DISPERSING OIL NEAR SHORE IN THE CALIFORNIA CURRENT REGION

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ABSTRACT

Mathematical models were used to develop scenarios for evaluating alternative nearshore responses to oil spills, including the use of chemical dispersants. The scenarios were used in ecological risk assessment (ERA) workshops designed to help fisheries, wildlife, and resource managers determine whether they would support preapproving the use of dispersants. Resource managers proposed a worst-case spill scenario for the Gulf of the Farallones. Models were used to compare five options—no response, mechanical, burning, and two levels of dispersants—showing the trajectories, fate, and concentration of oil in surface slicks and dispersed oil plumes. Participating biologists used current data on dispersant and dispersed oil toxicity to develop consensus-based toxicity guidelines. During the first several hours following dispersal, the simulated dispersed oil concentrations exceeded guidelines for early life-history stages of fishes and zooplankton; adult fish and crustaceans were at risk for two hours. The benefits and risks to fishes, seabirds, cetaceans, pinnipeds, sea otters, and shoreline resources (marshes, kelp beds, and protected areas) were compared for the five response options. Dispersants substantially reduced the amount of both floating and stranded oil relative to the other options. Furthermore, the higher dispersant level (85%) removed more oil than the lower level (35%). Risk assessments so far indicate that chemical dispersion can reduce the overall ecological effects of a nearshore oil spill. The final decision to preapprove dispersant use along the Pacific Coast will still require input from the political, social, and economic sectors.

INTRODUCTION

Chemical dispersion is an often-debated method for responding to oil spills, yet it is rarely used. During the past 30 years, mechanical containment and recovery, extensive shoreline cleanup, and highly publicized bird and wildlife rehabilitation have been the primary responses to oil spills along the coasts of Washington, Oregon, California, and northern Baja California. There is renewed interest in using dispersion as a response to reduce injuries to wildlife and shoreline oiling in the California Current region.

Dispersants are most effective when used early in a spill. Chemical dispersants are currently permitted on a case-by-case basis in Oregon, Washington, and offshore areas of California. Since most spills begin near shore, there is interest in preapproval or quick approval for dispersing spills in shallow water. Approval requires consultation with resource agencies at the time of a spill. Preapproval can greatly reduce decision time and help ensure that dispersion capability is available.

Recently, ecological risk assessment (ERA) workshops were held in Washington, Texas, and California to inform resource managers about traditional and alternative responses to oil spills as well as the need for preapproval, quick approval, or shallow-water approval processes (Aurand et al. 2001; Kraly et al. 2001; Walker et al. 2001). These workshops, supported by the Hazardous Materials Response Division (HazMat) of the National Oceanic and Atmospheric Administration (NOAA), focused on oil spill simulations to evaluate the efficacy of response.

This paper summarizes our current knowledge of dispersants, dispersing oil, the need for preapproval, methods used to simulate spill responses, and ecological risk assessment. In addition, we compare scenarios for dispersed and nondispersed oil spills, examining the trajectory, fate, and effects of a simulated oil spill near shore in northern California at the Gulf of the Farallones.

BACKGROUND

Dispersants and Dispersion

Dispersants are chemicals that break up oil slicks. Dispersants, such as Corexit 9500 and Corexit 9527, contain surfactants and solvents which reduce the surface tension of floating oil (NRC 1989; S. L. Ross 1997). During dispersant operations, neat or diluted mixtures of dispersants are loaded onto aircraft or boats and sprayed as a fine mist directly on the oil slicks. The dispersant mixture causes the oil to break up into tiny (10 to 100 micron) droplets. With adequate wave energy, such as a light wind chop, the oil droplets mix down into the water column and spread laterally, resulting in turbid clouds or plumes of oil within a few meters of the sea surface. Over the next few minutes and hours these plumes continue to dilute by mixing laterally and downward, and move out of the spill area with prevailing currents.

Treating oil slicks with dispersants quickly breaks up and submerges oil, effectively reducing the risk of oiling sea birds, marine mammals, and sensitive shorelines (NRC 1989). Dispersion also appears to greatly increase the rate at which oil is degraded (Cretney et al. 1981; Swannel and Daniel 1999) and, if used early in a spill, may help prevent the formation of water-in-oil emulsions (chocolate mousse) and tar balls (NRC 1989).

Dispersion effectiveness is limited by several constraints: (1) the oil must be dispersible (some heavy oils are not); (2) there must be sufficient wave energy to mix dispersed oil into the water column (light chop a minimum); (3) treatment must be done during the first few hours after the spill (weathered oil is less dispersible than fresh); and (4) the operation must be logistically feasible (NRC 1989). Conventional wisdom has held that the window of opportunity—the set of physical and temporal conditions that allow chemical dispersion to be effective—is narrow and generally limited to the first few hours to a day after a spill and to a modest range of fuel and oil types (NRC 1989; Reed et al. 1999). Thus the decision to disperse must be made quickly if it is to be effective.

Ironically, all response options, including dispersants, skimming, and shoreline cleanup, can also redistribute oil and cause ecological injuries above and beyond those caused by an untreated spill (table 1; API, in press). Finally, oil may disperse without application of chemical dispersants, because many light and medium oils disperse naturally (NRC 1989). Such was the case with the highly lethal *Tampico Maru* diesel spill in a cove off Baja California in 1958 (North et al. 1964).

Obviously, the benefits of intentionally dispersing oil must be weighed against possible damage to life in the water column, including fish and fish habitat. Both dispersants and fresh oil are toxic to zooplankton and sensitive life stages of fishes and invertebrates; oil is the more toxic of the two (NRC 1989; Singer et al. 1998; Clark et al., in press). Although dispersed oil does not sink to the seafloor, plumes of dispersing oil mix and mingle with the plankton and may drift over shallow-water benthic habitats such as oyster and clam beds or populations of shrimp, demersal fish, or sea grasses (if dispersed near shore). These organisms may become temporarily contaminated with oil or petroleum hydrocarbons (Page et al. 1983; NRC 1989; Michel and Henry 1997). If dispersed oil concentrations are high enough, and exposure long enough, populations may be injured or killed.

Historical research on dispersants included field trials in southern California in the 1970s using intentionally spilled and dispersed oil (McAuliffe et al. 1981).

TABLE 1
Countermeasures Available to Marine Spill Responders and Some of Their Ecological Impacts

Countermeasure (stressor)	Ecological impact
No response (natural recovery)	Low if oiling light
Open water response	
Containment boom	Oil in undertow water; chain rips sea grass
Skimmers	Noise; air pollution
In situ burning*	Smoke
Chemical dispersion*	Water column toxicity
Chemical herding*	Toxicity?
Shoreline cleanup	Injure eggs of shore spawners
No action (natural recovery)	Slow; toxicity; smothering
Manual removal	Damaging foot traffic
Mechanical removal	Physical shoreline damage
Sorbents/passive collection	Excess waste generation
Vacuum	Fuel consumption; foot traffic
Sediment reworking/tilling	Sediment physical damage
Berm relocation	Resuspension/dispersion
Surf washing	Resuspension/dispersion
Vegetation cutting/removal	Stress to marsh if not careful
Burning*	
Marsh	Smoke; combustion of biota
On beaches	Smoke
Deluge flooding	Nearshore oil dispersion
Ambient-temperature washing	
Low pressure	Nearshore oil dispersion
High pressure	Mortality to surviving biota
Warm and hot water washing	Mortality to surviving biota
Sand and slurry blasting	Mortality to surviving biota
Chemical countermeasures*	
Shoreline cleaners	Toxicity; dispersion
Solidifiers	Not enough experience
Bioremediation*	
Nutrient enhancement	Nutrient, metabolite toxicity
Bacterial inocula	Metabolite toxicity; nonindigenous microbes

Note: Each response is effective under certain conditions, but each can cause collateral effects or redistribute oil.
*Requires special approval.
Assembled from various sources, including API, in press, and Mearns 1996.

These sea trials provided not only a reality check for operations and monitoring but also necessary data for developing and testing mathematical models for forecasting dispersed oil concentrations in water (MacKay et al. 1982). Dispersion operations were approved at two California spills in the 1980s: the tanker *Puerto Rican* spill in November 1984 (Zawadski et al. 1987) and the *Pac Baroness* spill near Point Conception in September 1987 (Payne et al. 1991). These operations were limited, and their effectiveness was equivocal.

New Information in the 1990s

In a detailed review of dispersant use, fate, and effects, the National Research Council identified a number of uncertainties (NRC 1989). These uncertainties have been mostly resolved during the 1990s. The principal concerns were fate and toxicity (Aurand 1995a) and poor communication of existing knowledge (Bostrom

TABLE 2
Oiled and Dead Birds Recovered during Six California Oil Spills

Year	Incident	Location	Oil type	Volume L (gallons)	Number of oiled birds recovered
1990	*American Trader*	Huntington Beach	ANS Crude	1,514,000 (400,000)	1,017
1993	UNOCAL	Avila Beach	San Joaquin	23,846 (6,300)	>100
1997	*Kure*	Humboldt Bay	IFO 180	946,250 (250,000)	984
1997	Mystery spill	Point Reyes	Crude	No data	>500
1998	Mystery spill	Santa Cruz	Unknown	No data	1,535
1999	*Stuyvesant*	Eureka	IFO 180	7,570 (2,000)	1,270

Source: Michael Sowby, California Oil Spill Prevention and Response, Sacramento, October 2000, personal communication.

et al. 1997). During the 1990s several coordinated industry, government, and academic field and laboratory activities resolved issues dealing with dispersed oil fate and toxicity (Aurand 1995b; S. L. Ross 1997; Singer et al. 1998; Rhoton et al. 1999; George-Ares and Clark, 2000; Page et al. 2000; Clark et al., in press). The toxicity studies included sensitive early life stages of California Current nearshore organisms such as kelp mysids, giant kelp sporophytes, and larval abalone (Singer et al. 1998). Dispersant formulations have been refined, and there is a considerable body of new knowledge about their effectiveness (Clayton et al. 1993; Lunel et al. 1997; S. L. Ross 1997; Fiocco et al. 1999b; Lunel and Lewis 1999; Lessard and DeMarco 2000). The results of direct field trials (intentional oil spills) indicate that the conventional window of opportunity has widened to increase response time to two days, accommodate heavier oils, and lower dispersant-to-oil ratios (S. L. Ross 1997; Fiocco et al. 1999a). Finally, there are new data from laboratory, mesocosm, and field studies about oil-dispersion processes, better numerical models, and more effective treatment operations. These studies all suggest that more spills may be suitable for the use of dispersants.

Equally important is new and controversial information suggesting that small amounts of oil remaining after even extensive shoreline cleanup are sufficient to injure embryos of shore-spawning fishes such as Pacific herring (*Clupea pallasi*) and pink salmon (*Oncorhynchus gorbuscha*; Kocan et al. 1996; Marty et al. 1997; Carls et al. 1999; Heintz et al. 1999). Indeed, aggressive shoreline cleanup itself disperses oil into very shallow water, damages surviving shoreline biota, and delays recovery of shoreline habitat (table 1 and Mearns 1996). Thus, efforts to prevent shoreline oiling (through dispersant use) can reduce the long-term effects of an oil spill on fish habitats such as sediments, marshes, eelgrass, and kelp beds. Although this new knowledge raises more questions, it also brings into clearer focus important trade-offs of all response options.

Assessment of Oil Spill Risk

There has been a worldwide decline in both the volume of oil spilled and the frequency of very large oil spills (3.8 million liters or 1 million gallons) during the past decade (Etkin 1999). In the California Current region, however, there is no long-term trend for the 22-year period 1978 through 1999 for midsize spills greater than 37,850 L (10,000 gal).

Previous spills in the California Current region included 155 coastal and marine incidents involving a total spillage of 70 million L (18.5 million gal) of oil and fuel products. This total is about twice that spilled by the *Exxon Valdez* in Alaska. Of the California Current region spills, 121 occurred in California (61 million L, or 16 million gal), 25 in Washington (7.4 million L, or 1.95 million gal), and 9 in Oregon (1.8 million L, or 0.47 million gal). Per mile of shoreline, these 22-year totals are: California, 4,670 gal, or 17,800 L per mile; Oregon, 330 gal, or 1,280 L per mile; and Washington, 640 gal, or 2,450 L per mile. Many of these involved highly dispersible products.

Smaller spills (0.04–0.38 million L, or 10,000–100,000 gal) continue to occur with fishing and cargo vessels, pipelines, and shore facilities, so fish and wildlife continue to be injured regardless of spill volume. During the past decade thousands of sea- and shorebirds have been oiled from nearshore spills in the California Current region. We estimate that since 1990 more than 5,000 birds representing over 25 species were recovered oiled or oiled and dead in six notable California spills (table 2). These counts represent only a small fraction of the actual number injured, which were not counted.

Historically, there have been many lost opportunities in the United States to use dispersants to protect shorelines and wildlife. Kucklik and Aurand (1997) reported that of 207 spills of oil and fuel larger than 159,000 L (1,000 bbls, or 42,000 gal) between 1973 and 1994, 60 could have been treated with dispersants on the basis of oil type (dispersibility) and weather conditions. Most of these spills occurred near shore, well within individual state-defined limits of 2 or 3 nautical miles (nmi; or 3.7 and 5.6 km) or the 33 ft (10 m) or 60 ft (approximately 20 m) isobaths, inside of which there is currently no preapproval in the United States (other than Hawaii). Presumably many more smaller spills that were potential candidates for dispersion went unreported.

Current Dispersant-Use Policy

During the 1990s dispersants were preapproved for use in most U.S. Atlantic and Gulf of Mexico coastal waters beyond 2 or 3 nmi (3.7 or 5.6 km) and beyond the 33 or 60 ft (10 or 20 m) isobaths. For oil spills beyond this nearshore zone, in these regions, the U.S. Coast Guard (USCG) federal on-scene coordinator (FOSC) is preauthorized to order dispersant applications without additional consultation with state and federal resource trustees. During the last four years, under preapproval guidelines, at least four oil spills have been treated with dispersants in Louisiana and Texas (Calhoun et al. 1997; Gugg et al. 1999). In addition, the USCG and NOAA HazMat supported dispersant use at recent (2001) spills in the Galápagos Islands and near Barbers Point in Hawaii.

Dispersant preapproval has not been implemented for the U.S. West Coast. Dispersants are not banned in Washington or Oregon, but they cannot be used in inshore waters without deliberation and consultation on a case-by-case basis (at the time of the spill). In Washington a preapproval plan exists (WDOE 1993), but has not been implemented pending state approval of a monitoring plan. In Oregon, dispersant use remains on a case-by-case basis; Oregon has accepted the Washington guidelines, but has not yet applied them to a preapproval process. In California, preapproval does not exist, but the state does support an explicit "expedited" decision process: case-by-case use will be considered for spills beyond 0.5 nmi or the 60 ft (approximately 20 m) isobath, whichever is more restrictive. In all three states there is growing interest to preapprove dispersant use and to develop and stage dispersant response capabilities (chemicals, delivery systems, and aircraft).

The Preapproval Process in the California Current Region

The new knowledge gained since the 1989 NRC review sets the stage for revisiting dispersant preapproval in the California Current region. In addition, there is renewed local and national interest in reevaluating the use of chemical dispersants on oil slicks close to shore—0.5 nmi (California) or 3 nmi/60 ft isobath limit (other states). As noted above, most spills in the California Current states have been very close to shore. No authorization or preapproval exists for treating oil spills inshore or over shallow water anywhere in the California Current region or the United States.

Preapproval is important because it ensures dispersion capability, training, and use in spill-response drills. Many response tools are preapproved and can be implemented by the FOSC without further consultation. But alternative tools, such as dispersants and burning, require the FOSC to first consult with the regional response team (RRT), which includes representatives of all state and federal resource agencies and trustees.

To obtain approval or preapproval in the California Current states, the USCG must consult with state and federal wildlife and fisheries trustees on endangered species issues, managers of sanctuaries and reserves, and non-government organizations. Approval or preapproval must also satisfy requirements of federal essential fish habitat (EFH) regulations under the Magnuson-Stevens Act.

Scenarios for Ecological Risk Assessment

During 1998–2000 the USCG, together with several state agencies, hosted a series of ecological risk assessment (ERA) workshops (following Aurand 1995b) to evaluate and compare the benefits and risks of dispersing oil spills in nearshore and/or shallow-water areas. Work groups included resource trustee decision makers (risk managers) and resource scientists (risk assessors; Aurand et al. 2001). NOAA HazMat supported these workshops by providing model results for site-specific oil spill scenarios and other information needed to evaluate the effectiveness and effects of response operations.

In the California ERA workshops, risk managers decided on two worst-case scenarios, one off San Francisco in the Gulf of the Farallones and the other inside San Francisco Bay. In this paper, we highlight the "Pilot Station" spill located 6 nmi due west of the Golden Gate. It was decided by consensus that the scenario would involve release of 408,975 L (2,500 bbls[1]) of a heavy fuel oil, IFO 180, at midnight in the fall season. Local conditions included constant northwesterly winds at 15 knots, 55° water temperature, and 1–2 foot waves (chop); the release was made during slack tide before ebb.

This scenario was significant because it occurred between the boundaries of two national marine sanctuaries (Gulf of the Farallones NMS and Monterey NMS) and had the potential to enter San Francisco Bay, exposing both bay and open coastal fisheries and wildlife resources to oil slicks, dispersed oil plumes, and/or smoke from in situ burning. In addition, late fall marks the Davidson Current season, which is characterized by a strong northward current which could move a dispersed oil plume up-coast and through the Gulf of the Farallones NMS.

The dispersion alternative was implemented at 1200 hrs, 12 hours after the spill, as the spreading slick was moving toward San Francisco and the Marin County shorelines. From this point forward two alternative scenarios were modeled over the next 3–4 days: the undispersed surface oil slicks moving toward and impacting San Francisco and Marin County shorelines, and the

[1] 1 barrel (bbl) = 42 gallons (US) = 159 L.

dispersed plume moving where currents dictated, northward along the coast to Point Reyes.

This spill scenario had an additional complication: the spilled oil, IFO 180, is a heavy fuel oil, which is, according to conventional wisdom, difficult to disperse. Laboratory and field tests, however, indicate that it is now possible to disperse this type of heavy fuel oil (Fiocco et al. 1999a). Accordingly, workshop participants wished to evaluate two dispersant effectiveness strategies: 35% effectiveness and 80% effectiveness.

Five response options were compared:

- No response: the oil was allowed to evaporate and disperse naturally and to strand on shore with no treatment or cleanup.
- Mechanical recovery: participants determined that 20% of the oil (500 bbls) could be removed from the sea surface by skimming, with cumulative removal rates of 250 bbls by hour 12, 425 bbls by hour 36, and 500 bbls by hour 72.
- Burning: participants determined that 280 bbls of floating oil could be boomed off and burned at hour 12.
- Dispersion at 35% and 80% effectiveness: participants determined that all necessary dispersant approvals were in place, delivery vessels and aircraft were properly equipped, and treatment with 2,400 gallons of dispersant mixture, at a dispersant-to-oil ratio of 1:20, could be executed over a five-hour period centered on hour 12.

SPILL SIMULATION METHODS

Two existing operational models and a simple box model were used to produce oil spill spreading and trajectory maps, charts of oil transformations, and concentrations of dispersed oil.

Oil Spill Spreading and Trajectory

We simulated the spreading, breakup, and trajectories of the oil spills with NOAA HazMat's On-Scene Spill Model (OSSM; Torgrimson 1984).[2] Inputs included maps, coastal outline and shoreline descriptors, bathymetry, numerical circulation models, statistical climatological simulations, location and type of the spilled substance, oceanographic and meteorological observations, and other data. Current speeds and directions were derived from tidal currents and current-meter records as modified by bathymetry. The output included time-series maps showing the overall size and shape of the oil slick footprint, the concentrations of oil (percent cover) within the footprint, and their confidence limits.

[2]A recent update of the modeling system environment, "General NOAA Oilspill Modeling Environment" (GNOME) is given in Beegle-Krause 1999, and is also documented and available for use on our public Web site (*http://response.restoration.noaa.gov*). Recently, NOAA HazMat introduced ADIOS 2 (see detailed documentation and the model at the same Web site).

Fate and Transformation

Oil properties (density, viscosity, volume, chemical composition) are rapidly transformed by spreading, evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation (collectively referred to as weathering). Oil decreases in mass and increases in viscosity because of evaporation and natural dispersion, and then increases in mass through the formation of water-in-oil emulsion (mousse). Transformation imposes increasing constraints on response. Viscous oil and mousse are difficult to disperse, difficult or impossible to skim without special equipment, and nearly impossible to burn.

Transformations of floating oil properties were computed by means of automated data inquiry for oil spills (ADIOS; Lehr et al. 1992). ADIOS integrates a library of approximately one thousand oils with a short-term oil fate and cleanup model to help estimate the amount of time that spilled oil will remain in the marine environment. The model output can be used to develop cleanup strategies. Input includes wind speed, salinity, water temperature, wave height, and type of oil. Output included a time series of means and confidence limits for viscosity, percent evaporation, water content, and natural dispersion. The volume of emulsion (mousse) was calculated as the sum of oil remaining plus its water content.

Dispersion Simulation

After the application of dispersants, oil droplets quickly mix down into the surface layer to a depth of 1.5 times the wave height (Delvigne and Sweeney 1988). The chemically dispersed oil droplets (smaller than about 60 microns) are neutrally buoyant and do not return to the surface. Wind causes Langmuir circulation (wind-generated convection cells found in the ocean that are responsible for vertical mixing down to a few tens of meters from the surface) and sets up circulation cells (tens to hundreds of meters apart) which move the neutrally buoyant droplets vertically, downward from the surface and stopping at the point in the water column where density increases rapidly (pycnocline; MacKay et al. 1982).

We simulated the dispersion of oil by using simple one-dimensional box modeling. The volume to be dispersed was determined by fate modeling (above) and by the ERA workshop managers' judgment on the effectiveness of a dispersant operation. During the first two hours after dispersion the volume of spilled oil was mixed vertically down to 1.0 m (1.5 times a wave height of 0.6 m defined by wind speed). Over the next 18 hours the dispersed oil was mathematically mixed down to the top of the pycnocline (7 m). The spreading and trajectory of the water mass containing dispersed oil was simulated with OSSM, but the wind was removed as a direct factor (the wind's indirect contribution to the current was retained).

Dispersed Oil Concentrations

We computed mean dispersed oil concentrations, in mg/L or parts per million (ppm), simply by dividing the dispersed oil volume (in liters or gallons) by the volume of water containing the dispersed oil (i.e., the product of the plume footprint area and its thickness). The calculation was performed for each of several time intervals (1, 2, 3, 4, 5, 6, 12, 18, 24, 36, 48, 72, and 96 hours). The result was a time series of mean dispersed oil concentrations that decrease continuously as the contaminated water volume increases.

Uncertainty

Several types of uncertainty were also addressed in the simulations. As noted above, uncertainties regarding the speed, spreading, and transport of undispersed surface slicks were defined by seasonal climatological variability and estimated errors in wind direction and speed (Galt 1997, 1998). The actual concentration of dispersed oil in the water column is also expected to have a large variability around the estimated mean concentration. The primary reasons for the variability are the patchiness of the surface oil distribution at the time of dispersant application, the uneven application of the chemical dispersant, and the spatial variations of the vertical mixing functions such as wind waves and Langmuir circulation. A variance of three around estimates of mean dispersed oil concentrations was suggested by MacKay et al. (1982) on the basis of a comparison of model results with actual data from intentional oiling field experiments in southern California. To account for all sources of variability and uncertainty, we computed upper dispersed oil concentrations as 5× the mean, and lower dispersed oil concentrations as 0.2× the mean. The range of dispersed oil concentrations represents our best professional judgment as to realistic oil concentrations on the basis of direct observation and other modeling activities related to dispersion processes.

Assessing the Ecological Effects of Dispersed Oil

The ERA workshop participants agreed that toxicity to marine fishes and invertebrates was their primary concern regarding the hazards associated with dispersing oil. There is a large body of data about the acute and chronic toxicity to adult and juvenile marine organisms of mechanically and chemically dispersed oil and dispersants. These data were presented to, and examined by, resource biologists during the course of the ERA workshops. The data were then used to develop consensus guidelines of concern.

TABLE 3
Ranges of 96-Hour EC50s and LC50s for Early Life History Stages of 7 Species of Fishes and Invertebrates Subjected to Various Treatments

	Type of exposure in ppm (mg/L)	
Treatment	Constant	Spiked
Corexit 9500	30–150	90–1,000
PBC: Prudhoe Bay crude oil	3–15	8–26
PBC + Corexit 9500	1–8	5–18
Arabian crude oil	0.6–6	15–80
Arabian + Corexit 9500	0.8–1.6	29–58
Venezuelan crude oil	0.2–0.4	1
Venezuelan + Corexit 9500	No data yet	No data yet

Source: data in CROSERF Progress Report, Coelho and Aurand (1999).

Toxicity of dispersants and dispersed oil. Historically, oil toxicology data are largely based on 48- or 96-hour bioassays during which marine organisms are exposed to constant concentrations of dispersants, oil, or chemically dispersed oil. But in the ocean over a 48- or 96-hour time scale, dispersion causes constantly declining concentrations of oil. Fortunately, Singer et al. (1998), Rhoton et al. (1999), and Clark et al. (in press) have compared traditional constant-exposure with "spike" or "pulse" bioassays that attempt to mimic the concentration profile of dispersed oil during a chemical dispersion episode. The half-life of mean dispersed oil concentration in these spike exposures is about 2 hours. Results of the spike-exposure studies clearly indicate that zooplankton and early life stages of marine plants and animals are less sensitive to spiked exposures than to constant exposures (table 3). Therefore, in developing consensus guidelines for concentrations of concern, participating risk assessors considered both the spike-exposure data as well as the longer-term (96 h) "acute" toxicity data.

Consensus guidelines. Participants in each ERA workshop were polled to determine their levels of concern (discomfort level) about a range of exposure times and dispersed oil concentrations. Assessments were done separately for adult fish; adult crustaceans (shrimp, crab); and zooplankton and sensitive life stages of fish and crustaceans. In each workshop it was quickly agreed that the most sensitive forms were zooplankton and the early life stages of fishes and crustaceans. Also, the guidelines proposed independently in all three workshops were in remarkable agreement about concentrations and exposure times of concern (table 4).

For this paper, we apply these guidelines to the plume oil concentration data to determine what concentrations and exposure times are of concern.

TABLE 4
Ecological Risk Assessment Workshop Participants' Levels of Concern for Various Marine Organisms during Exposure to Dispersed Oil

	Concentration in ppm (mg/L)					
	Sensitive life stage[a]		Adult crustacean		Adult fish	
Exposure time (hours)	High concern[b]	Medium concern	High concern	Medium concern	High concern	Medium concern
3	10	5	50	10	100	50
24	1	1	5	2	10	2
96	1		1	1	1	1
168	0.5	0.5	0.5	0.5	0.5	0.5

[a]Includes zooplankton as well as fish and invertebrate eggs and larvae.
[b]Concern becomes medium or high when concentrations at time are exceeded.

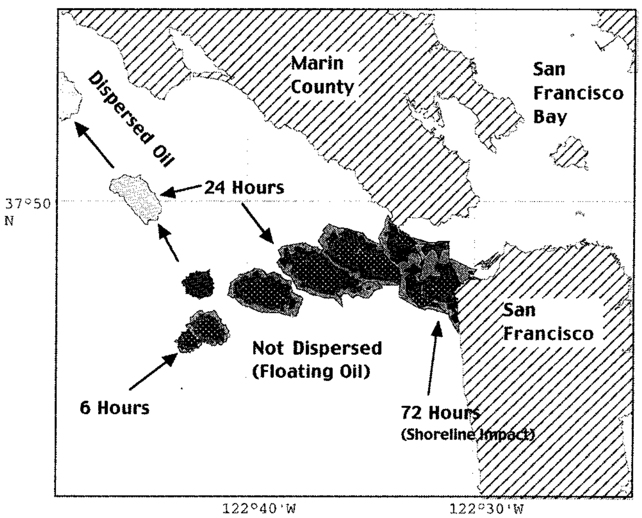

Figure 1. Trajectories and spreading of undispersed floating oil and dispersed oil plumes from Pilot Station scenario off San Francisco. Footprints are 6-hour intervals and then 12-hour intervals.

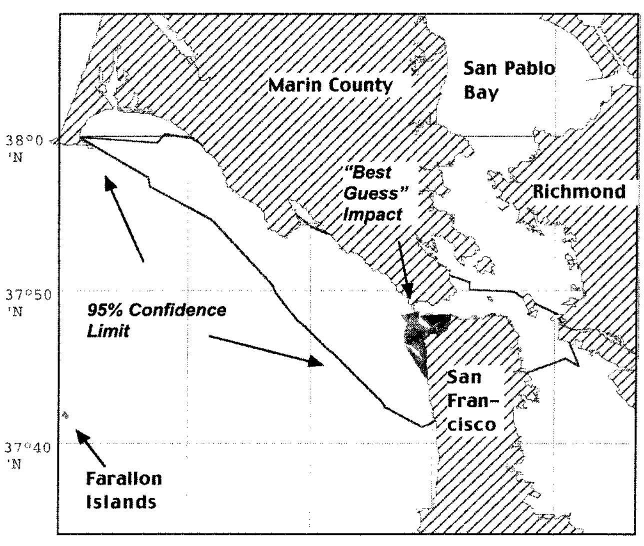

Figure 2. The 72-hour 95% confidence limits around floating (nondispersed) oil footprint following spill of 2,500 bbls of IFO 180 fuel oil at the San Francisco Pilot Station. We are 95% confident that oil will contact the shoreline within the boundaries of the drawn polygon.

SIMULATION RESULTS

The oil spill scenario at the San Francisco Pilot Station consisting of 2,500 bbls IFO 180 initially moved westward for several kilometers (0 to 6 hours), then turned to the northeast (6 to 12 hours) before moving rapidly eastward (fig. 1). Oiling of the San Francisco and Marin County shoreline began 60 to 72 hours after the spill, and then entered San Francisco Bay. The 95% confidence limits (fig. 2) indicate a chance of oil reaching the shoreline anywhere along the Marin County coastline as far north as Bolinas Lagoon, and extending south of San Francisco. The modeled oil spill produced oil slicks within boundaries of the Monterey Bay and Gulf of the Farallones National Marine Sanctuaries.

Fate and Transformation of the Five Response Options

The fate and transformation of the spilled oil was evaluated for five response options. Dispersants removed the greatest amount of oil, and the more effective dispersant level removed the most oil (fig. 3). Relative to the other options, dispersants substantially reduced the amount of both floating and stranded oil (fig. 3). Chemical dispersion also resulted in the lowest emulsion volumes compared with the other response options (fig. 4).

1. The **no response** option created a floating surface slick that was reduced from 2,500 to 1,975 bbls during the first 48 hours by evaporation (479 bbls) and natural dispersion (46 bbls, fig. 3a). By 72 hours, 770 bbls of oil were stranded on shorelines, reducing the floating oil to 1,125 bbls. At the end of 96 hours 979 bbls of oil remained floating, 883 bbls were stranded on beaches, 561 bbls evaporated, and 77 bbls dispersed naturally. Over 3,700 bbls of emulsion had formed by 72 hours (fig. 4a).
2. The **mechanical response** (skimming) option began six hours after the spill (fig. 3b). The amount of oil removed by mechanical response ranged from about 75 to 200 bbls per day through 96 hours, resulting in

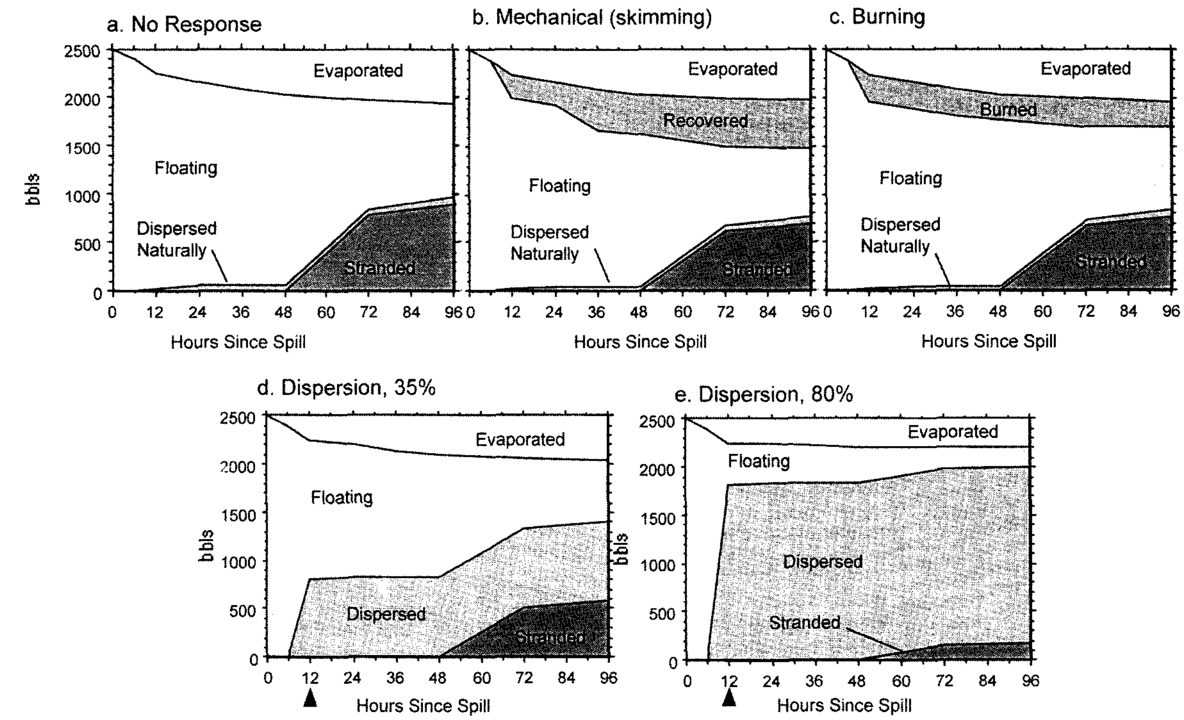

Figure 3. Fates of 2,500 barrels of IFO 180 oil spilled at Pilot Station off San Francisco when subjected to five response alternatives: *a*, no response; *b*, mechanical removal (skimming); *c*, in-situ burning; *d*, dispersion of 35% of the oil, and *e*, dispersion of 80% of the oil. Units are volumes in barrels (bbls; 1 bbl = 42 gal). Each panel shows how much oil was evaporated, removed (only by mechanical means and burning), dispersed, and stranded on shorelines.

a total recovery of 500 bbls of oil. Relative to the no response alternative, mechanical recovery slightly reduced the amount of oil stranding on shorelines, to 700 bbls, and it reduced the amount of naturally dispersed oil from 77 to 68 bbls. The amount of oil remaining on the sea surface at 96 hours was 720 bbls.

3. The **burning response** option occurred at 12 hours, removing 280 bbls of floating oil (fig. 3c). This action had less of an effect on the subsequent fate and transformations of the oil than did the mechanical response. For example, after 96 hours (84 hours after burning) 772 bbls of oil were stranded on shore and 856 bbls of oil were floating.

4-5. The **dispersion response** scenarios at the 35% and 80% levels of effectiveness 12 hours after the spill removed 790 and 1,805 bbls, respectively, into the water column (fig. 3d, e). Oil not removed or dispersed began to absorb water and emulsify after 48 hours, resulting in rapidly increasing volumes of emulsion. The 80% dispersion alternative resulted in a floating emulsion volume of 500 bbls (fig. 4b) and a stranded emulsion volume of about 300 bbls (fig. 4c).

Dispersion stopped the oil's eastern trajectory and placed it into the northerly-moving currents (figs. 1 and 5). From this point forward the dispersed plume would move north parallel to shore and generally above the 40 to 60 m isobath. The plume would round Point Reyes between 48 and 72 hours after dispersion, then continue moving north (fig. 5) and diluting (fig. 6a). After dispersion (12 hours) the plume would reach a maximum (assigned) pycnocline depth of 7 meters, some 30–50 m above the seafloor (fig. 6b).

Dispersed Plume Oil Concentrations

Dispersed oil plume concentrations were analyzed for both dispersion effectiveness concentrations, but not for the other response options. The mean concentrations of dispersed oil are shown, for both the 35% and 80% dispersion effectiveness scenarios, on the map in figure 5, and as time-series graphs in figures 6, 7, and 8. Upper and lower confidence limits (for the 35% effectiveness scenario only) are shown in figure 6a. Within the plume resulting from 35% dispersion, the mean dispersed oil concentrations dropped from a first-hour peak of 272 ppm (ml/L) to about 0.3 to 0.4 ppm (figs. 5, 6a, and 7a). After rounding Point Reyes the mean plume concentration would decrease slowly from 0.3 to <0.1 ppm. If dispersion were 80% effective, the oil concentrations would range from 622 ppm at the first hour to 0.8 ppm in transit from the dispersion site to Point Reyes, and then to less than 0.1 ppm as the plume traveled farther north (fig. 5).

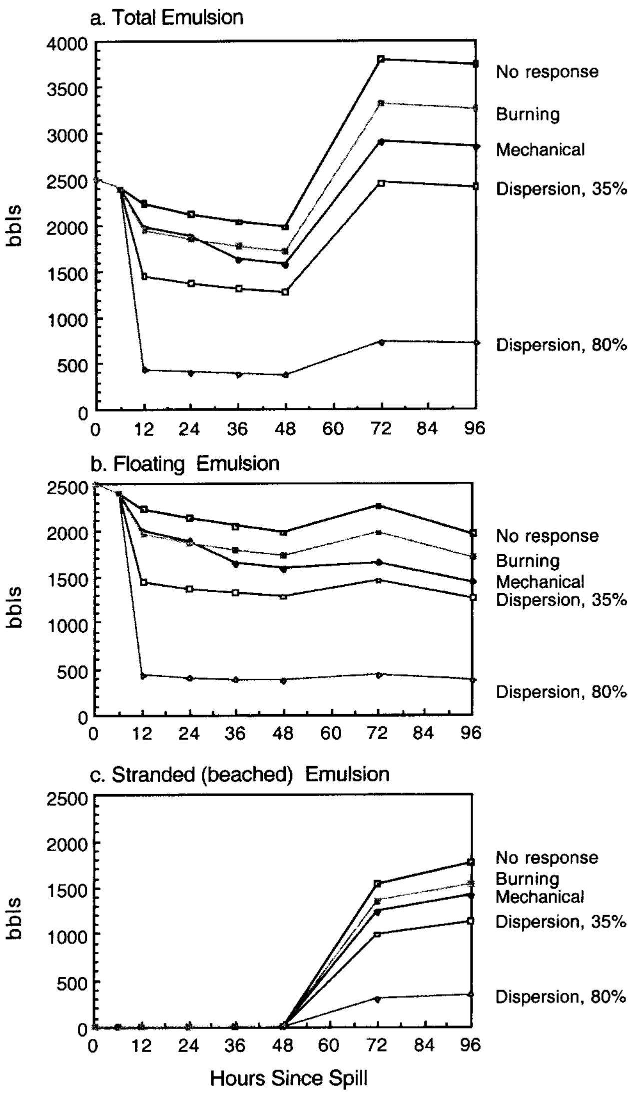

Figure 4. Changes in volumes of water-in-oil emulsion of 2,500 bbls of IFO 180 oil spilled at Pilot Station off San Francisco and subjected to five response alternatives: *a*, total emulsion; *b*, floating emulsion; and *c*, emulsion stranded on shorelines (beached). Each panel shows emulsion volumes resulting from each of the five response scenarios.

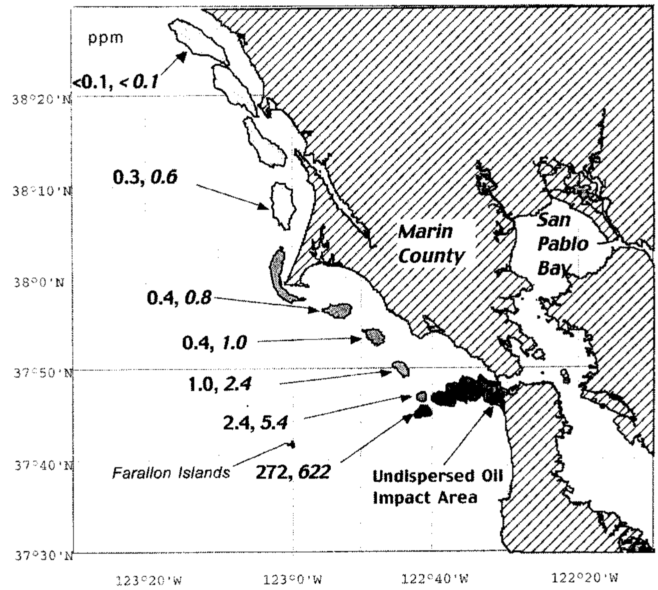

Figure 5. Mean concentrations (ppm) of oil in 35% effectiveness (bold) and 80% effectiveness (italic) dispersed plume, starting 1 hour after dispersion, as it moved northward over 96 hours.

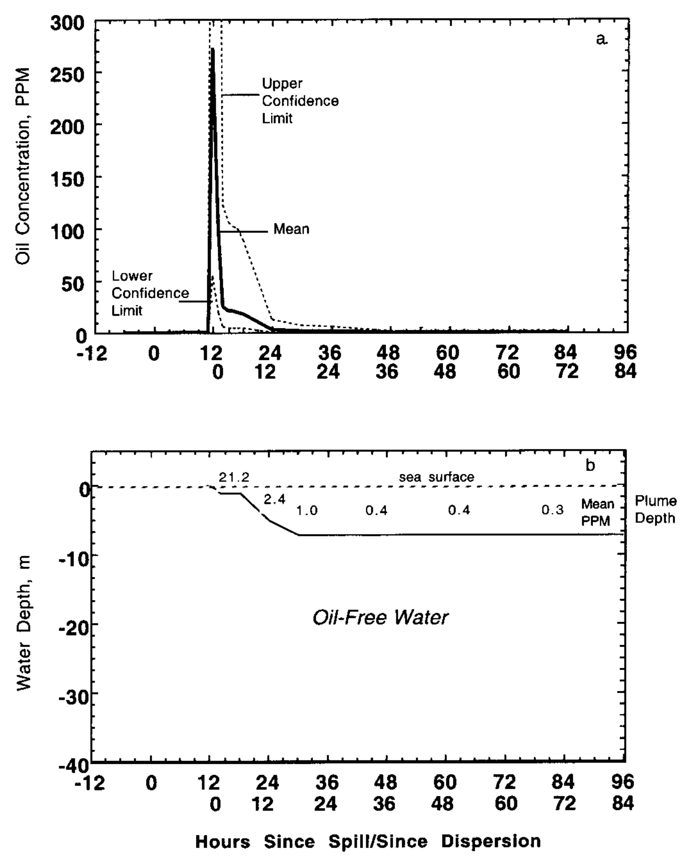

Figure 6. Comparison of 35% effectiveness dispersed oil concentration time series with dispersed plume depth and bottom depth along the plume trajectory. Dashed lines in *a* are upper and lower confidence limits; solid line is the mean (based on dispersion of 790 bbls). *b*, A temporal cross-section along the dispersed plume path over bottom depths of 40 meters or deeper.

Consensus Guidelines on Oil Toxicity

Dispersed oil toxicity differed between the two levels of dispersion effectiveness. At 35% dispersion effectiveness, the consensus guideline of medium concern for adult fish (50 ppm during the first 3 hours and 10 ppm at 24 hours) was exceeded by mean dispersed oil concentrations during the first 6 hours but not thereafter (fig. 7a). This means that there was a chance that some adult fish in the upper meter, such as herring, forage fish, or salmon, were exposed to a concentration of medium concern to the risk assessors for less than six hours.

The consensus guideline of medium concern for adult crustacea (crabs, shrimp; 10 ppm during the first three hours and 2 ppm by 24 hours) was exceeded by the

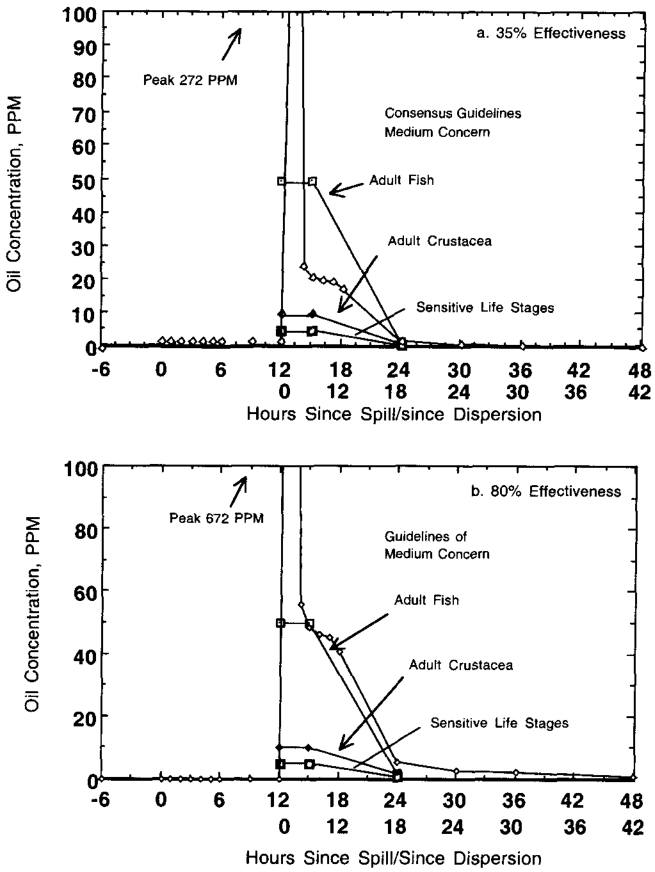

Figure 7. Time series of mean plume concentrations of dispersed oil plotted over consensus concentrations of medium concern to ERA workshop risk assessors. Plots are for two levels of dispersion effectiveness: *a*, 35%, or 790 bbls dispersed, and *b*, 80%, or 1,805 bbls dispersed.

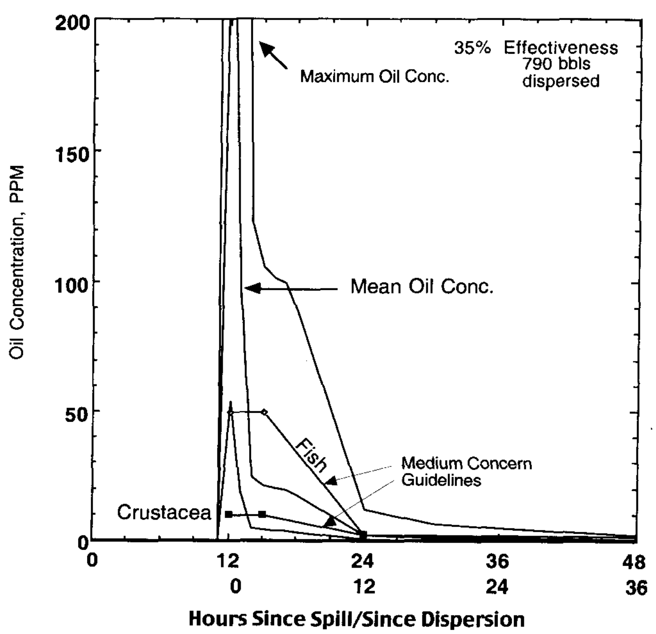

Figure 8. Close-up view of mean and maximum plume concentrations of dispersed oil from 35% effectiveness treatment, plotted over consensus concentrations of medium concern to ERA workshop risk assessors.

mean plume concentration for the first 12 hours after application of dispersants. Over this period the oil was mixing from one to three meters deep. This means that there was a chance that shrimp or crab in the upper several meters of the water column were, for up to 12 hours, at risk of exposure to a concentration of medium concern to the risk managers. However, from about 12 hours onward, dispersed oil concentrations fell below this level of concern.

The consensus guideline of medium concern for zooplankton and early life stages of fishes and invertebrates (5 ppm during the first 3 hours) was also exceeded by the mean concentration during the first 12 hours after application of dispersants (fig. 7a). These observations indicate that zooplankton, including fish and invertebrate eggs and larvae, in the upper three meters of the water column were exposed to oil concentrations at or above the medium concern level of the risk assessors.

The foregoing presentation focused on mean concentrations. Within a dispersed plume, oil is not uniformly distributed. There will be patches of dispersed oil with concentrations that range from as high as five times the mean to one-fifth the mean, indicating that a small fraction of the biota in the upper water column will be exposed to oil in concentrations and durations that exceed the consensus guidelines. Figure 8 presents a "close-up" view showing the maximum expected concentrations and the extent to which they exceed the consensus guidelines of medium concern. Further, at 80% dispersion effectiveness (over 1,800 bbls dispersed) all concentrations would be proportionately higher and would exceed the consensus guidelines longer than at 35% dispersion effectiveness (fig. 7b).

DISCUSSION

Ecological Considerations

The ecological and fisheries trade-offs of the dispersant simulation are clear (Kraly et al. 2001). On one hand, dispersion affects plankton and early life stages of fish in several square kilometers of water during the first day after dispersion. Alternatively, not dispersing or otherwise removing large quantities of surface oil results several days later in the oiling of seabirds and the shoreline occupied by shorebirds and beach-spawning forage fishes.

Dispersing crude oil in the Gulf of the Farallones resulted in a several-square-kilometer area of oil mixed in the upper 3 meters of water. The concentrations of oil 1 hour after dispersion ranged from 200 to 600 ppm, and declined rapidly to 0.5–5 ppm 12 to 24 hours after dispersion. Under consensus guidelines, exposure concentrations and times within the plume would be of medium to high concern to risk assessors for plankton, fish eggs, and fish larvae, but of much less concern with respect to adult crustaceans. Adult fish were exposed to oil concentrations of medium concern only during the first 2 hours after dispersion. If dispersion was 85% effective, the shorelines of San Francisco and southern Marin County, and resident shorebirds, would have been spared a considerable amount of oiling from emulsion (mousse). The main body of dispersed oil would have moved offshore to the north. If dispersion was only 35% effective, oiling of shoreline and birds would have been proportionately greater.

Under the no response, mechanical recovery, and burning scenarios, floating oil would have continued to disperse slightly, emulsify, increase in volume, and increase in viscosity, making open-water mechanical recovery difficult, and subsequent dispersion or burning nearly impossible. Seabirds foraging from the Farallon Islands and the mainland would have been oiled and in need of rehabilitation. The oil that would strand on shorelines would be emulsion (mousse). It would have come ashore as brown, sticky mats, stranding along the high-tide line on sand and gravel beaches, and could impair the reproduction of shore-spawning fishes. If temperatures rose, the stranded mousse would become less viscous, and then penetrate into the sand and gravel. Residual oil would remain in the gravel after manual cleanup unless methods such as berm relocation or surf washing were used. Heroic methods would also damage the eggs of beach-spawning fishes and invertebrates and, ironically, disperse oil into the very shallow nearshore zone occupied by algae, seagrasses, crabs, and juvenile fishes such as Pacific herring (*Clupea harengus harengus*), rockfishes (*Sebastes* spp.) and salmonids. Residual oil might be present for years, depending on wave exposure. We estimated the amounts of emulsion stranding on shorelines, but not lengths of shoreline affected, or numbers and kinds of seabirds at risk from oiling, which are topics worthy of further analysis.

Limitations

In this part of the ERA analysis, the only biological response that was simulated was immediate death; we did not attempt to account for sublethal toxic effects. Adult salmon have a low mortality risk because of their ability to detect and avoid dispersed oil (Green et al. 1982; Nakatani and Nevissi 1991). Alternatively, shellfish such as oysters and clams can temporarily bioaccumulate (and then depurate) dispersed oil (Michel and Henry 1997), which could lead to temporary closures of shellfish fisheries.

The scenarios and workshop proceedings were based on the results of models, not oil spills. In Europe, experience in dispersing real spills was gained during the large nearshore *Sea Empress* spill in Wales (Lunel 1998). Additionally, numerous sea trials in the North Sea have tested dispersion technology and provided new data to resolve uncertainties in models (Lunel et al. 1997) and give clearer guidance for dispersant operations (Lunel and Lewis 1999). In comparison to sea trials testing dispersants and dispersant use in real oil spills, we believe our dispersion simulation is extremely conservative, overestimating both oil concentrations and duration.

The scenarios modeled were conservative in terms of the effectiveness of dispersant application, and in terms of the scales and amounts of oil that can actually be dispersed. The ranges of effectiveness used here, 35%–80%, are realistic, especially for medium crude oils, and are considerably higher than for mechanical removal (booms and skimmers) at sea states and wind conditions typical of the California Current. The main benefit of dispersion was the reduction (not elimination) of floating surface oil and quantity of emulsified oil.

One final caveat is that this modeling exercise did not account for the long-term fate of dispersed oil. Entrainment in the planktonic food web and enhanced biodegradation via the microbial and planktonic food web (Swannel and Daniel 1999) are distinct possibilities.

Recommendations

The consensus guidelines offered by ERA workshop facilitators and participants (table 4) make effective use of existing toxicity data. But we urge that the consensus guidelines be revisited and further reviewed as new data become available.

The granting of preapproval to use dispersant in response to oil spills requires input from regulators and the public. If preapproval cannot be granted, managers and responders should at least consider dispersion as an option during future spills, call for modeling if appropriate, and include dispersion as an option in future spill drills. Because this scenario was modeled for late fall conditions, future nearshore modeling scenarios should be conducted for late winter and spring, when the early life stages of California Current nearshore fishes are present (e.g., Watson et al. 1999).

The model results need further validation through comparison to oil concentrations and durations achieved when dispersants are applied to real oil spills. There is great need for high-quality monitoring data to verify modeling and to confirm the effectiveness and biological effects of dispersant operations. A modified fluorimetry system and protocol is available and in use by the USCG for rapid response monitoring of dispersion effectiveness (Henry et al. 1999). The use of fluorimetry and pertinent visual observations (Levine 1999), coupled with modeling, would provide valuable new information and allow for better planning simulations.

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