Kroons [US$124–268]; *Ship owners:* 188,371 Kroons [US$12,684] per tonne oil discharged
Finland	Act on Protection of the Sea Water Act Act on the Prevention of Pollution from Ships	*Individuals:* Day fines on the basis of income/blameworthiness; *Corporations:* 5000–5 million Markka [US$888–888,000]; *Gross negligence/willful misconduct:* Fines *plus* to 6 years prison
France	MARPOL 73/78 Implementation	*Large tanker violations:* To 1 million Francs [US$146,228] *and* up to 2 years prison; *Smaller tanker violations:* To 300,000 Francs [US$43,875] *and* up to 1 year prison
Germany	Penal Code	*Intentional discharges:* To 10,000 DM [US$5388] per day or 5 years prison; *Administrative fine:* To 100,000 DM [US$53,883]; *Oil record violation:* To 50,000 DM [US$26,911]
Greece	Mercantile Marine Law	*Most vessel cases:* 5,000,000 Drachmas [US$16,145]; *Most serious vessel cases:* 250,000,000 Drachmas [US$807,240]; *Onshore facilities (prefecture):* To 10,000,000 Drachmas [US$32,290]; *Onshore facilities (national):* To 10,000,000 Drachmas [US$322,896]; Polluters subject to 10 days to 5 years prison (can be bought for 200,000 Drachmas [US$646] per month)

TABLE 1.16 (Continued)

Nation	Marine oil spill law	Fines and penalties
India	Water Prevention and Control Act of 1974 Environmental Protection Act of 1986	*Giving false information:* 10,000 Rupees [US$224] *and/or* 3 months Prison; *Tampering with monitors:* 10,000 Rupees [US$224] *and/or* 3 months prison; *Allowing pollution:* 6 months to 6 years prison *plus* possible fine; *Repeat pollution offenses:* 1½ to 7 years prison *plus* possible fine; *Other pollution offenses:* 10,000 Rupees [US$224] *and/or* 3 months prison *plus* 5000 Rupees [US$112] per day
Indonesia	Law Concerning Environmental Management	*Pollution incidents:* 500,000,000 Rupiah [US$56,000] *and* up to 10 years prison; *Pollution with death/injury:* To 750,000,000 Rupiah [US$84,000]; *Negligence: Additional* 100,000,000 Rupiah [US$11,200] *and* 3 years prison; *Negligence with death/injury: Additional* 150,000,000 Rupiah [US$16,800] *and* 5 years prison
Ireland	Marine Pollution Law	*District court cases:* To 1000 Punts [US$1345]; *Higher court cases:* To 25,000 Punts [US$33,635]
Japan	Marine Pollution Prevention Law	*Intentional spill:* To ¥10,000,000 [US$93,370]; *Unintentional but at fault:* To ¥5,000,000 [US$46,685]
Kenya	Merchant Shipping Act	12,050 Shillings [US$158]
Latvia	Administrative Code	*Oil record violations:* 250 Lats [US$426] Latvian master/crew, 500 Lats [US$853] foreign master/crew; *Pollution violations:* 250 Lats [US$426] Latvian master/crew, 2000 Lats [US$3413] foreign master/crew; *Failure to report:* 250 Lats [US$426] Latvian master/crew, 500–3000 Lats [US$853–5119] foreign master/crew; *Administrative fines:* 20–250 Lats [US$34–426] Latvian-flagged vessel; 1162–5812 Lats [US$1984–9918] foreign-flagged vessel; All violators must pay environmental damage fee of 32 Lats [US$54] per kg oil spilled *plus* 2500 Lats [US$4266] per tonne oil spilled as natural resources tax.
Lithuania	Administrative Law Violation Code	*Pollution prevention violations:* To 1,000,000 Litas [US$247,688] *plus* 5 years prison *plus* 8000–100,000 Litas [US$1,982–24,782] *or* 240 Litas [US$59] per kg oil spilled
Malaysia	Merchant Shipping (Oil Pollution) Act of 1994 Merchant Shipping Act of 1952	*Failure to obey official orders:* To 50,000 Ringgit [US$13,160] per day; Violations of pollution prevention regulations: To 10,000 Ringgit [US$2632] *and/or* up to 1 year prison
Mauritius	Ports Act	20,000–400,000 Rupees [US$788–15,754] depending on cleanup costs
Mexico	Federal Oceans Law General Law of Ecological Balance and Environmental Protection (Ecology Law) National Waters Law General Health Law Ocean Dumping Law Coastal Zone Regulation	*Coastal Zone Regulation violations:* 50–500 times minimum daily wage (MDW); *Ecology Law (marine pollution):* 20–20,000 times MDW; *National Waters Law wastewater discharges:* 100–10,000 times MDW; *Ocean Dumping Law violations: Dumping Annex I:* 300–1300 Pesos [US$33–143]; *Vessel/platform abandonment:* 300–750 Pesos [US$33–83]; *Failure to report emergency dumping:* To 750 Pesos
Netherlands	National Maritime Law	To 300,000 Guilders [US$142,418]
Nigeria	Oil in Navigable Waters Act	*Discharges:* 2000 Naira [US$22]; Oil record violation: 1000 Naira [US$11] *and/or* 6 months prison; *Illegal night transfer operation:* 200 Naira [US$2]; *Ballast/waste discharge in harbor:* 20 Naira [US$0.20] per day
Norway	Norwegian Pollution Control Act	*Vessel owners:* 50,000–120,000 Krona [US$6347–15,233] *and/or* 5–10 years prison; *Crew:* 1-month's salary
Panama	National Maritime Law	To 200,000 Balboas [US$197,720]
Philippines	Pollution Control Law Marine Pollution Decree	*Facility discharges:* To 5000 Pesos [US$1000] per day; *Persons responsible:* To 1000 Pesos [US$20] per day *and/or* 2–6 years prison; *Vessel/offshore discharges:* 200,000 Pesos [US$4000] *and/or* 30 days to 1 year prison
Poland	Act on Marine Areas of Republic of Poland and on Maritime Administration Act on the Prevention of Pollution of the Sea from Ships	*Oil dumping violations:* 1,000,000 Special Drawing Rights [US$1,317,289]; *Crew/master pollution violations:* To 20-months' average national salary
Russia	Instruction for the Prevention of Pollution from Ships	*Pollution violations:* To 3000 times minimum national salary
Singapore	Prevention of Pollution Sea Act	To Sing$500,000 [US$293,028] *and/or* 2 years prison
South Africa	Marine Pollution (Prevention of Pollution from Ships) Act	*Serious offenses:* 200,000 Rands [US$32,693]; *Most serious offenses:* 500,000 Rands [US$81,733]
Sweden	Act Concerning Measures for the Prevention of Water Pollution from Ships Ordinance Concerning Measures for the Prevention of Water Pollution from Ships Decree by National Maritime Administration	Day-fines (money-fines for crimes <30 day-fines); *Day-fines:* 30–150 or if joint punishment for several violations, to 200. Amount of day-fines: 30–1000 Krona [US$4–121], Joint punishment to 5000 Krona [US$606]; *Money-fines:* 100–2000 Krona [US$12–242], Joint punishment to 5000 Krona [US$606]
Taiwan	Water Pollution Control Act of 1974	*Violations with human fatality:* To 300,000 NTD [US$9000]; *Violations with serious harm to humans:* To 150,000 NTD [US$4500]; *Other pollution incidents:* 30,000–300,000 NTD [US$900–9000]

(*Continued*)

TABLE 1.16 (Continued)

Nation	Marine oil spill law	Fines and penalties
Thailand	Enhancement and Conservation of National Environmental Quality Act	*Order violations:* 100,000 Baht [US$2476] *and/or* 1 year prison; *Responsible for pollution:* 500,000 Baht [US$12,378] *and/or* 5 years Prison; *False information:* 100,000 Baht [US$2476] *and/or* 1 year Prison; *False information through public media:* 500,000 Baht [US$12,378] *and/or* 5 years prison; *Polluting source owner:* 100,000 Baht [US$2476] *and/or* 1 year prison
Ukraine	1995 Water Resources Act	To 600,000 Hryvnias [US$131,901]
United Kingdom	Merchant Shipping (Prevention of Oil Pollution) Regulations of 1996	*Magistrate's Court*: To £250,000 [US$409,641]; *Crown Court (most serious offenses):* unlimited fines
United States	Oil Pollution Act of 1990 Federal Water Pollution Control Act Comprehensive Environmental Response, Compensation, and Liability Act of 1980	*Class I civil penalties:* To US$10,000–25,000 maximum; *Class II civil penalties:* To US$10,000 per day to US$125,000 maximum; *Judicial civil penalties:* To US$25,000 per day or to US$1000/bbl (US$7000/t) spilled; *Gross negligence:* US$100,000 minimum to US$3000/bbl (US$21,000/t) spilled; Also fines and penalties by state.
Venezuela	Penal Law of the Environment	To 17,150,000 Bolivars [US$25,000] *plus* imprisonment
Vietnam	1993 Law on Environmental Protection 1996 Environmental Protection Government Decree	*Contingency plan violation:* 2–8 million Dong [US$142–568]; *Causing oil spill:* 30,000,000–50,000,000 Dong [US$3550–7100]; *Violations with negligence or repeat offenses*: *Additional* 50–100 million Dong [US$3550–7100]; *Failure to report:* 50,000–200,000 Dong [US$4–14]; *Failure to report with negligence or repeat offenses:* 5–20 million Dong [US$355–1420]; *Failure to remove oil:* 50,000–200,000 Dong [US$4–14]; *Failure to remove oil with negligence or repeat offenses:* 5–20 million Dong [US$355–1420]

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