Final Report

Transport and Impacts of Oil Spills in San Francisco Bay – Implications for Response

Prepared at the Request of
Carl Jochums
California Department of Fish & Game
Oil Spill Prevention and Response (OSPR)
425 G Executive Court North
Fairfield, CA 94534-4019

Submitted to
Bruce Joab, SSEP Coordinator and Contract Manager
Office of Spill Prevention and Response
CA Department of Fish and Game
1700 K Street, Suite 250
Sacramento, CA 95811
Phone 916-322-7561

for
SSEP Contract No. PO775010

Prepared by
Deborah French-McCay and Jill Rowe
Applied Science Associates, Inc.
55 Village Square Drive
South Kingstown, RI USA
401-789-6224
dfrenchmccay@asascience.com

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Summary

Oil spill modeling was used to predict transport and potential areas of impact for spills originating in San Francisco Bay. Probabilistic modeling predicted the likelihood of oil reaching various areas of the bay, coastal waters and shorelines, as well as the time history of these movements, indicating the timing of response activities required to combat the spill. In a paired study (Etkin et al., 2009), consequences of response alternatives were evaluated for specific scenarios selected from these modeling results to assess the potential reductions in shoreline oiling associated with various protective shoreline booming strategies. In Phase 1 of the study, we examined spills of heavy fuel originating at three locations (1) near the San Francisco docks, (2) at Richmond Long Wharf, and (3) at Martinez in Carquinez Strait. In Phase 2, we examined spills of crude, heavy fuel, and diesel originating at two locations (1) near the San Francisco docks and (2) at Martinez in Carquinez Strait.

For a spill near the San Francisco docks, oil rapidly moved with tides and wind transport throughout the central bay and northern part of the south bay, as well as through the Golden Gate into coastal waters, as observed in recent spills in San Francisco Bay. After a spill at Richmond Long Wharf, oil was rapidly transported by the tides throughout the central bay and San Pablo Bay. After a spill at Martinez, oil remained primarily in Carquinez Strait and Suisun Bay, moving back and forth with the tide. For the scenarios examined, oil came ashore within 48 hours in much of the affected area under most environmental conditions. While in many locations booms would need to be placed in the first 10s of hours after oil is released in order to deflect oil coming ashore, some oil remained out in the bay in the tidal excursion for days, allowing more time to deploy equipment and respond in areas remote from the release.

For spills of median expected volume (369 MT = 100,000 gal) based on statistical analysis of historical spill volumes, the modeling study quantified: (1) water surface oiled, an index of impacts to birds, marine mammals and socioeconomic resources; (2) shoreline (including wetlands) oiled to varying degrees; (3) timing of oil moving into inlets and coming ashore; and (4) probability of exposure of and impact to water column biota. Such indices may be used to compare results of various spill volumes/situations and alternative response scenarios to measure their relative effectiveness.

For the scenarios examined herein, bird impacts were highest for the light fuel (diesel) when spills occurred in the open bay, owing to its faster spreading rate, leading to more areas being oiled. However, in the Martinez area, bird impacts were highest for the viscous and persistent HFO because the area of water swept by oil is confined (by land) and the heavy oil remains on the water and in the marshes much longer than the diesel or crude. Fish and invertebrate impacts were higher the less viscous and more entrainable oil is into the water column.

Vegetation impacts are less for lighter oils, as the more persistent oils cover vegetation to a degree that can impact growth. However, the wetland and mudflat areas where invertebrates would be impacted are larger for lighter oils, owing to its faster spreading rate, leading to more areas being oiled.

1. Introduction

Trajectory and fate modeling can provide quantitative assessments of potential consequences of spill scenarios assuming various mechanical response alternatives. This methodology is a useful tool for contingency planning, risk assessment, and educational purposes. Consequence measures can include area and degree of shoreline oiling, water surface area swept by oil, and other indices of oil impacts. This modeling approach has been previously applied in a number of studies to evaluate response efficacy (Etkin et al., 2002, 2003, 2005, 2006a, 2006b, 2007a, 2007b; French-McCay et al., 2005a,b, 2006).

The California Fish and Game, Office of Spill Prevention and Response (OSPR) wanted to test the hypothesis that adding large-area exclusionary booming in addition to boom deployments already designated in the Area Contingency Plan (ACP) would significantly reduce oiling of locations that are of particular concern due to their environmental sensitivity. San Francisco Bay was chosen for study (of areas in California) because is an area of relatively high spill risk, as well as sensitivity. In preparation for such evaluations, stochastic (probabilistic) modeling was used to identify appropriate scenarios for detailed study, such as worst case for impacts to specific resources (e.g., marshes in Suisun Bay, socioeconomic resources in Marin County). The results quantified the likelihood of oil reaching various areas of the bay, coastal waters and shorelines, as well as the time history of these movements, indicating the timing of response activities required to combat the spill. Potential magnitudes of impacts were evaluated for the spill size examined. The stochastic modeling allowed us to determine the worst case scenario for oiling particular locations of interest, as well as scenarios where opportunities exist for more effective response to reduce impacts in these locations.

In Phase 1 of the study, we examined hypothetical spills of 369 MT (100,000 gal) of HFO originating at three locations (1) near the San Francisco docks, (2) at Richmond Long Wharf, and (3) at Martinez Refinery near the Carquinez Strait (Figure 1). Modeling was performed in stochastic (probabilistic) mode, i.e., by randomly varying spill date and time, and so environmental conditions during and after the release among potential conditions that would occur. We present the results as statistical descriptions of probabilities of oil exposure (and so impacts) and likely timing of oil movements (which have implications to the response). From the stochastic results, we selected individual (deterministic) model runs to examine in detail with respect to booming strategies in locations of interest. Etkin et al. (2009) describe modeling evaluations of alternative booming strategies for example scenarios identified from these stochastic analyses. In Phase 1, alternative booming strategies for HFO spills are examined for three locations of concern: Tiburon area, Richmond Inner Harbor, and Grizzly-Honker Bays (Figure 1). Results of Phase 1 were published in French McCay et al. (2008) and Etkin et al. (2008). In Phase 2 of the study, spills impacting Richmond Inner Harbor and Grizzly-Honker Bays were examined in more detail, including considering spills of HFO, crude oil and diesel.

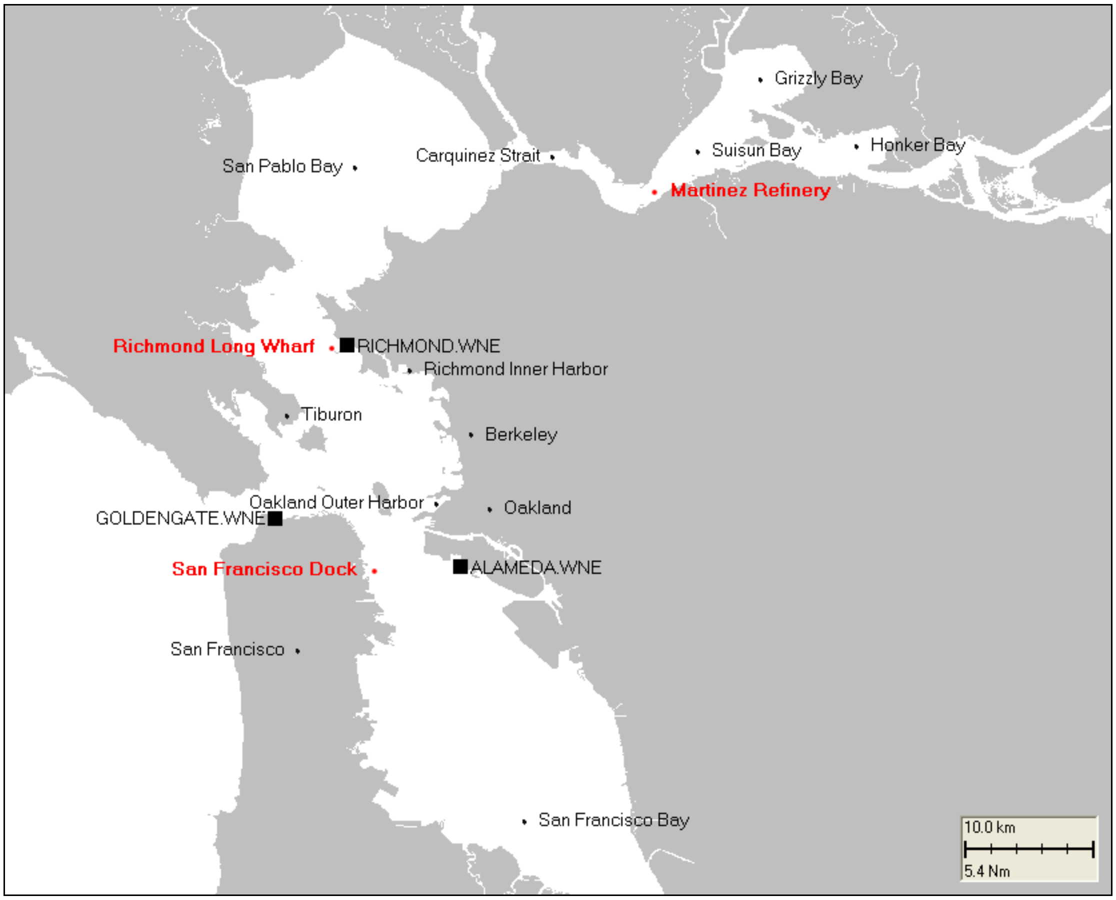

Figure 1. Oil spill release points and wind stations ("WNE) for hypothetical modeling in San Francisco Bay, California, USA.

2. Oil Spill Model

2.1 Oil Fates Model

Applied Science Associates' (ASA's) SIMAP oil spill model (French McCay, 2003, 2004) was used for the analysis. The oil fate model uses wind data, current data, and transport and weathering algorithms to calculate the mass of oil components in various environmental compartments (water surface, shoreline, water column, atmosphere, sediments, etc.), oil pathway over time (trajectory), surface oil distribution, and concentrations of the oil components in water and sediments. Processes simulated include slick spreading, evaporation of volatiles from surface oil, transport on the water surface and in the water column, randomized dispersion, emulsification, entrainment of oil as droplets into the water column, resurfacing of larger droplets, dissolution of soluble components, volatilization from the water column, partitioning, sedimentation, stranding on shorelines, and degradation. Oil mass is tracked separately for lower-molecular-weight aromatics (1 to 3-ring aromatics), which are soluble and cause toxicity to aquatic organisms (French McCay, 2002), other volatiles, and non-volatiles. The lower molecular weight aromatics dissolve both from the surface oil slick and whole oil droplets in the water column, and they are partitioned in the water column and sediments according to equilibrium partitioning theory (French et al., 1996; French McCay, 2003, 2004).

"Whole" oil (containing non-volatiles and volatile components not yet volatilized or dissolved from the oil) is simulated as floating slicks, emulsions and/or tarballs, or as dispersed oil droplets of varying diameter (some of which may resurface). Sublots of the spilled oil are represented by Lagrangian elements ("spillets"), each characterized by mass of hydrocarbon components and water content, location, thickness, diameter, density, and viscosity. Spreading (gravitational and by transport processes), emulsification, weathering (volatilization and dissolution loss), entrainment, resurfacing, and transport processes determine the thickness, dimensions, and locations of floating oil over time. The output of the fate model includes the location, dimensions, and physical-chemical characteristics over time of each spillet representing the oil (French McCay, 2003, 2004).

The physical fates model has been validated with more than 20 case histories, including the *Exxon Valdez* and other large spills (French McCay, 2003, 2004; French McCay and Rowe, 2004), as well as test spills designed to verify the model's transport algorithms (French et al., 1997).

2.2 Biological Effects Model

The biological exposure model in SIMAP estimates the area, volume, or portion of a stock or population affected by surface oil, concentrations of oil components in the water, and sediment contamination (French McCay, 2003, 2004). For wildlife (birds, mammals, and sea turtles), the number or fraction of a population suffering oil-induced effects is proportional to the water-surface area swept by oil of sufficient quantity to provide a lethal or sublethal dose to an exposed animal. The probability of exposure is related to behavior: i.e., the habitats used and percentage of the time spent in those habitats on the surface of the water. Thus, an exposure index for seabirds and other offshore wildlife is the water area swept by more than 10-μm thick (> 10 g/m^2) oil (which is sufficient to provide a lethal dose, French et al., 1996; French McCay and Rowe, 2004; French McCay, 2009). For shorebirds and other wildlife on or along the shore, an exposure index is length of shoreline oiled by > 10 g/m^2.

The most toxic components of oil to water column and benthic organisms are low molecular weight compounds, which are both volatile and soluble in water, especially the aromatic compounds (Neff *et al.*, 1976; Rice *et al.*, 1977; Neff and Anderson, 1981; Malins and Hodgins, 1981; National Research Council, 1985, 2002; Anderson, 1985; French McCay, 2002). This is because organisms must be exposed to hydrocarbons in order for uptake to occur and aquatic biota are exposed primarily to hydrocarbons (primarily aromatics) dissolved in water. Thus, exposure and potential effects to water column and bottom-dwelling aquatic organisms are related to concentrations of dissolved aromatics in the water. The effects of the dissolved hydrocarbon components are additive.

Mortality is a function of duration of exposure – the longer the duration of exposure, the lower the effects concentration (see review in French McCay, 2002). At a given concentration after a certain period of time, all individuals that will die have done so. The LC50 is the lethal concentration to 50% of exposed organisms.

The incipient LC50 ($LC50_\infty$) is the asymptotic LC50 reached after infinite exposure time (or long enough that that level is approached, Figure 2). Percent mortality is a log-normal function of concentration, with the LC50 the center of the distribution.

The value of $LC50_\infty$ ranges from 5-400 μg/L for 95% of species exposed to dissolved PAH mixtures for over 96 hrs (French McCay, 2002). The $LC50_\infty$ for the average species is about 50 μg/L of dissolved PAH. These LC50 values have been validated with oil bioassay data (French McCay, 2002), as well as in an application of SIMAP to the *North Cape* oil spill where field and model estimates of lobster impacts were within 10% of each other (French McCay, 2003).

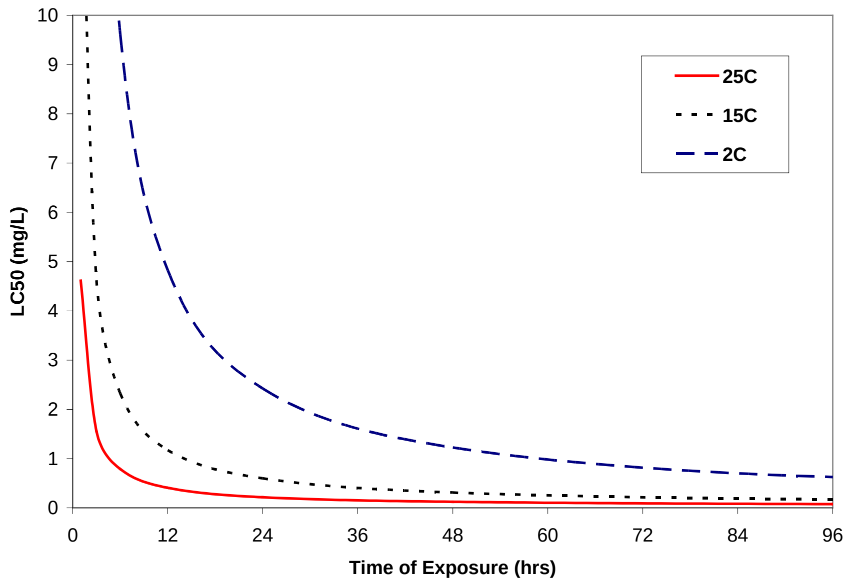

Figure 2. LC50 of dissolved PAH mixtures from oil, as a function of exposure duration and temperature.

In SIMAP, aquatic organisms are modeled using Lagrangian particles representing schools or groups of individuals. Pre-spill densities of fish, invertebrates, and wildlife (birds, mammals, reptiles, and amphibians) are assumed evenly distributed across each habitat type defined in the application of the model. (Habitat types may be defined to resolve areas of differing density for each species, and the impact in each habitat type is then separately computed.) Mobile fish, invertebrates, and wildlife are assumed to move at random within each habitat during the simulation period. Benthic organisms either move or remain stationary on/in the bottom. Planktonic stages, such as pelagic fish eggs, larvae, and juveniles (i.e., young-of-the-year during their pelagic stage(s)), are moved with the currents.

Mortality of fish, invertebrates, and their eggs and larvae was computed as a function of temperature, concentration, and time of exposure. Percent mortality was estimated for each of a large number of Lagrangian particles representing organisms of a particular behavior class (i.e., planktonic, demersal, and benthic, or fish that are classed as small pelagic, large pelagic, or demersal). For each Lagrangian particle, the model evaluates exposure duration, and corrects the LC50 for time of exposure and temperature (Figure 2) to calculate mortality. The percent mortalities were summed, weighed by the area represented by each Lagrangian particle to estimate a total equivalent volume for 100% mortality. In this way, mortality was estimated on a volume basis, rather than necessitating estimates of species densities to evaluate potential impacts. In addition to the mortality estimates, the volume exceeding 1 μg/L total dissolved aromatics was used as an index for exposure for fish, invertebrates, and plankton. The algorithms for these calculations and their validation are described in French McCay (2002, 2003, 2004, 2009).

3. Model Input Data

3.1 Geographical

For geographical reference, SIMAP uses a rectilinear grid to designate the location of the shoreline, the water depth (bathymetry), and the shore or habitat type. The grid was generated from a digital coastline using the ESRI Arc/Info compatible Spatial Analyst program. The cells were then coded for depth and habitat type. The model identifies the shoreline using this grid.

Digital shoreline data were gridded from Environmental Sensitivity Indices (ESI) coverages in the Environmental Sensitivity Atlas Geographical Information System (GIS) for the area obtained from the National Oceanic and Atmospheric Administration (NOAA) HAZMAT office in Seattle, Washington (on CD-ROM). ESI codes were translated to equivalent habitat codes for SIMAP. These initial grids were then reviewed and edited by Carl Jochums (OSPR) to refine the representation of habitats and shore types in the two areas of focus in Phase 2 of this study: (1) in Grizzly Bay and Honker Bay (which is near Grizzly Bay, termed "Grizzly Bay" below) near the Carquinez Strait; and (2) in Richmond Inner Harbor, the Berkeley shoreline area, and outer Oakland Harbor (termed "Richmond-Berkeley area" below).

Vegetated subtidal habitats (seagrass and kelp beds) were mapped from coverages also provided in Environmental Sensitivity Atlas CD-ROM. Other subtidal areas were assumed to be sand (outside the bay) or silt-mud bottom (inside the bay). Depth data were averages in each cell of soundings obtained from Hydrographic Survey Data supplied on CD-ROM by the U.S. Department of Commerce, NOAA, National Geophysical Data Center. The grid cell size was 0.12^{o} of longitude and latitude (i.e., 176m east-west by 222m north-south)

3.2 Currents

A previously-developed tidal hydrodynamic model application for San Francisco Bay estuary (Sankaranarayanan and French-McCay, 2003a) was used to calculate tidal currents for the analysis. This hydrodynamic modeling utilized Applied Science Associate's time-dependent generalized non-orthogonal boundary-fitted model in spherical coordinates developed by Muin and Spaulding (1997a). The coded application of this model, called BFHYDRO (Boundary Fitted HYDROdynamic model), has been successfully applied to coastal and estuarine waters. Some other applications where the model was validated include Mount Hope Bay (Swanson, et al., 2006), Providence River (Muin and Spaulding, 1997b), and Bay of Fundy (Sankaranarayanan and French-McCay, 2003b). The boundary-fitted model technique matches the model coordinates with the shoreline boundaries and allows the user to adjust the model grid resolution as desired.

The hydrodynamic model domain included San Francisco Bay beginning at the San Joaquin Delta, and including the coastal area from Monterey Bay to Point Reyes (Figure 3). We applied BFHYDRO in the two-dimensional (2-D), vertically averaged mode because the bay is highly energetic and predominantly well mixed vertically. The model was driven with freshwater inflow at the San Joaquin Delta (two conditions: dry season, low delta outflow; wet season, high delta outflow) and tidal forcing at the open ocean boundary. The circulation in the bay is almost completely tidally driven and for that analysis, the density driven (i.e., salinity induced) flows, were not considered. The freshwater inflow at the delta had little influence on the current flows.

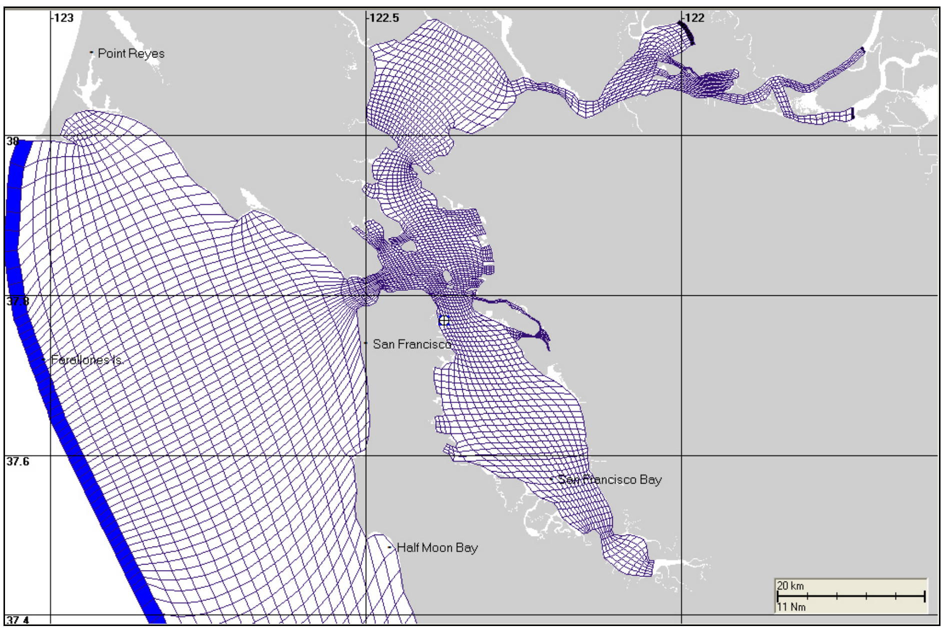

Figure 3. Hydrodynamic model grid.

3.3 Environmental

Because of the large spatial variability of winds in and just outside of San Francisco Bay, multiple wind records (Figure 1) of hourly wind speed and direction were used for the model runs: San Francisco NOAA buoy #46026 and San Francisco Bay Ports 9414750 (Alameda), 9414750 (Golden Gate), and 9414863 (Richmond); from a period of complete data, 11 February 1996 to 31 May 2001. While a longer wind record would be desirable, statistical analysis of the available longer-term (buoy) wind records showed year-to-year variability was relatively low, while spatially variability between stations was quite high. As the focus of the study was on the median and distribution of consequences, and not on extreme events, the shorter more spatially-complete wind record was judged more appropriate and adequate. The wind data were spatially interpolated between stations using a linear distance-weighed scheme for both speed and direction. While three wind stations would not be sufficient to hindcast a specific event, where localized wind patterns would be important, the general wind patterns the three stations provide yield reasonable distributions of expected oil impacts, measured as the area of surface water and shoreline oiled, as well as subsurface volume contaminated greater than a threshold concentration. These measures of impact are much less variable with wind direction than are trajectories.

Wind-driven surface currents are calculated within the SIMAP fates model, based on local wind speed and direction. Wind driven surface drift was specified as 3.5% of wind speed in the downwind direction, a typical drift for inshore waters (ASCE, 1996).

Temperature was 15^{o}C and salinity was 32 ppt, based on annual means in San Francisco Bay (French et al., 1996). The air immediately above the water was assumed to have the same temperature as the water surface, this being the best estimate of air temperature in contact with the water and floating oil. Water temperature was used in the model for calculation of evaporation rates of volatile and semi-volatile components. Thus, temperature affects evaporation rate, and so surface oil volume, but not the trajectory of the spill. Salinity has little influence on the fate of the heavy fuel oil modeled in this study.

The horizontal and vertical dispersion coefficients were assumed to be 1 m^2/sec and 1 cm^2/sec, respectively. These are reasonable values based on Okubo (1971), Okubo and Ozmidov (1970) and modeling experience. The vertical dispersion coefficient in the surface wave-mixed layer was calculated from wind speed using the algorithm developed by Thorpe (1995).

Suspended sediment was assumed 10 mg/l, a typical value for coastal waters (French et al., 1996). The sedimentation rate is set at 1 m/day.

3.4 Oil Characteristics

Properties for heavy fuel oil (HFO), crude oil and diesel were developed from published sources, as in Tables 1-3.

Table 1. Oil properties for heavy fuel oil used in the simulations.

Property	Value	Reference
Density @ 25 deg. C (g/cm3)	0.9749	Jokuty et al. (1999)
Viscosity @ 25 deg. C (cp)	3180	Jokuty et al. (1999)
Surface Tension (dyne/cm)	27	Jokuty et al. (1999)
Pour Point (deg. C)	7	Jokuty et al. (1999)
Adsorption Rate to Suspended Sediment	0.01008	Kolpack et al. (1977)
Adsorption Salinity Coef.(/ppt)	0.023	Kolpack et al. (1977)
Fraction monoaromatic hydrocarbons (MAHs)	0.00182	Wang et al. (1995)
Fraction 2-ring aromatics	0.00379	Wang et al. (1995)
Fraction 3-ring aromatics	0.01594	Wang et al. (1995)
Fraction Non-Aromatics: boiling point < 180^{o}C	0.00818	Jokuty et al. (1999)*
Fraction Non-Aromatics: boiling point 180-264^{o}C	0.04521	Jokuty et al. (1999)*
Fraction Non-Aromatics: boiling point 264-380^{o}C	0.09706	Jokuty et al. (1999)*
Minimum Oil Thickness (mm)	1	McAuliffe (1987)

Property	Value	Reference
Maximum Mousse Water Content (%)	30	Median value form NOAA (2000)
Mousse Water Content as Spilled (%)	0	-
Water content of fuel (not in mousse, %)	0	-
Degradation Rate (/day), Surface & Shore	0.01	NAS (1985)
Degradation Rate (/day), Hydrocarbons in Water	0.01	NAS (1985)
Degradation Rate (/day), Oil in Sediment	0.001	Haines and Atlas (1982)
Degradation Rate (/day), Aromatics in Water	0.01	French et al. (1996)
Degradation Rate (/day), Aromatics in Sediment	0.001	French et al. (1996)

* – Environment Canada's Oil Property Catalogue (Jokuty et al., 1999) provided total hydrocarbon data for volatile fractions of unweathered oil. The aromatic hydrocarbon fraction was subtracted from the total hydrocarbon fraction to obtain the aliphatic fraction of unweathered oil.

Table 2. Oil properties for Alaskan North Slope crude oil used in the simulations.

Property	Value	Reference
Density @ 25 deg. C (g/cm3)	0.8714	Jokuty et al. (1999)
Viscosity @ 25 deg. C (cp)		Jokuty et al. (1999)
Surface Tension (dyne/cm)	27.3	Jokuty et al. (1999)
Pour Point (deg. C)	-32	Jokuty et al. (1999)
Adsorption Rate to Suspended Sediment	0.01008	Kolpack et al. (1977)
Adsorption Salinity Coef.(/ppt)	0.023	Kolpack et al. (1977)
Fraction monoaromatic hydrocarbons (MAHs)	0.02192	Jokuty et al. (1999)
Fraction 2-ring aromatics	0.003076	Jokuty et al. (1999)
Fraction 3-ring aromatics	0.007284	Jokuty et al. (1999)
Fraction Non-Aromatics: boiling point < 180^{o}C	0.20408	Jokuty et al. (1999)*
Fraction Non-Aromatics: boiling point 180-264^{o}C	0.121224	Jokuty et al. (1999)*
Fraction Non-Aromatics: boiling point 264-380^{o}C	0.186616	Jokuty et al. (1999)*
Minimum Oil Thickness (mm)	0.05	McAuliffe (1987)
Maximum Mousse Water Content (%)	72.9	Jokuty et al. (1999)
Mousse Water Content as Spilled (%)	0	-
Water content of oil (not in mousse, %)	0	-
Degradation Rate (/day), Surface & Shore	0.01	NAS (1985)
Degradation Rate (/day), Hydrocarbons in Water	0.01	NAS (1985)
Degradation Rate (/day), Oil in Sediment	0.001	Haines and Atlas (1982)
Degradation Rate (/day), Aromatics in Water	0.01	French et al. (1996)
Degradation Rate (/day), Aromatics in Sediment	0.001	French et al. (1996)

* – Environment Canada's Oil Property Catalogue (Jokuty et al., 1999) provided total hydrocarbon data for volatile fractions of unweathered oil. The aromatic hydrocarbon fraction was subtracted from the total hydrocarbon fraction to obtain the aliphatic fraction of unweathered oil.

Table 3. Oil properties for diesel fuel oil used in the simulations.

Property	Value	Reference
Density @ 25 deg. C (g/cm3)	0.83	Lee et al. (1992)
Viscosity @ 25 deg. C (cp)	2	Lee et al. (1992)
Surface Tension (dyne/cm)	27.4	Jokuty et al. (1999)*
Pour Point (deg. C)	-36.0	Jokuty et al. (1999)*
Adsorption Rate to Suspended Sediment	0.01008	Kolpack et al. (1977)
Adsorption Salinity Coef.(/ppt)	0.023	Kolpack et al. (1977)
Fraction monoaromatic hydrocarbons (MAHs)	0.023336	Jokuty et al. (1999)*
Fraction 2-ring aromatics	0.010175	Lee et al. (1992)
Fraction 3-ring aromatics	0.001976	Lee et al. (1992)
Fraction Non-Aromatics: boiling point < 180°C	0.186664	Jokuty et al. (1999)*
Fraction Non-Aromatics: boiling point 180-264°C	0.426825	Jokuty et al. (1999)*
Fraction Non-Aromatics: boiling point 264-380°C	0.000000	Jokuty et al. (1999)*
Minimum Oil Thickness (mm)		McAuliffe (1987)
Maximum Mousse Water Content (%)	0	Jokuty et al. (1999)
Mousse Water Content as Spilled (%)	0	-
Water content of fuel (not in mousse, %)	0	-
Degradation Rate (/day), Surface & Shore	0.01	NAS (1985)
Degradation Rate (/day), Hydrocarbons in Water	0.01	NAS (1985)
Degradation Rate (/day), Oil in Sediment	0.001	Haines and Atlas (1982)
Degradation Rate (/day), Aromatics in Water	0.01	French et al. (1996)
Degradation Rate (/day), Aromatics in Sediment	0.001	French et al. (1996)

* – Environment Canada's Oil Property Catalogue (Jokuty et al., 1999) provided total hydrocarbon data for volatile fractions of unweathered oil. The aromatic hydrocarbon fraction was subtracted from the total hydrocarbon fraction to obtain the aliphatic fraction of unweathered oil.

3.5 Shoreline Oil Retention

Retention of oil on a shoreline depends on the shoreline type, width and angle of the shoreline, viscosity of the oil, the tidal amplitude, and the wave energy. In the NRDAM/CME (French et al., 1996), maximum shore holding capacity per unit area was based on observations from the *Amoco Cadiz* spill in France and the *Exxon Valdez* spill in Alaska [based on Gundlach (1987)] and later work summarized in French et al., 1996). These assumptions were used in the present study, as listed in Table 4. The maximum width of oiling on the shore was assumed to be 0.5 m in San Pablo Bay and central-to-south San Francisco Bay; and 0.1 m in Suisun Bay and Carquinez Strait (due to the lower tidal range in that area).

Table 4. Maximum oil thickness and natural removal rates by shore type.

Shore Type	Maximum Oil Thickness (mm)	Natural Removal (Erosion) Half Time (days)
Rocky	2	1
Gravel	15	10
Sand	25	5
Tidal flat	10	1
Wetland	40	500

3.6 Scenario Specifications

3.6.1 Stochastic Modeling

As part of Phase 1 of the study, we examined hypothetical spills of HFO originating at three locations (1) near the San Francisco docks (37^{o} 46. 46.0844'N, 122^{o} 22.5861'W), (2) at Richmond Long Wharf (37^{o} 46.0776'N, 122^{o} 22.7353'W), and (3) at Martinez Refinery in Carquinez Strait (38^{o} 2.0819'N, 122^{o} 7.4519'W), as shown in Figure 1. The spill size was the median expected volume, 369 MT (100,000 gal), based on statistical analysis of historical spill volumes (Etkin et al., 2002). The release was assumed to be at the water surface and over a period of 24 hours.

As there are many possible environmental conditions (winds, currents) that might occur after a spill, modeling was performed in stochastic (probabilistic) mode, i.e., by randomly varying spill date and time, and so environmental conditions during and after the release among potential conditions that would occur. Stochastic modeling, randomizing environmental and other model inputs, may be used to select worst-case and representative scenarios (50th percentile in rank order of consequences) for detailed evaluation. For example, as described in the companion paper (Etkin et al., 2008), specific spill scenario runs may be selected based on maximized impacts to specific locations of concern where alternative booming strategies are to be examined.

One hundred model simulations were run for each of 100 randomly-selected start dates and times for the period from January 1996 to December 2001. In a previous study (Sankaranarayanan and French McCay, 2003b), 100 runs were found adequate based on tests with up to 200 runs, i.e. probability of oil reaching various locations varied less than 5% if greater than 100 runs were made. The model time step was 0.1 hour (6 min) and each model run was a simulation for 30 days after the spill date.

3.6.2 Modeling of Individual Scenarios

Individual scenarios were selected from the results of the stochastic model runs for additional study regarding response strategies by Etkin et al. (2009). The objective of the response strategy study was to examine scenarios where opportunities exist for more effective response to reduce impacts in specific locations of concern. Thus, we selected individual runs (conditions) that would oil the locations of concern, but with the timing of the oiling some hours after release (allowing for realistic opportunities to respond), and studied implications of adding response equipment and changing the timing of their deployment. The response strategies and results are described in the companion report by Etkin et al. (2009). Herein, we present the trajectories and estimated impacts of the individual scenarios examined.

In Phase 1 of the study, Etkin et al. (2009) examined hypothetical spills of 100,000 gallons of HFO at three locations in the San Francisco Bay: (1) near the San Francisco Docks, (2) at Richmond Long Wharf, and (3) at Martinez in Carquinez Strait (Figure 1). In Phase 2, Etkin et al. (2009) examined hypothetical spills of 100,000 gallons of three oil types (crude, diesel and HFO) originating at two locations: one from the San Francisco docks (stochastic) scenario and one from the Martinez Refinery scenario.

For each spill scenario, a particular location for protective booming was evaluated. Specific spill scenario runs were selected based on maximized impacts to these locations. Each of these locations is known to contain marshes and bird-rafting areas. For the San Francisco Docks spill scenario, the impacts to Richmond Inner Harbor were analyzed. For the spill from the Richmond Long Wharf, impacts to Richardson Bay, Tiburon, and Belvedere Cove were analyzed (Phase 1 only). For the spill from Martinez in Carquinez Strait, impacts to Grizzly and Honker Bays were analyzed.

4. Results

4.1 Phase 1: Stochastic Modeling (Heavy Fuel Oil Spills)

Results of the HFO spill simulations were 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 (water surface, shoreline, dissolved aromatics in water) are analyzed over all runs to determine the median and 95th percentile consequences expected for the spill scenario. The same model run is not the 50th or 95th percentile case for water surface, shoreline, and water column impacts. In fact, when shoreline impacts are highest, water column impacts tend to be relatively low, and *visa versa*. The impact measures from the stochastic modeling provide a quantitative method for determining which conditions are 50th and 95th percentile cases for the resource of interest, as well as worst case of the 100 runs simulated.

Birds and other wildlife are impacted in proportion to the water (e.g., seabirds) and shoreline (e.g., shorebirds) surface area oiled above a threshold thickness for effects. Shoreline habitat impacts are proportional to surface area oiled above a threshold thickness for effects.

Toxicity data (French McCay, 2002) indicate that the 96-hour LC50 for dissolved aromatics (primarily PAHs) averages about 50 μg/l (ppb) for a variety of aquatic species from different habitats and degrees of sensitivity. The 96-hour LC50 for sensitive species (defined as two standard deviations below the mean, French McCay, 2002) is about 5 ppb. Thus, to the nearest order of magnitude and being conservative (protective of the most sensitive species), the volume of water exposed to >1 ppb dissolved aromatic concentration is used as an indicator of potential effects to water column biota. However, toxicity to aquatic organisms increases with time of exposure, such that organisms may be unaffected by brief exposures to the same concentration that is lethal at long times of exposure.

Recreational, tourism, boating/shipping, and other socioeconomic impacts are functionally related to the length of shore and area of water oiled. Cleanup costs are related to volume spilled, water surface area, and area (or length) of shore oiled. As most of the cleanup costs are shoreline-related (Etkin et al., 2003), the shoreline oiling serves as a relative index of cleanup costs.

Thus, the impact indices utilized for water surface and shorelines were:

- Water surface exposed to floating hydrocarbons, as the area covered by more than 0.01 μm of oil (~ $0.01 g/m^2$) at any time after the spill. This threshold is that of sheen (NAS, 1985). Results were also compiled for heavier oiling (i.e., >1 μm of oil, ~$1g/m^2$ and >10 μm of oil, ~$10g/m^2$). The impact threshold for lethal impact to birds on water, developed by French et al. (1996) and French McCay (2009), is 10 g/m^2.
- Shoreline area exposed to hydrocarbons of >$0.1g/m^2$ (~ 0.1μm thick). The thickness is the mean over a model grid cell, i.e., the cumulative mass of oil coming ashore within a cell, divided by the diagonal length of the cell (shore segment length) times the intertidal zone width. The cleanup threshold assumed by (Etkin et al., 2003), as well as the impact threshold for oiling of birds on shorelines developed by French et al. (1996) and French McCay (2009) is 100 g/m^2.

For a spill near the San Francisco docks (Figure 4), oil rapidly moved with tides and wind transport throughout the central bay and northern part of the south bay, as well as through the Golden Gate into coastal waters, as observed in recent spills in San Francisco Bay. After a spill at Richmond Long Wharf (Figure 5), oil was rapidly transported by the tides throughout the central bay and San Pablo Bay. After a spill at Martinez (Figure 6), oil remained primarily in Carquinez Strait and Suisun Bay, moving back and forth with the tide.

Figures 4, 5 and 6 show the timing of oil movements to different sections of the bay (for oil greater than the threshold thickness of 1 μm, ~$0.01g/m^2$) for the three scenarios (releases from San Francisco docks, Richmond and Martinez, respectively). The scales are set to only show the earliest potential transport of oil to each location in the grid, up to 48 hours after the spill. The large tidal excursions potentially move the oil rapidly from the San Francisco docks or Richmond spill sites to most areas of the central bay (the specifics depending on the winds), whereas the likely transport of oil from Martinez reaches more limited locations in and near the Carquinez Strait area in the first 48 hours after the spill (with limited excursions beyond that area later on).

The effectiveness of booming would depend on the timing of deployments relative to the movement of oil into sensitive areas. The booms need to be in place in advance of the oil to be effective protection. In this modeling study, the majority of spill runs showed oil reaching the areas of interest considerably in advance of 48 hours after the spill, when most booming is planned to be completed in the Area Contingency Plan. Thus, for spills where the release is of short duration (as opposed to those where there is a more protracted release and time to mobilize and deploy equipment), booming as described in the ACP may not be very effective.

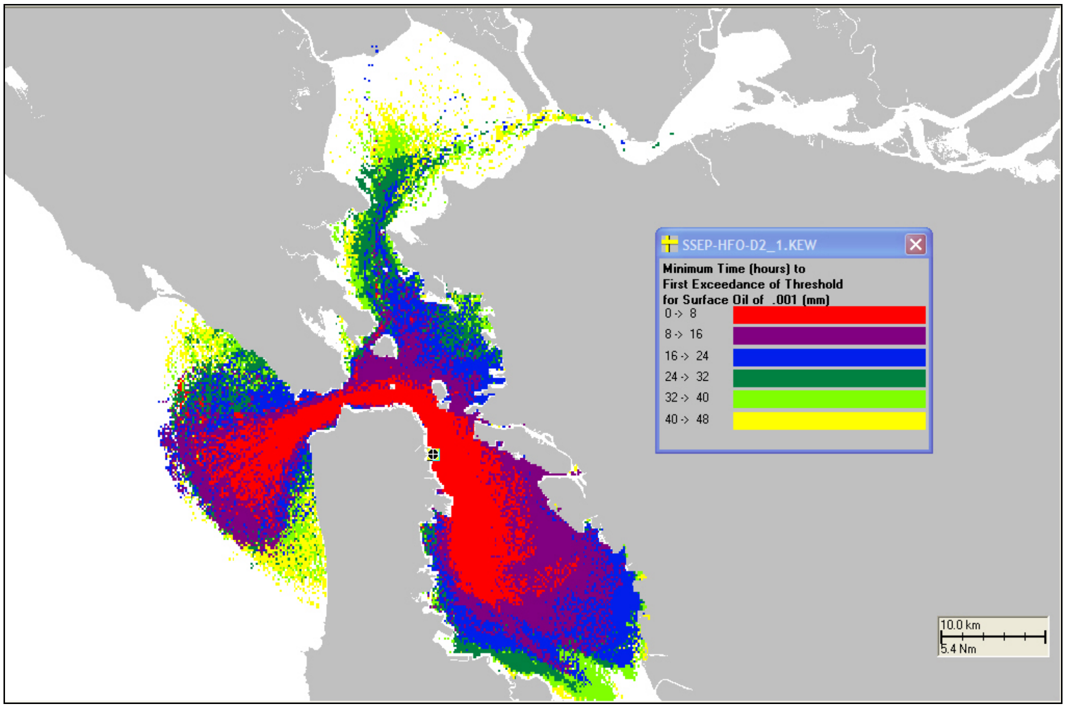

Figure 4. Timing of oil movements to different sections of the bay (for oil thickness > 1 μm, ~0.01g/m^2) for HFO releases from San Francisco docks.

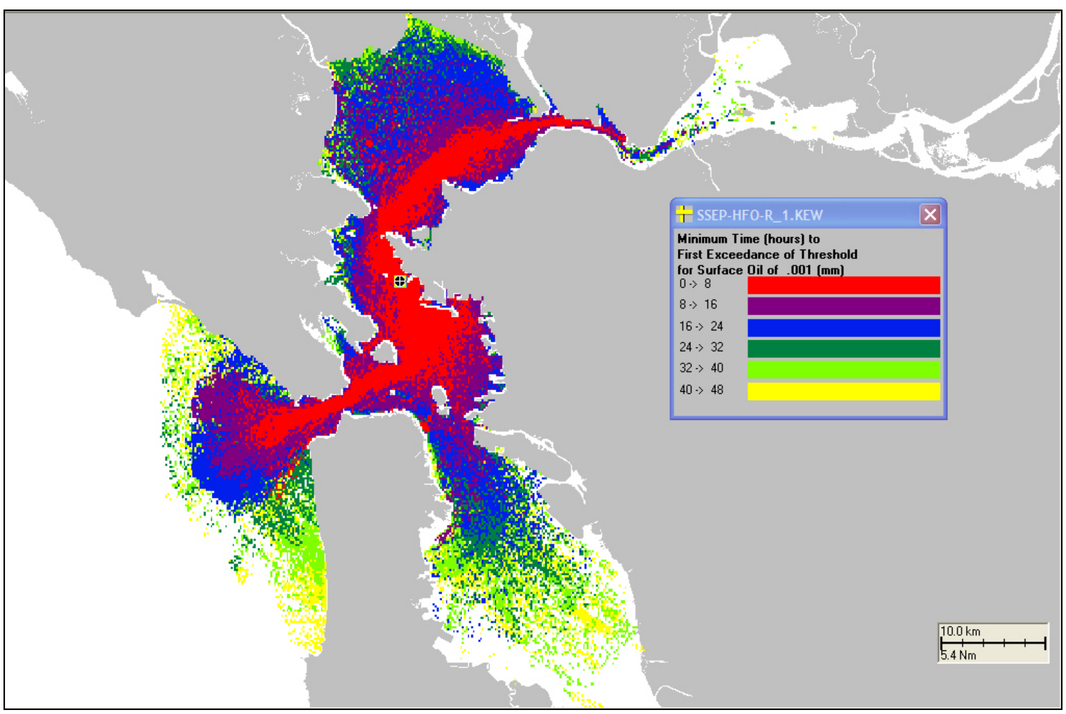

Figure 5. Timing of oil movements to different sections of the bay (for oil thickness > 1 μm, ~0.01g/m^2) for HFO releases from Richmond Long Wharf.

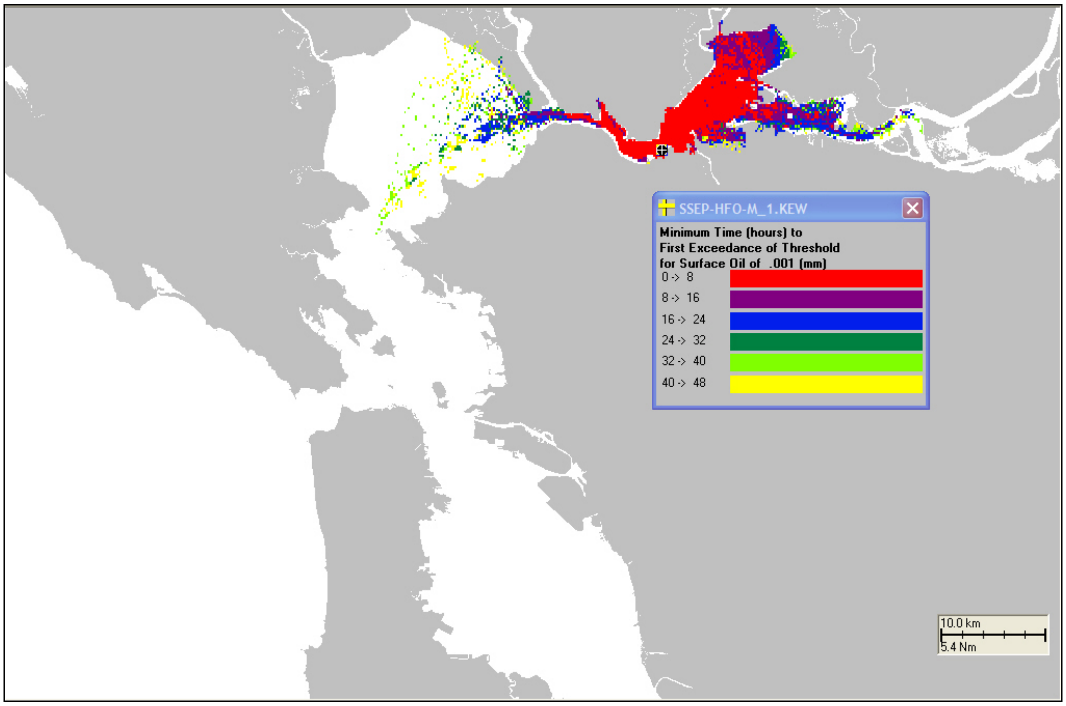

Figure 6. Timing of oil movements to different sections of the bay (for oil thickness > 1 μm, ~0.01g/m^2) for HFO releases from Martinez Refinery.

Table 5 summarizes the stochastic modeling results for HFO surface floating oil exposure for the heavy fuel scenarios. Because the oil is highly viscous, the spreading is inhibited to a minimum thickness of 1mm (Table 1). Thus, the area swept by oil is for oil at least 1 mm thick and the areas are the same for all smaller thresholds considered. The areas affected in Table 5 would be those where birds would be oiled by lethal doses of oil (based on the model algorithms described in French et al., 1996 and French McCay 2004). Floating oil would be most widespread for spills near the San Francisco docks and least spread out for the Martinez area spill site. This is due to the degree of tidal excursion and restriction of the water body near Martinez.

Table 5. Water surface area (km2) swept by oil (HFO) with thickness greater than various thresholds. [SD = standard deviation; 10g/m2 is the threshold for impacts to birds; oil is assumed not to spread thinner than this threshold, such that the areas are the same for all lower thresholds]

Threshold	Statistic	Dock	Richmond	Martinez
0.01g/m^2	Mean area (km^2)	566	333	166
(~ 0.01μm)	SD of area (km^2)	366	122	82
10g/m^2	Mean area (km2)	566	333	166
(~ 10μm)	SD of area (km2)	366	122	82

Table 6 summarizes the shoreline oiling for the stochastic scenarios. The area of shoreline oiled is highest for the Richmond spill and least for the Martinez spill scenario. In any spill at these locations, there would be considerable areas oiled outside the Golden Gate Bridge boundary for both the San Francisco docks and the Richmond spill origins.

Table 6. Shoreline oiled (m2) by HFO with average thickness greater than the threshold 0.1g/m2 (~ 0.1μm thick). [SD = standard deviation]

Location	Dock	Richmond	Martinez
Outside the Golden Gate: Mean area (m^2)	2,921	1,579	0
Outside the Golden Gate: SD of area (m^2)	2,856	1,752	0
Inside the Golden Gate: Mean area (m^2)	39,940	45,975	29,227
Inside the Golden Gate: SD of area (m^2)	6,039	6,362	3,977
Total: Mean area (m^2)	42,860	47,554	29,227
Total: SD of area (m2)	5,734	6,206	3,977

Table 7 summarizes the volumes affected by > 1ppb dissolved aromatic concentration at some time after the spill. Figures 7 through 12 show the probability of exceeding 1 ppb and areas affected by concentrations up to various maximal levels. In most areas contaminated, the concentrations averaged over the upper 1m and the summary grid cells used in the figures (area 39,152 m^2) were < 10 ppb. However, in small localized areas, concentrations were 10-50 ppb, and occasionally higher (Figures 8, 10, 12). This only occurred in <10% of weather events (Figures 7, 9, 11). The contamination was short-lived in all three scenarios, as indicated by the times listed in Table 7 where the volume containing concentrations > 1ppb fell below 1 cubic meter. This is both due to the high viscosity of the oil type, which inhibited entrainment, and the fact that the central bay is deep, has strong currents, and high natural dispersion rates. Entrainment only resulted in significant concentrations during high-wind events. As the Martinez spill generally moved into sheltered waters, maximum concentrations were lower for that scenario than the other two in the open bay areas (Figures 8, 10, 12).

Table 7. Water volume (m3) contaminated with greater than 1 ppb dissolved aromatic concentration at some time after an HFO spill of 100,000 gal. and the time that volume decreased to < 1 m3. [SD = standard deviation]

Statistic	Dock	Richmond	Martinez
Mean volume (m^3)	93,176	80,901	54,211
SD of volume (m^3)	645,749	772,749	223,591
Mean time (hours) volume > 1ppb falls below 1 m^3	56	241	680
SD of time (hours) volume > 1ppb falls below 1 m^3	187	339	160

The percentages of spilled hydrocarbon mass reaching the sediments are listed in Table 8. The fraction settling is highest in the main part of the bay and lowest for the Martinez spill in the Carquinez Strait. Spills involving high wind events that caused high waves and relatively more entrainment resulted in higher sedimentation in shallow water.

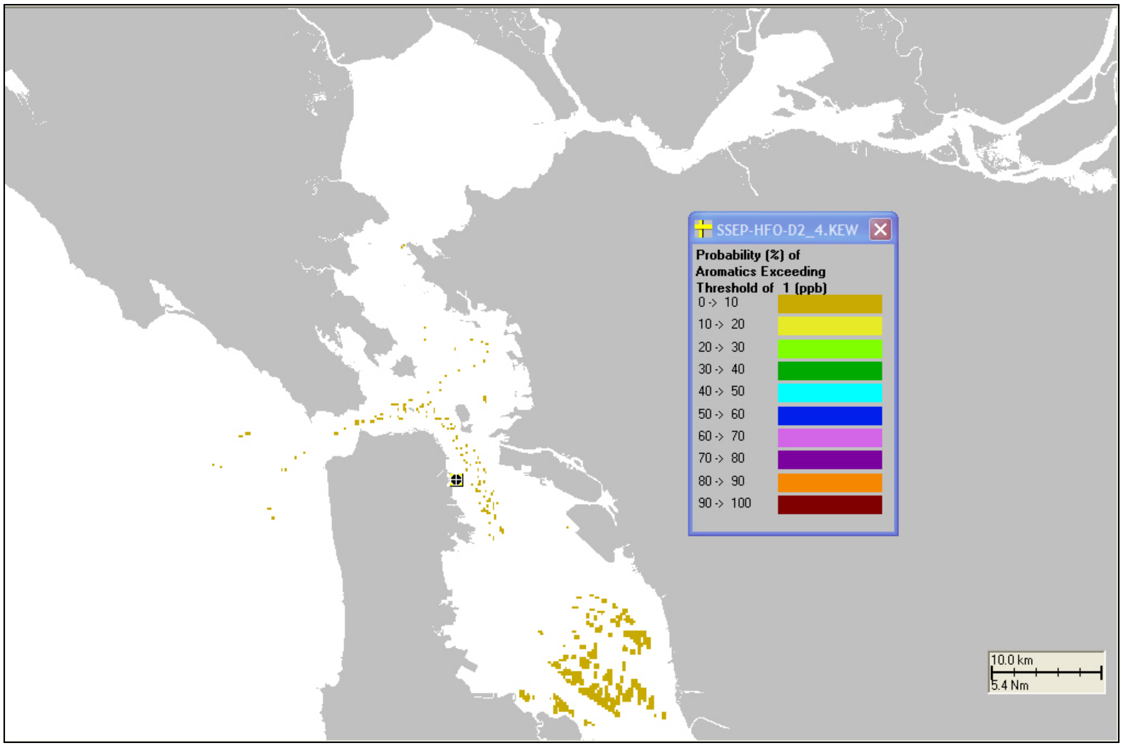

Figure 7. Probability of dissolved aromatic concentration in the upper 1m of the water column exceeding 1 ppb at some time after a 100,000 gal HFO spill at the San Francisco docks.

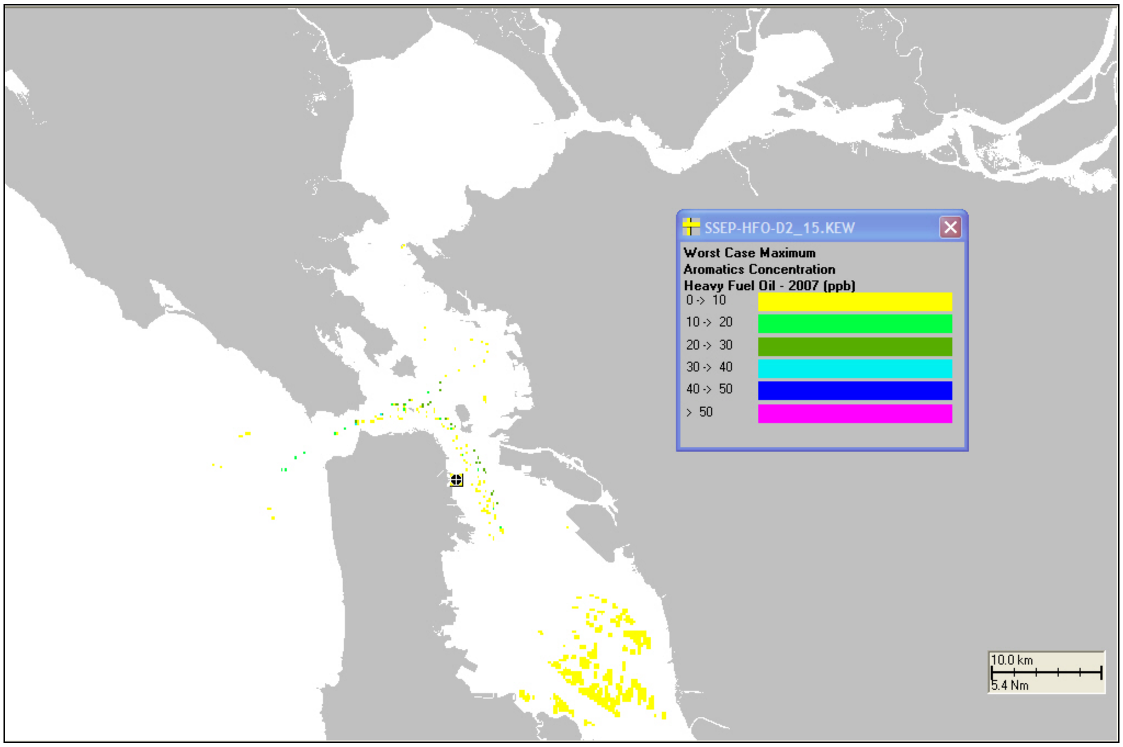

Figure 8. Maximum possible dissolved aromatic concentration in the upper 1m of the water column at some time after a 100,000 gal HFO spill at the San Francisco docks.

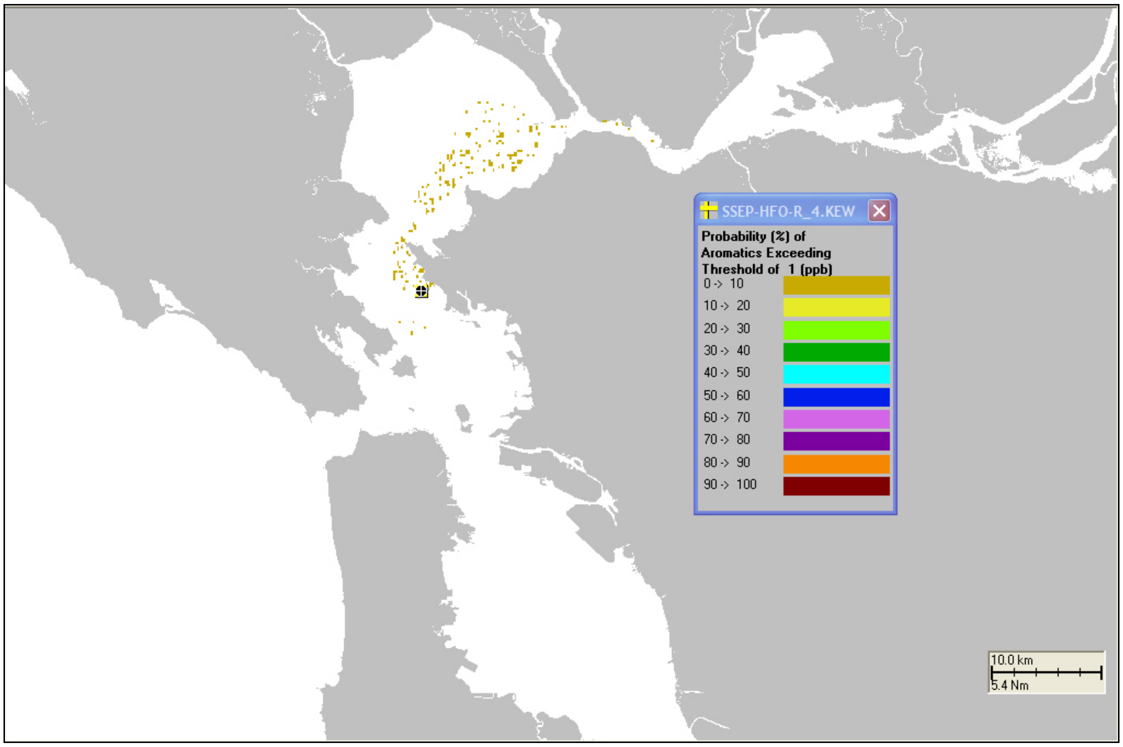

Figure 9. Probability of dissolved aromatic concentration in the upper 1m of the water column exceeding 1 ppb at some time after a 100,000 gal HFO spill at Richmond Long Wharf.

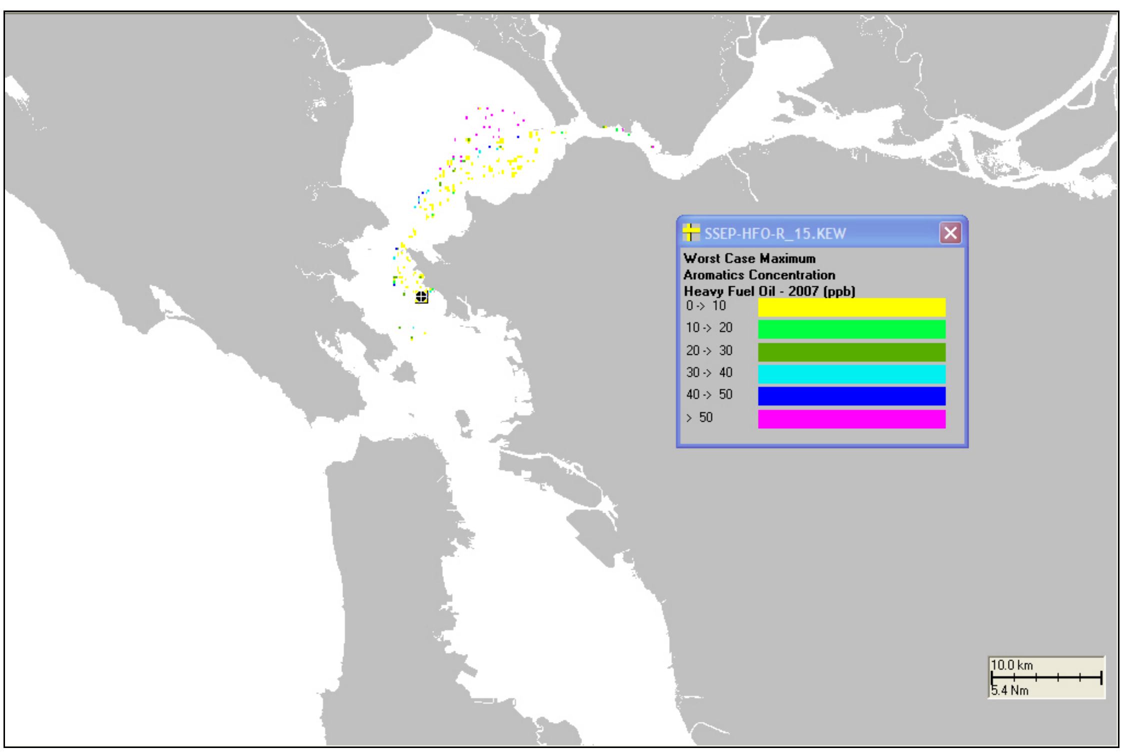

Figure 10. Maximum possible dissolved aromatic concentration in the upper 1m of the water column at some time after a 100,000 gal HFO spill at Richmond Long Wharf.

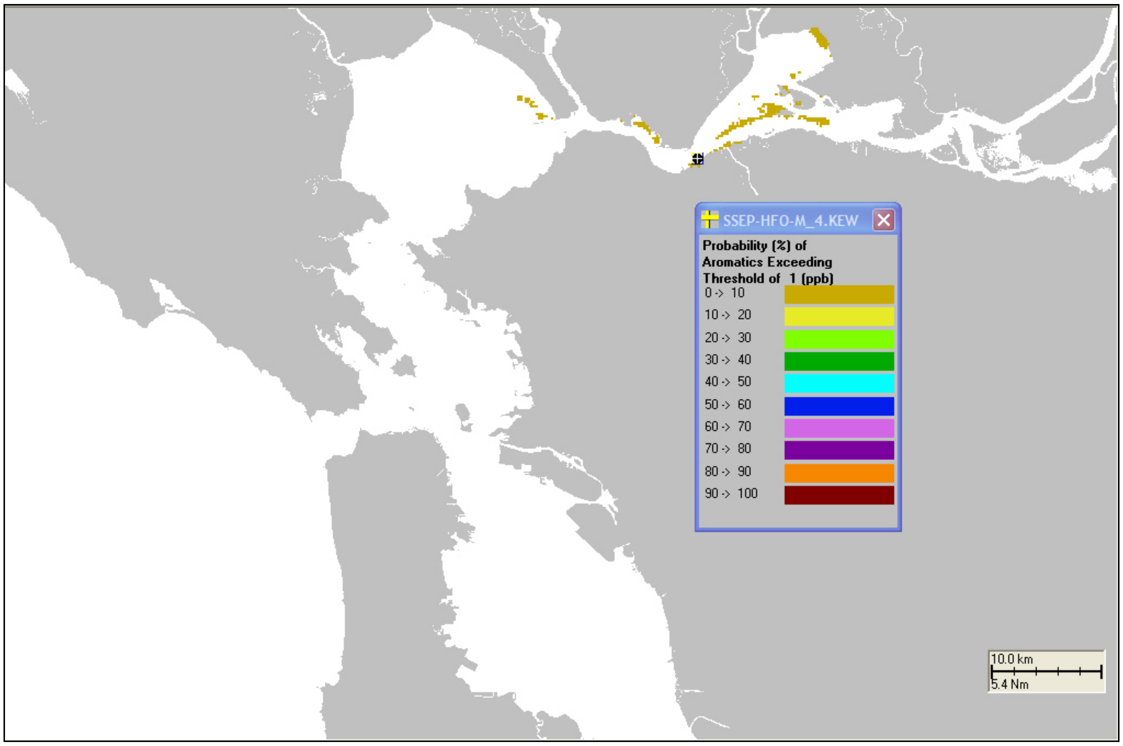

Figure 11. Probability of dissolved aromatic concentration in the upper 1m of the water column exceeding 1 ppb at some time after a 100,000 gal HFO spill at Martinez Refinery.

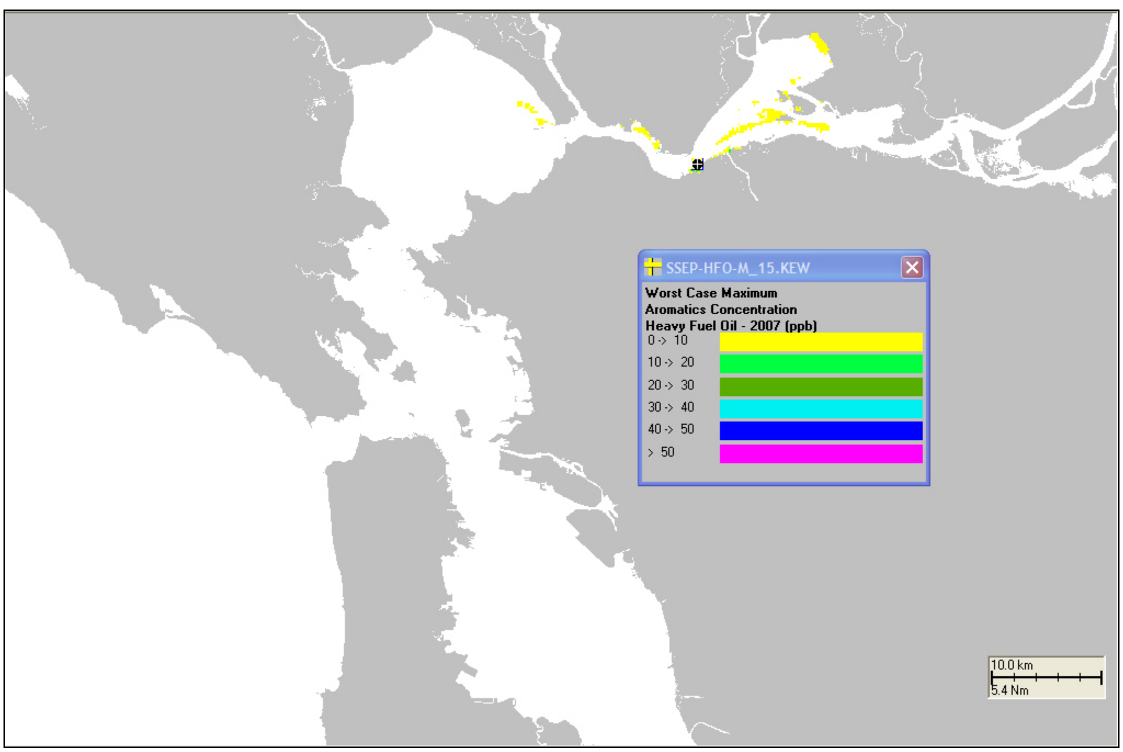

Figure 12. Maximum possible dissolved aromatic concentration in the upper 1m of the water column at some time after a 100,000 gal HFO spill at Martinez Refinery.

Table 8. Percentage of total hydrocarbon mass spilled reaching the sediments, after a 100,000 gal HFO spill. [SD = standard deviation]

Statistic	Dock	Richmond	Martinez
Mean (%)	9.1	13.0	2.7
SD (%)	8.6	6.9	2.0

4.2 Phase 2: Modeling of Individual Scenarios

Figures 13 (impacting Tiburon area and Richmond Inner Harbor) and 15 (impacting Grizzly and Honker Bays) show the trajectories and timing of oil movements for individual HFO spills examined by Etkin et al. (2009) in Phase 1, whereas Figures 14 and 16 show the degree of surface oil exposure (i.e., the maximum g/m^2 of oil in the location at any time after the spill). Figures 17 and 19 show the trajectories and timing of oil movements for individual HFO spills examined in Phase 2, and Figures 18 and 20 show the degree of surface oil exposure (i.e., the maximum g/m^2 of oil in the location at any time after the spill). The crude oil and diesel trajectories examined in Phase 2 follow the same paths and timing, but with additional spreading locally around the pathway (not shown). Note that the tide moved the oil quickly to Richmond Inner Harbor in the scenario examined in Phase 1 (Figure 13), but in the Phase 2 example (Figure 17), there would be more time to respond to oil coming ashore in that area. The Phase 2 Martinez run used in the Phase 2 study (Figure 19) involves more oil reaching Grizzly and Honker Bays.

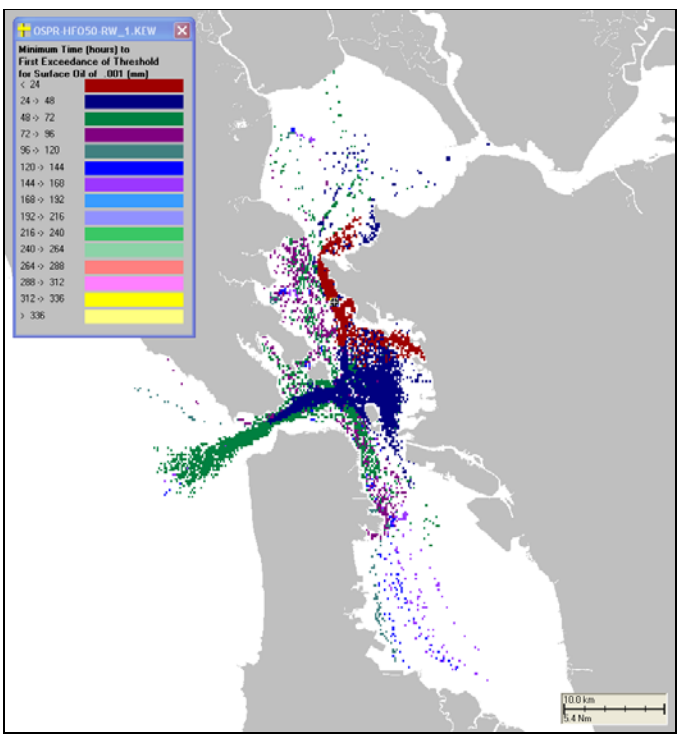

Figure 13. Trajectory and timing of movements for a 100,000 gal HFO spill impacting Tiburon area and Richmond Inner Harbor, for which response options were evaluated in Phase 1.

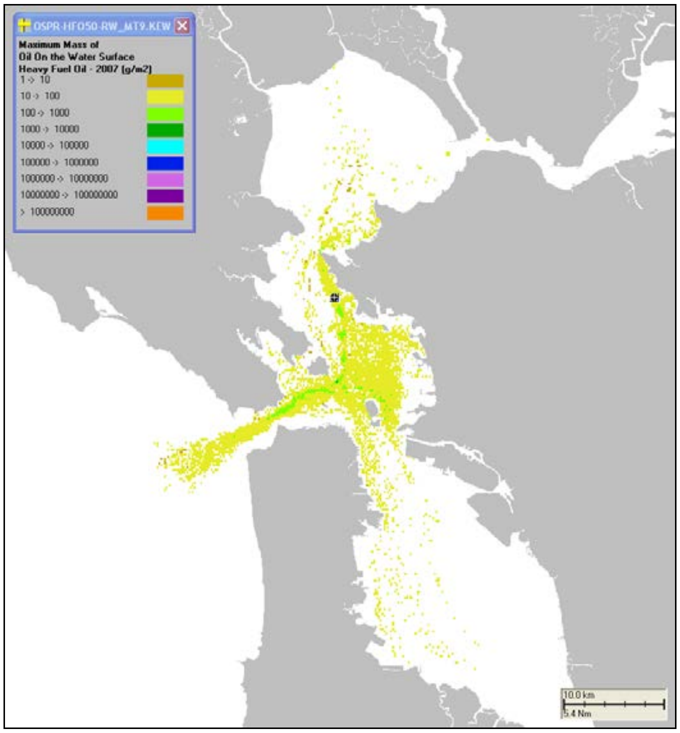

Figure 14. Maximum surface oil exposure at any time after a 100,000 gal HFO spill impacting Tiburon area and Richmond Inner Harbor, for which response options were evaluated in Phase 1.

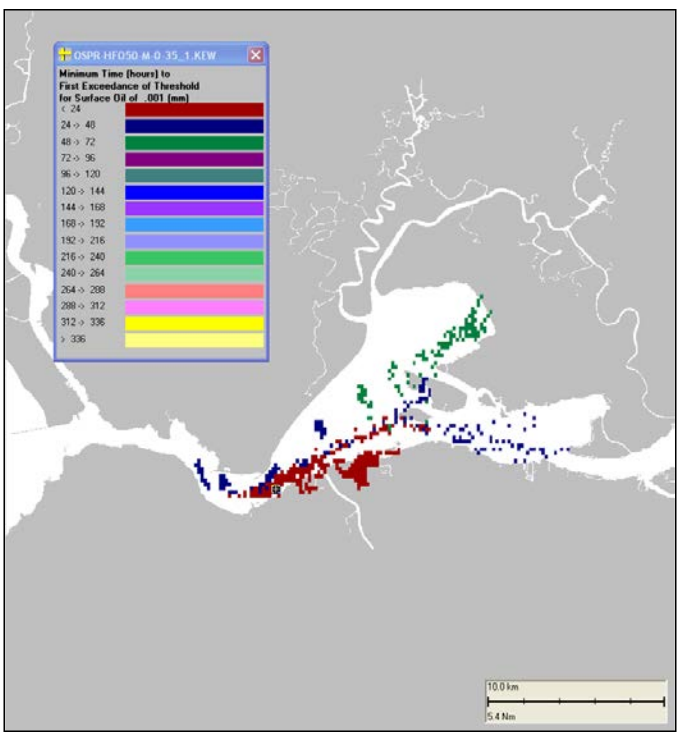

Figure 15. Trajectory and timing of movements for a 100,000 gal HFO spill at Martinez, for which response options were evaluated in Phase 1.

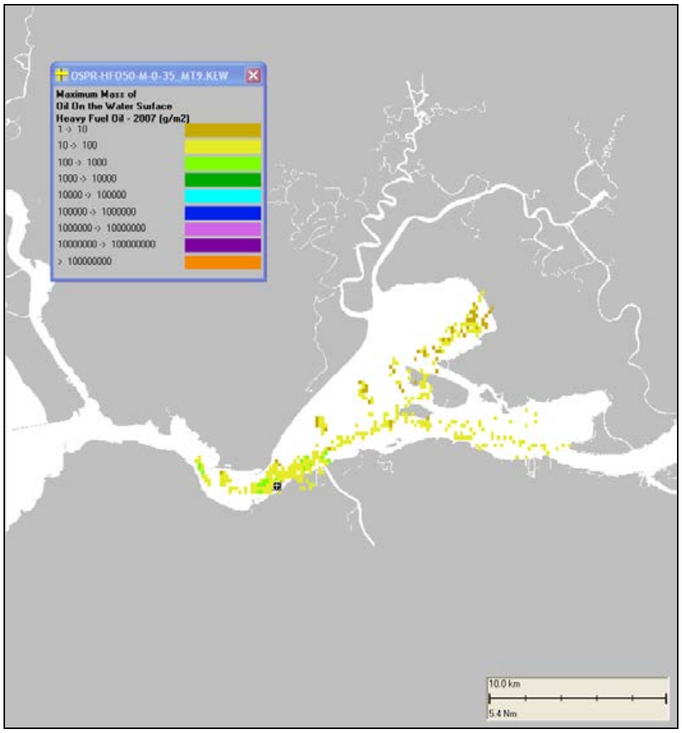

Figure 16. Maximum surface oil exposure at any time after a 100,000 gal HFO spill at Martinez, for which response options were evaluated in Phase 1.

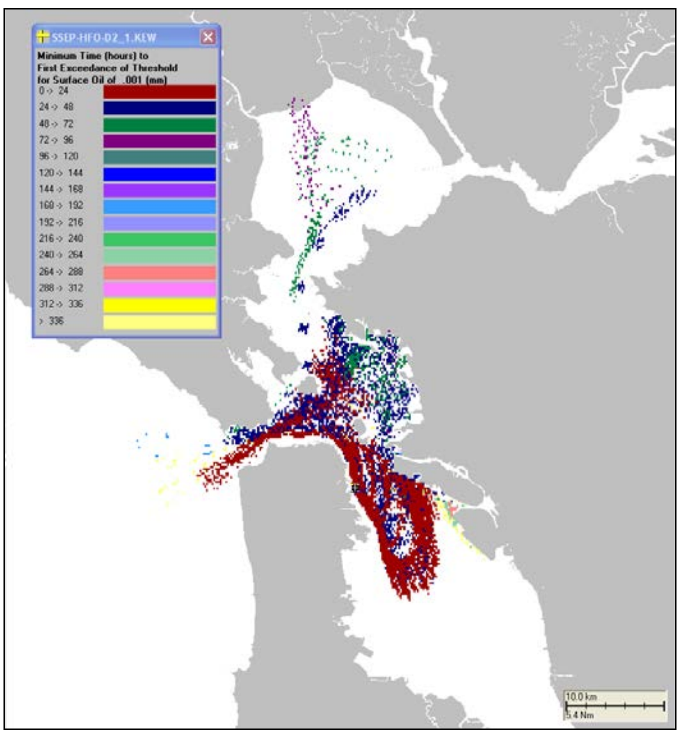

Figure 17. Trajectory and timing of movements for a 100,000 gal HFO spill at the San Francisco Docks, for which response options were evaluated in Phase 2.

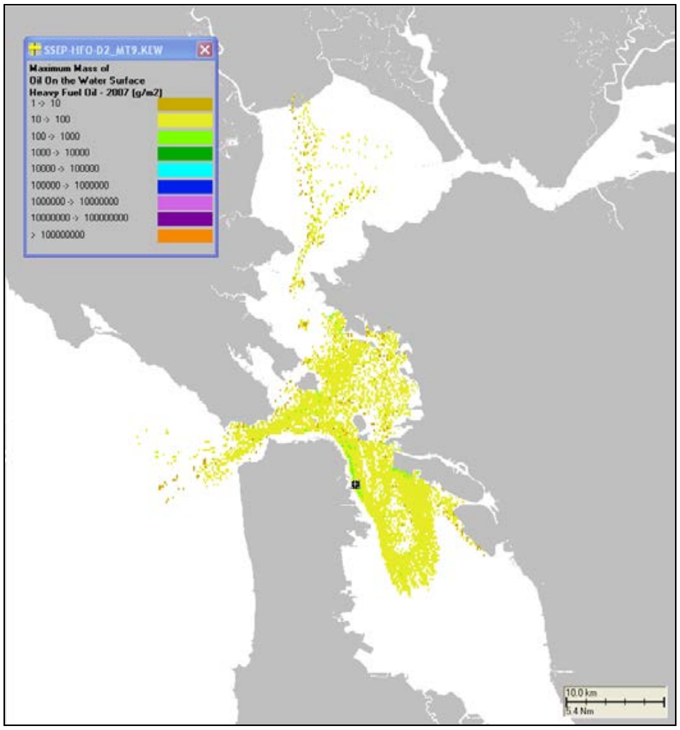

Figure 18. Maximum surface oil exposure at any time after a 100,000 gal HFO spill at the San Francisco Docks, for which response options were evaluated in Phase 2.

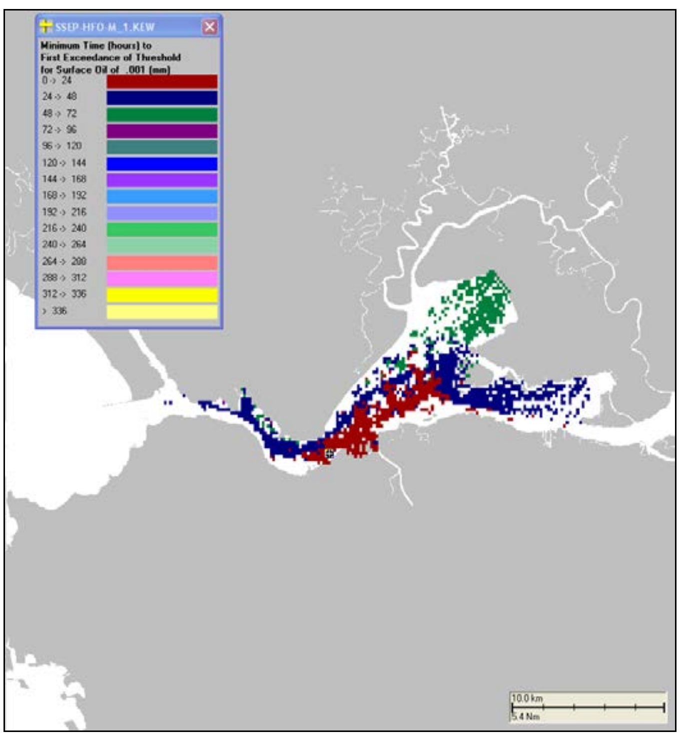

Figure 19. Trajectory and timing of movements for a 100,000 gal HFO spill at Martinez, for which response options were evaluated in Phase 2.

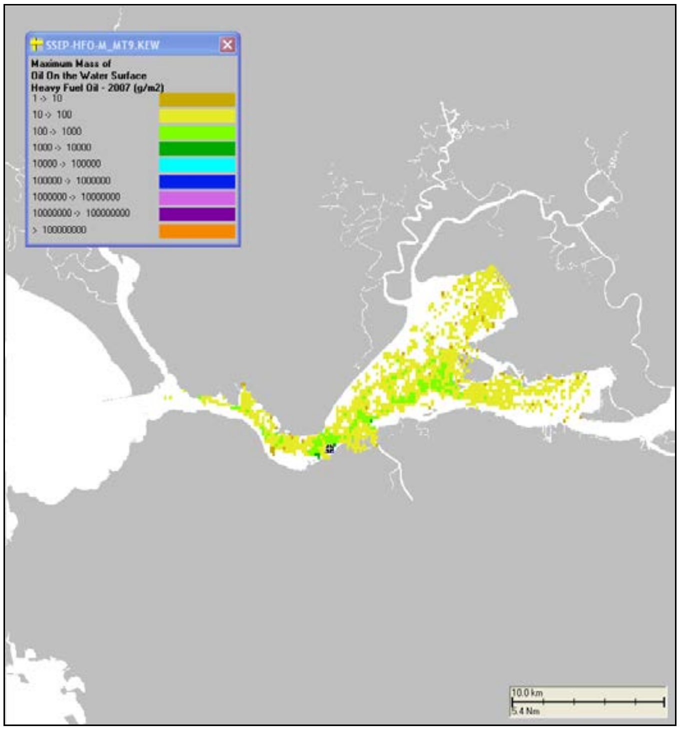

Figure 20. Maximum surface oil exposure at any time after a 100,000 gal HFO spill at Martinez, for which response options were evaluated in Phase 2.

Figures 4-6 and 13-20 show that oil released at San Francisco would be transported to the southern and central parts of San Francisco Bay, as well as into San Pablo Bay. However, most oil released at Martinez would not be transported west of the Carquinez Strait, and any oil that is transported through Carquinez Strait would be unlikely to move south out of San Pablo Bay. Note that Figures 13-20 show selected trajectories with release timing and under environmental conditions that maximize impacts in the locations of concern in this study: Tiburon area, Richmond Inner Harbor, Grizzly Bay and Honker Bay.

Tables 9-11 show the results for the biological modeling on the individual spills studied in Phase 2, listing numbers of birds oiled and total fish and invertebrate losses, assuming summer-season species densities as in French et al. (1996). The fish and invertebrate losses include direct kills of biomass, as well as production foregone (the future growth of the killed animals if they had not been impacted by the spill). The bird impacts are highest for the light fuel (diesel) when spills occurred in the open bay, owing to its faster spreading rate, leading to more areas being oiled (Table 9). However, in the Martinez area, bird impacts are highest for the viscous and persistent HFO because the area of water swept by oil is confined (by land) and the heavy oil remains on the water and in the marshes much longer than the diesel or crude (Table 10). Fish and invertebrate impacts are higher the less viscous and more entrainable oil is into the water column (Table 11).

Table 9. Numbers of birds oiled by 100,000 gal spills occurring in summer at the San Francisco docks and impacting the Richmond-Berkeley area.

Group	Heavy Fuel oil	Crude oil	Diesel
Waterfowl	185	198	345
Seabirds	192	213	430
Wading birds	91	150	615
Shorebirds	425	701	2,881
Total	892	1,262	4,270

Table 10. Numbers of birds oiled by 100,000 gal spills occurring in summer at Martinez and impacting the Grizzly Bay area.

Group	Heavy Fuel oil	Crude oil	Diesel
Waterfowl	94	71	67
Seabirds	89	67	63
Wading birds	575	317	299
Shorebirds	2,693	1,485	1,398
Total	3,451	1,940	1,826

Table 11. Biomass of fish and invertebrates lost after a 100,000 gal spill occurring in summer either at the San Francisco docks or at Martinez.

Spill Location	Heavy Fuel oil	Crude oil	Diesel
San Francisco	16.4	31.2	45.2
Martinez	18.9	128.6	203.8

Tables 12 and 13 show the model results for the individual spills studied in Phase 2, listing areas of wetlands and mudflats oiled by enough oil to impact vegetation (>1,000 g/m^2) or invertebrates (>100 g/m^2), based on the review of impact thresholds in French McCay (2009). Vegetation impacts are less for lighter oils, as the more persistent oils cover vegetation to a degree that can impact growth. However, the wetland and mudflat areas where invertebrates would be impacted are largest for diesel, owing to its faster spreading rate, leading to more areas being oiled. Crude oil impacts to invertebrates in these intertidal zones are intermediate of those from diesel or HFO.

Table 12. Areas of wetlands and mudflats impacted by oil from 100,000 gal spills occurring in summer at the San Francisco docks and impacting the Richmond-Berkeley area.

Group	Heavy Fuel oil	Crude oil	Diesel
Wetland vegetation	45,020	11,203	11,652
Wetland invertebrates	45,368	52,182	84,741
Mudflat invertebrates	202,358	266,966	279,424
Wetland + Mudflat invertebrates	247,726	319,148	364,165

Table 13. Areas of wetlands and mudflats impacted by oil from 100,000 gal spills occurring in summer at Martinez and impacting the Grizzly Bay area.

Group	Heavy Fuel oil	Crude oil	Diesel
Wetland vegetation	565,546	163,705	256,612
Wetland invertebrates	565,833	453,095	604,264
Mudflat invertebrates	1,203,508	930,955	989,983
Wetland + Mudflat invertebrates	1,769,341	1,384,050	1,594,247

5. Conclusions

The statistically quantifiable methods demonstrated here may be used for estimating potential impacts, for both contingency planning and ecological risk assessment. We demonstrated the approach here for three scenarios using stochastic modeling.

For the stochastic scenarios examined, oil came ashore within 48 hours in much of the affected area under most environmental conditions. While in many locations booms would need to be placed in the first 10s of hours after oil is released in order to deflect oil coming ashore, some oil remained out in the bay in the tidal excursion for days, allowing more time to deploy equipment and respond in areas remote from the release.

The risk of water column impacts resulting from heavy oil spills in San Francisco Bay are low for most events, but potential would result in 10% of events for the spill volume examined (369 MT = 100,000 gal). The concentrations would be expected to be relatively high compared to effects levels only in localized areas and shallow waters where oil collects against the shoreline.

Bird impacts were highest for the light fuel (diesel) when spills occurred in the open bay, owing to its faster spreading rate, leading to more areas being oiled. However, in the Martinez area, bird impacts were highest for the viscous and persistent HFO because the area of water swept by oil is confined (by land) and the heavy oil remains on the water and in the marshes much longer than the diesel or crude. Fish and invertebrate impacts were higher the less viscous and more entrainable oil is into the water column.

Vegetation impacts are less for lighter oils, as the more persistent oils cover vegetation to a degree that can impact growth. However, the wetland and mudflat areas where invertebrates would be impacted are larger for lighter oils, owing to its faster spreading rate, leading to more areas being oiled.

6. Acknowledgements

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