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Modeling Fates and Impacts for Bio-Economic Analysis of Hypothetical Oil Spill Scenarios in San Francisco Bay

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Abstract

Oil spill modeling was performed for hypothetical oil spill scenarios in San Francisco Bay to evaluate potential bio-economic impacts (biological impacts, natural resource damages, and response costs). The scenarios are hypothetical groundings on rock pinnacles near Alcatraz Island and the vessel traffic lanes. Three spill sizes (20^{th}, 50^{th}, and 95^{th} percentile volumes) from tankers and larger freight vessels and four oil types (gasoline, diesel, heavy fuel oil, and crude oil) were modeled using Applied Science Associates' (ASA) modeling software SIMAP. The scenarios were first run in stochastic mode to determine the frequency distribution of fates and impacts. From these data, the 50^{th} and 95^{th} percentile runs (based on variation in environmental conditions) were identified and examined in detail to determine impacts and costs. This paper focuses on the oil fates and biological effects.

The results show that the diesel and crude oil spills would cause higher impacts in the water column than the heavy fuel and gasoline, because of the much higher volatility and lower toxicity of gasoline and because the heavy fuel oil spill volumes were smaller. However, the majority of the impacts and resulting NRDA damages were for birds, with the water column losses relatively low because of the high dilution potential in the bay.

The results are to be used by the Army Corps of Engineers San Francisco District in a cost-benefit analysis evaluating the trade-off of oil spill risk versus removal of the rocks. This work is significant as it demonstrates a statistically quantifiable method for estimating potential impacts that may be used in ecological risk assessment and cost-benefit analyses. The statistically-defined spill volumes and consequences provide an objective measure of the magnitude, range and variability of impacts to wildlife, aquatic organisms and shorelines for potential spills of four oil/fuel types shipped in the bay, each having distinct environmental fates and effects.

1 Introduction

The United States Army Corps of Engineers San Francisco District (ACOE) is evaluating the oil spill risks associated with the four submerged rock pinnacles (Harding, Shag, Arch and Blossom Rocks) located adjacent to Alcatraz Island in San Francisco Bay. As these rocks are located near navigation channels, the concern is the potential for a loaded oil tanker or freighter striking these pinnacles and causing an oil spill. The purpose of this study was to evaluate the ecological and financial consequences of such spills using bio-economic oil spill modeling. The present paper summarizes the oil fates and biological impacts results for the first set of model scenarios, for hypothetical spills at Shag Rock. Details of the model assumptions and results may be found in French McCay et al. (2002).

Since the modeling is to provide information for a risk analysis, a Monte Carlo simulation approach was used. Twelve basic spill scenarios were analyzed, comprised of the various combinations of the two basic inputs; oil type (gasoline, diesel, crude oil, and heavy fuel oil) and spill size (small, medium and large). For each scenario, the model was run numerous times (100 was found adequate to provide statistical significance based on tests with up to 200 runs), with each run using a randomly varied spill date, such that environmental conditions were varied within the possible range of conditions (i.e., tidal current patterns, river flow conditions and wind data). For each of the twelve scenarios, the 50th and 95th percentile runs, in terms of impacts, were examined in detail for ecological impacts and financial consequences as NRDA, socioeconomic, and response costs.

In order to define the potential spill volumes, a probability distribution of oil spill size was created by Etkin and Michel (2002) based on relevant historical oil spill events, shipping traffic in San Francisco Bay, and analysis of various spillage volumes. Four fuel types were selected as representative of fuels shipped through San Francisco Bay: Alaska North Slope crude oil (AK crude), heavy fuel oil (HFO), diesel and gasoline. The medium spill was the mean spill size, the small spill was the 20th percentile spill, and the large spill was defined as the 95th percentile spill for the relevant vessel type (Table 1). These percentiles represent the probability distribution of spill size *given that a spill occurred*.

Table 1 Oil Types and Spill Volumes.

Oil Type	**20th Percentile**	**50th Percentile**	**95th Percentile**
Gasoline (Product Tanker)	151.42 MT (50,000 gal)	817.65 MT (270,000 gal)	3785.41 MT (1,250,000 gal)
Diesel (Product Tanker)	161.98 MT (50,000 gal)	874.68 MT (270,000 gal)	4049.44 MT (1,250,000 gal)
AK Crude (Crude Tanker)	331.64 MT (100,000 gal)	1989.84 MT (600,000 gal)	9949.20 MT (3 million gal)
Heavy Fuel Oil (Freighter)	92.26 MT (25,000 gal)	369.04 MT (100,000 gal)	1513.06 MT (410,000 gal)

2 Model Description

2.1 Physical Fates Model

The SIMAP (Spill Impact Model Application Package) model system developed by Applied Science Associates (ASA) was used for this study. This model is comprised of three-dimensional oil fate and bio-economic impact models that address impacts, NRDA and response costs. SIMAP was developed from the oil fates and biological effects submodels in the Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME), which ASA developed for the US Department of the Interior for use in Natural Resource Damage Assessment (NRDA) regulations. The NRDAM/CME (Version 2.4, April 1996) was published as part of the CERCLA type A NRDA Final Rule (Federal Register, May 7, 1996, Vol. 61, No. 89, p. 20559-20614). The technical documentation for the NRDAM/CME is in French et al. (1996a,b,c).

While the NRDAM/CME is focused on natural resource damage assessment for specific hindcasts, SIMAP is designed to evaluate fates and effects of both real and hypothetical spills. SIMAP may be run in stochastic mode to evaluate a probability distribution of results, rather than just a single result for a specific hindcast. Most of the updates of the model to develop SIMAP are designed for allowing the use of site-specific data and for evaluation of probabilities of impacts. Below is a summary of the conceptual design of the model. Details may be found in technical reports and papers as indicated below.

The physical fates model estimates the distribution of oil (as mass and concentrations) on the water surface, on shorelines, in the water column and in the sediments. The model is three-dimensional, using a latitude-longitude grid for environmental and geographical data. Algorithms based on state-of-the-art published research include spreading, evaporation, transport, dispersion, emulsification, entrainment, dissolution, volatilization, partitioning, sedimentation, and degradation. Oil mass is tracked separately for lower molecular weight aromatics (1 to 3-ring aromatics) which cause toxicity in the model, other volatiles, and non-volatiles. The lower molecular weight aromatics dissolve from the whole oil and are partitioned in the water column and sediments according to equilibrium partitioning theory (French et al. 1996a, 1999). The algorithms and assumptions of the 3-d fates model are described in French et al. (1999).

In the SIMAP fates model, crude oils and petroleum products are represented by seven components. Six of the pseudo-components (all but the residual) evaporate in the model. Table 2 defines the characteristics of the seven pseudo-components. The seven modelled pseudo-components are:

1 Monoaromatic Hydrocarbons (MAHs)
2 2-ring Polynuclear Aromatic Hydrocarbons (PAHs)
3 3-ring PAHs
4 Volatile aliphatics;
5 Semi-volatile aliphatics;
6 Low volatility aliphatics; and
7 Residual fraction (both aromatics and aliphatics).

Table 2 Definition of Four Distillation Cuts in the Model

All hydrocarbons	**Volatiles**	**Semi-volatiles**	**Low Volatility**	**Residual (non-volatile)**
Aromatics	MAHs (1 ring)	2 ring PAHs	3 ring PAHs	≥4 ring aromatics
Non-aromatics	Volatile aliphatics	Semi-volatile aliphatics	Low volatility aliphatics	High molecular weight aliphatics
Number of Carbons	C4 – C10	C10 – C15	C15 – C20	> C20
Distillation cut #	1	2	3	4
Boiling Point (^{o}C)	< 180	180 - 265	265 - 380	>380
Boiling Point (^{o}F)	< 356	356 - 509	509 -716	> 716

The MAHs and the PAHs are the soluble and bioavailable components that cause toxicity. The MAHs include benzene, toluene, ethylbenzene and xylenes, known as BTEX, as well as alkyl-substituted benzenes. The C3 benzenes (trimethylbenzenes, ethyl-methylbenzenes, and others with three carbon substitutions) are soluble and contribute to toxicity, along with the soluble PAHs and MAHs. Wang et al. (1995) have identified these as important constituents of concern in oils and fuels.

Oils are lighter than water at the time they are spilled. If released under water, as assumed in this study (because of the assumed grounding cause on rocks at least 11m deep), oil droplets are formed, which surface rapidly because of the buoyancy of the oil relative to water. The surfaced oil is transported by wind and currents, until it strands on shorelines. Oil may be entrained into the water by high winds. Entrained droplets may adsorb to suspended sediments and settle to the bottom due to the higher density of the combined material. This occurs most commonly in shallow waters with high wave activity. In addition to these processes, the model simulates dissolution of the toxic aromatic components from the entrained droplets, and the fate (and effects) of these aromatics in the water column and sediments.

The SIMAP fates model quantifies, in space and over time, for each individual model run:

- The spatial distribution of oil mass and volume on water surface over time
- Oil mass, volume and thickness on shorelines over time
- Subsurface oil droplet concentration, as total hydrocarbons, in three dimensions over time
- Dissolved aromatic concentration in three dimensions over time
- Total hydrocarbons and aromatics in the sediments over time

2.2 Stochastic Model

In order to determine risks to ecological resources, multiple scenarios and conditions need to be evaluated to develop an expectation of risk of oil reaching each site of concern. The stochastic model in SIMAP (French et al., 1999) is used to determine the range of distances and directions oil spills are likely to travel from a particular site, given historical wind and current speed and direction data for the area. To sample the universe of possible environmental conditions, long-term wind and current data are compiled. For each model run used to develop the statistics, the spill date is randomized. This provides a probability distribution of wind and current conditions during the spill. The stochastic model performs a large number of simulations for a given spill site, varying the spill time, and thus the wind and current conditions, for each run. Output of the model is the time histories of a large number of spill trajectories. The results are ordered into a probability density function (PDF) such that the 50th (median) and other percentile spill dates-times may be identified. In this study the 50th and 95th percentile runs were subjected to further analysis.

2.3 Biological Effects Model

The biological effects model uses habitat-specific and seasonally-varying estimates of fish, shellfish, bird, mammal and reptile abundances, and productivity of plant and animal communities at the base of the food chain, to determine biological effects resulting from the spill. The model performs these calculations by first estimating the portion of a stock or population affected. The fractional loss is multiplied by abundance or biomass per unit area to quantify an impact as number or kg of biomass lost.

A rectangular grid of habitats represents the area potentially affected by the spill, with each grid cell coded for habitat type. Habitats include deepwater, near shore, wetland and shoreline environments. A contiguous grouping of habitat grid cells with the same habitat code represents an ecosystem in the biological submodel. Fish, birds, mammals and rates of lower trophic level productivity are assumed constant and evenly distributed across an ecosystem for the duration of the spill simulation (two weeks). Fish, birds and mammals are assumed to move at random within each ecosystem. Planktonic stages (eggs and larvae in the water column) are moved with the currents.

In the model, surface slicks interact with wildlife (birds and marine mammals). A portion of wildlife in the area swept by the slick are assumed to die based on probability of encounter with the slick and mortality once oiled (Table 3, from French et al., 1996a). Estimates for these probabilities are derived from information on behavior and field observations of mortality under similar circumstances. Wildlife mortality is directly proportional to abundance per unit area and the percent mortalities in Table 3. Thus, uncertainty (e.g., 95% confidence limits) is proportional to the uncertainty in the input data.

Table 3 Combined probability of encounter with the slick and mortality once oiled, if present in the area swept by a slick exceeding a threshold dose volume

Wildlife Group	**Probability**
Dabbling waterfowl	99%
Near shore aerial divers	35%
Surface seabirds	99%
Aerial seabirds	5%
Waders and shorebirds	35%
Wetland wildlife	35%
Cetaceans	0.1%
Furbearing mammals	75%
Pinnipeds	1%

Fish and their eggs and larvae are affected by dissolved contaminant concentration (in the water or sediment). Mortality is calculated using laboratory acute toxicity test data (LC50, concentration lethal to 50% of test individuals) corrected for temperature and time of exposure, and assuming a log-normal relationship between percent mortality and dissolved concentration. LC50s for the most toxic component of oil, dissolved aromatics, are used to define the center of that log-normal function. The toxicity parameters (i.e., LC50s) and algorithm are those described in French McCay (2001). Movements of biota, either active or by current transport, are accounted for in determining time and concentration of exposure. Organisms killed are integrated over space and time by habitat type to calculate a total percentage killed.

The map of percent mortality is multiplied times abundance to estimate fish and invertebrates killed as numbers or biomass (kg). Each species and stage is assigned a behavior group: planktonic (move with currents), demersal and stationary (on the bottom exposed to near bottom water), benthic (in the sediments and stationary), demersal fish (on the bottom exposed to near bottom water and moving slowly), small pelagic fish (moving randomly and slowly in the water column), or large pelagic fish (moving randomly and rapidly in the water column). The percent mortality of the exposure group is multiplied times abundance at the time exposed and in the habitat type to calculate the species' mortality. (See French et al., 1996a for details.)

The biological effects model computes reduction of fish and shellfish population size and catch in the present and future years using standard fisheries models. The injury includes losses due to mortality of adults, juveniles and young-of-the-year due to the spill. Relatively high natural mortality rates of fish eggs and larvae are considered in the model, since a high number killed at the time of the spill would have died anyway. Young-of-the-year (eggs, larvae, and juveniles less than one year old) of each fish species category are tracked as percents of the one-year-old population. Young-of-the-year and older age classes are not assumed to necessarily inhabit the same environment concurrently, and their losses are calculated separately.

The biomass (kg) of animals killed represents biomass that had been produced before the spill. In addition to this injury, if the spill had not occurred, the killed organisms would have continued to grow until they died naturally or to fishing. This lost future (somatic) production (termed "production foregone") is estimated using the fisheries population model and added to the direct kill injury. The total injury is the total production lost. The loss is expressed in present day (i.e., present year) values using a 3% annual discount rate for future losses. Restoration should compensate for this loss. The scale of restoration needed is equivalent to production lost when both are expressed in values indexed to the same year (i.e., the year of the spill).

3 Input Data

3.1 Geographical Data

SIMAP uses a rectilinear grid to designate the location of the shoreline, the water depth (bathymetry), and the shore or habitat type. 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 NOAA HAZMAT in Seattle, Washington (on CD-ROM). ESI codes were translated to equivalent habitat codes for SIMAP. 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 obtained from Hydrographic Survey Data supplied on CD-ROM by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center.

3.2 Environmental Data

Because of the large spatial variability of winds in and just outside of San Francisco Bay, multiple wind records 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). For the SIMAP stochastic model random dates are chosen; therefore all four wind files had to be inclusive. The hourly mean wind speed and direction used for the model runs were from 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.

Surface water temperature was varied by month, based on data for San Francisco Bay in French et al. (1996b). 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 floating oil. Salinity for San Francisco Bay was assumed 32 ppt (French et al., 1996b) throughout the bay.

Along with the winds at the water surface, the currents are extremely important in determining the transport and fate of oil. In order to model these complex features of the rocks, channels and the bay geometry with appropriate resolution, ASA's boundary fitted coordinate hydrodynamic model (BFHYDRO) was used to generate the applicable hydrodynamic data sets suitable for use in the SIMAP model system. The boundary conforming system used is defined in general curvilinear coordinates to map the model grid to the shoreline of the water body being studied. It also allows enormous versatility in grid sizing so that many of the smaller features such as the rocks, rivers and embayments, may be resolved, along with the larger open water areas, without being penalized by an excessively small grid size, (enormous number of cells). The model has is fully described with test cases and a sample application in Muin and Spaulding (1997a,b).

The model domain included the entire San Francisco Bay beginning at the San Joaquin Delta, and including the coastal area from Monterey Bay to Point Reyes. In that the bay is highly energetic and predominantly well mixed vertically, we applied BFHYDRO in the two-dimensional (2-D), vertically averaged mode. The 2-D model was driven with freshwater inflow at the San Joaquin Delta and tidal forcing at the open ocean boundary to predict the hydrodynamic circulation in the bay. Two freshwater conditions were modeled along with tides: dry season (low delta outflow) and wet season (high delta outflow) to create two hydrodynamic current data sets with which to run the oil model. The circulation in the bay is almost completely tidally driven and for the present analysis, the density driven (i.e., salinity induced) flows, were not considered.

Wind-driven surface currents are calculated within the SIMAP fates model, based on local wind speed and direction using the algorithms of Youssef and Spaulding (Youssef, 1993; Youssef and Spaulding, 1993, 1994).

3.3 Dissolved Aromatic Toxicity

The PAH LC50 value for diesel, crude oil and heavy fuel oil for infinite exposure time was assumed to be 48 ppb, based on French McCay (2001). All species were assumed to be of average sensitivity in this analysis, as most species are of near average sensitivity and sufficient data are not available to determine appropriate LC50s for each affected species within the range of possible values. Similarly, the LC50 for MAHs (including BTEX = benzene, toluene, ethylbenzene, xylene, and C3 benzenes) dominant in gasoline assumed in the modeling was the value for species of average sensitivity (50^{th} percentile), 3.12 ppm.

The LC50s above are for the concentration of *dissolved* MAHs and PAHs that would be lethal to 50% of exposed organisms for a long enough times of exposure for mortality to occur. For PAHs, this is for at least a week of exposure at warm temperature. For chemicals in general, toxicity is higher, and the LC50 lower, at longer time of exposure and higher temperature (French McCay, 2001). The duration of exposure is estimated in SIMAP and the LC50 is corrected accordingly and for temperature.

3.4 Biological Abundances

The NRDAM/CME (French et al., 1996c) contains mean seasonal or monthly abundances for 77 biological provinces in US coastal and marine waters. The biological data for fish and invertebrates in province 46, San Francisco Bay, are assumed the SIMAP simulations of spills.

Wildlife species include aquatic birds and marine mammals. The model uses average number per unit area (#/km^2) in appropriate habitats. French et al., (1996a,c) describes the assignment of each species to a set of habitats that it uses. The species is assumed uniformly distributed across its preferred habitats. Thus, the habitat grid defines the habitat map, and so the abundance of each species.

Bird abundance data were compiled in 1997 by ASA and Ecological Consulting (Portland OR, Glenn Ford, personnel communication) as part of an update to the NRDAM/CME for California Fish and Game (i.e., for NRDAM/CAL). Abundance varies monthly or seasonally, depending on available data. Separate data sets were developed and used here for inside San Francisco Bay (Table 4) and in coastal waters just outside the bay (Table 5). Waterfowl include diving ducks, loons and grebes. Seabirds include common murres, cormorants, gulls, and terns.

Table 4 Total Wildlife by Group in San Francisco Bay (#/km^2)

Group	Winter	Spring	Summer	Fall
Waterfowl	91.9	6.3	0	82.9
Seabirds	20.9	34.1	33.9	21.2
Wading birds	189.2	191.5	222.5	191.8
Shorebirds	2255.7	837.4	1901.4	3044.4
Kingfishers	0.2	0.2	0.2	0.2
Pinnipeds (seals)	1.4	0.2	0.2	1.4

Table 5 Total Wildlife by Group Outside San Francisco Bay (#/km^2)

Group	Winter	Spring	Summer	Fall
Waterfowl	2042.8	299.3	264.6	2103.4
Seabirds	38.7	59	206.6	95.8
Wading birds	188.1	190.4	221.4	190.8

Shorebirds	2309.8	891.5	1955.5	3098.5
Kingfishers	0.2	0.2	0.2	0.2
Pinnipeds (seals)	0.8	0.6	0.7	0.9

3.5 Summary of Fates Model Inputs

Table 6 summarizes the fates model input parameters for all scenarios.

Table 6 Inputs to the Fates Model for All Scenarios

Name	Description	Value(s)
Spill Site	Location of the spill site	Shag Rock 37^o 50.0604' N 122^o 26.43480' W
Depth of release	Depth below the water surface of the release or 0 for surface release	11-12 m = bottom of ship deep enough to hit rock
Spill duration	Hours over which the release occurs	3 hours
Model time step	Time step used for model calculations	0.1 hour
Model duration	Length of each model simulation	7 days
Number of runs	Number of random start times to run in stochastic mode	100
Number of oil spillets	Number of Lagrangian elements used to simulate whole oil	10,000
Number of aromatic spillets	Number of Lagrangian elements used to simulate dissolved aromatics in the water	10,000
Horizontal turbulent diffusion coefficient	Randomized turbulent mixing parameter in x & y	1 m^2/sec
Vertical turbulent diffusion coefficient	Randomized turbulent mixing parameter in z	0.0001 m^2/sec

The removal of mass by cleanup and application of dispersants were not included in the model simulations. Oil is transported assuming no response, with the exception of deflection booms in designated protection areas according to the regional response plan. Oil reaching shore accumulates up to a holding capacity (varying by shore type and viscosity) and remains on shore, weathering at a natural rate (French et al 1996a, 1999).

4 Results

4.1 Physical Fates

Figures 1-4 contains plots for the worst case maximum exposure to floating oil for all scenarios evaluated for each fuel (1 g/m^2 ~ 1 micron thick). Thus, these are the highest possible exposure for the 95^{th} percentile volume under the worst environmental conditions (99^{th} percentile of the 100 model runs) for each grid cell in the model grid, evaluated independently. Note that these maps are the maximum exposure at any time after the spill. The time of exposure may be as short as 1 hour.

In addition, the plots are composites of results for multiple runs for varying spill dates and times. The footprints for potential exposure for all four fuels are similar. However, the oil thickness and duration of exposure is much less for the gasoline and diesel, which evaporate and disperse rapidly.

Exposures to each oil constituent (water surface, shoreline, dissolved aromatics in water) are analyzed over all runs to determine the median and 95th percentile conditions expected for that scenario. Runs producing the 50th and 95th percentile result were identified for further impact analysis. Note that 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 runs are 50th and 95th percentile cases for the resource of interest.

Birds and other wildlife are impacted in proportion to the water and shoreline surface area oiled above a threshold thickness for effects. Shoreline habitat impacts are proportional to surface area oiled above a threshold thickness for effects.

Contamination in the water column changes rapidly in space and time, such that a dosage measure as the product of concentration and time is a more appropriate index of impacts than simply peak concentration. As 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. Toxicity data indicate that the 96-hour LC50 (which may serve as an acute lethal threshold) for dissolved aromatics (primarily PAHs) averages about 50 μg/l (ppb). Thus, this lethal exposure dosage threshold is 5,000 ppb-hours.

Recreational, tourism, boating/shipping, and other socioeconomic impacts are functionally related to the length of shore and area of water oiled. Duration of the impact on water may be captured by the sum of oil area and/or thickness (microns or g/m^2) times time oiled. Cleanup costs are related to volume spilled, water surface area, and area (or length) of shore oiled.

Impact indices were plotted as rank-order distributions:

- Water surface exposed to floating hydrocarbons, as the sum of area covered by more than 1g/m^2 times duration of exposure (m^2-hours)
- Shoreline area exposed to hydrocarbons of >100g/m^2 (about 0.1mm thick), which was the cleanup threshold assumed by Etkin (2002b) and is also the impact threshold assumed for oiling of birds. 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 for that shore type.
- Water volume exposed to > 1 ppb of dissolved aromatic concentration at some time after the spill
- Exposure dose of dissolved aromatics (ppb-hours) in the water volume exposed to > 1 ppb of dissolved aromatic concentration at some time after the spill

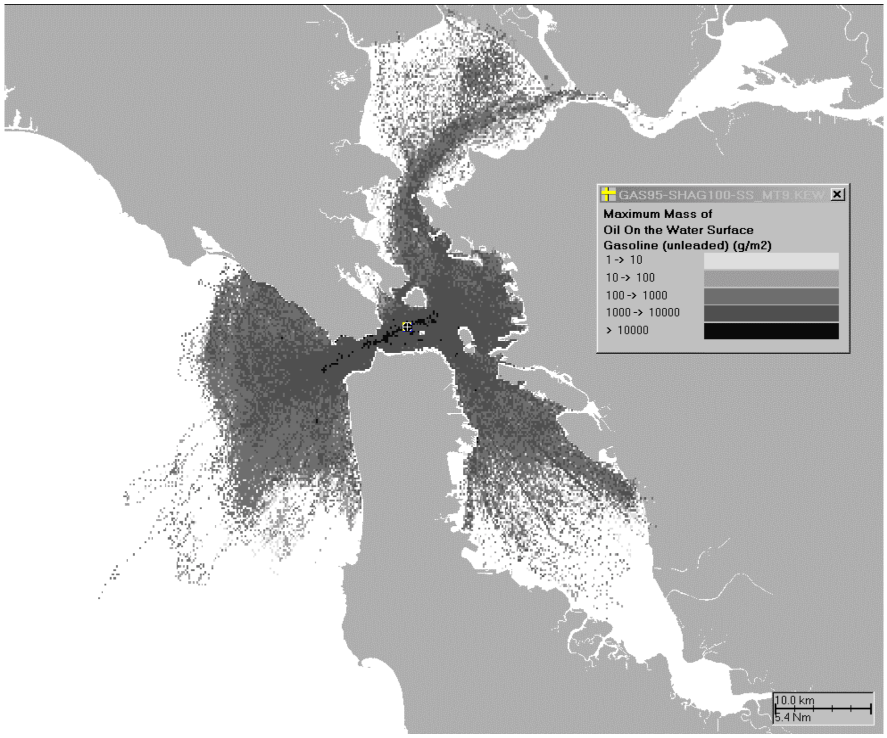

Figure 1 Maximum Possible Water Surface Exposure to Floating Oil (g/m^2): Gasoline

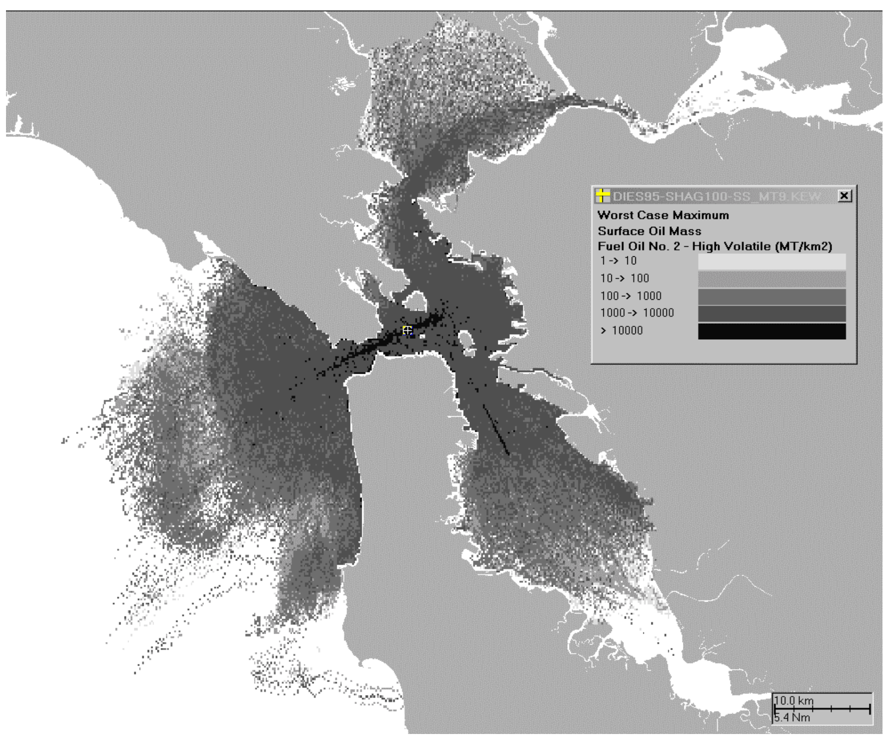

Figure 2 Maximum Possible Water Surface Exposure to Floating Oil (g/m^2): Diesel

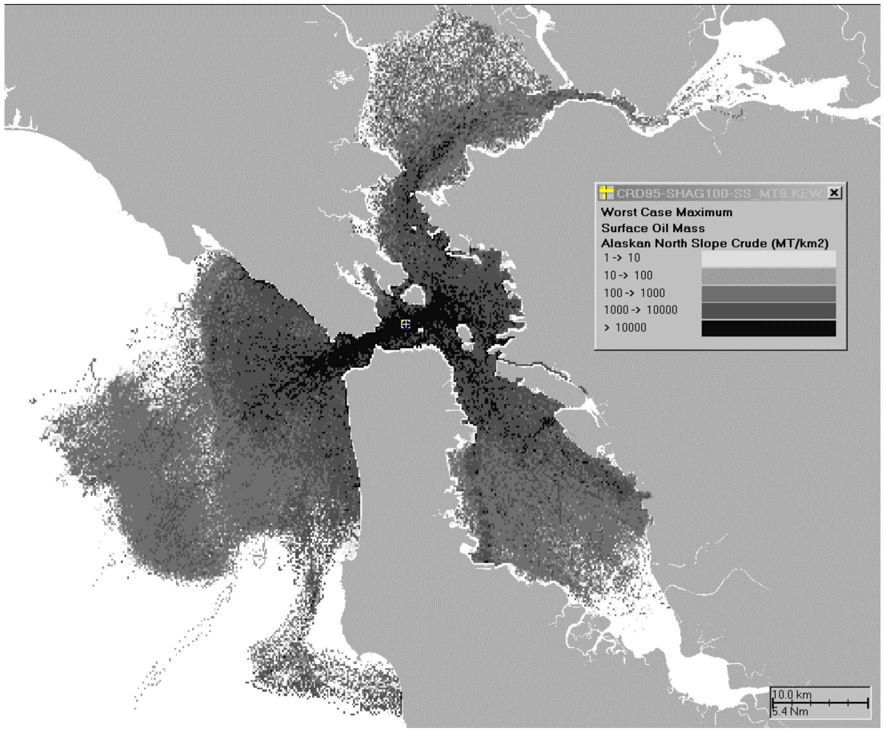

Figure 3 Maximum Possible Water Surface Exposure to Floating Oil (g/m^2): Crude

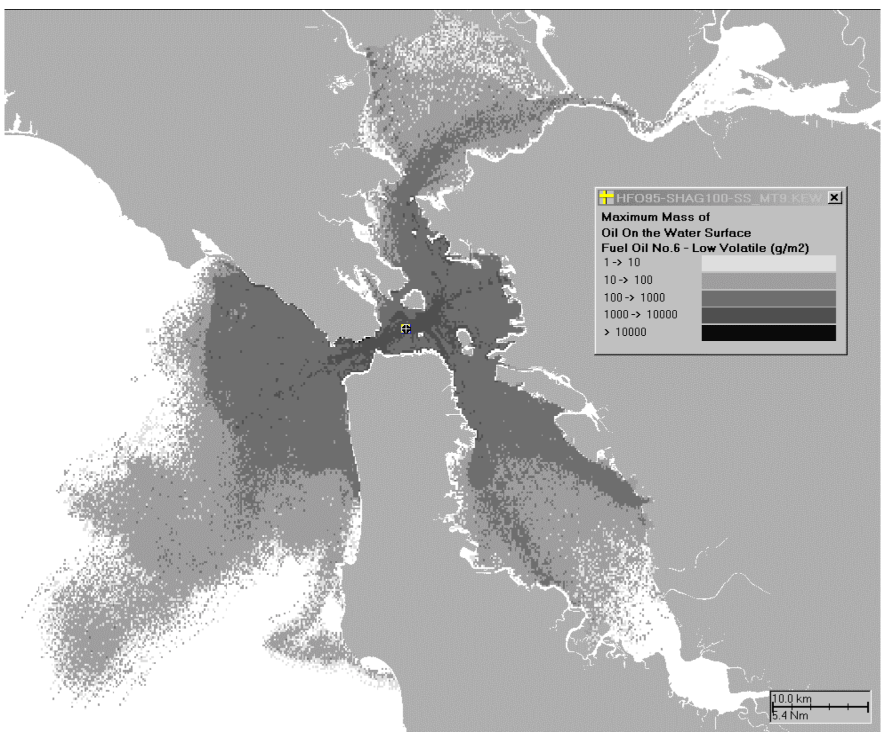

Figure 4 Maximum Possible Water Surface Exposure to Floating Oil (g/m^2): HFO

Figures 5-8 show the distribution of model results for all runs within the crude oil 95th percentile volume scenario, indicating the range of possible impacts depending on the weather conditions and currents at the time of the spill. Similar figures were generated for the other 11 scenarios. In most cases, there is a smooth frequency distribution about the median case. However, occasionally extreme events occur, i.e., the weather conditions are just right to cause the most impact. These figures indicate the median and distribution of impact indices, including the degree of variability and likelihood of extreme events.

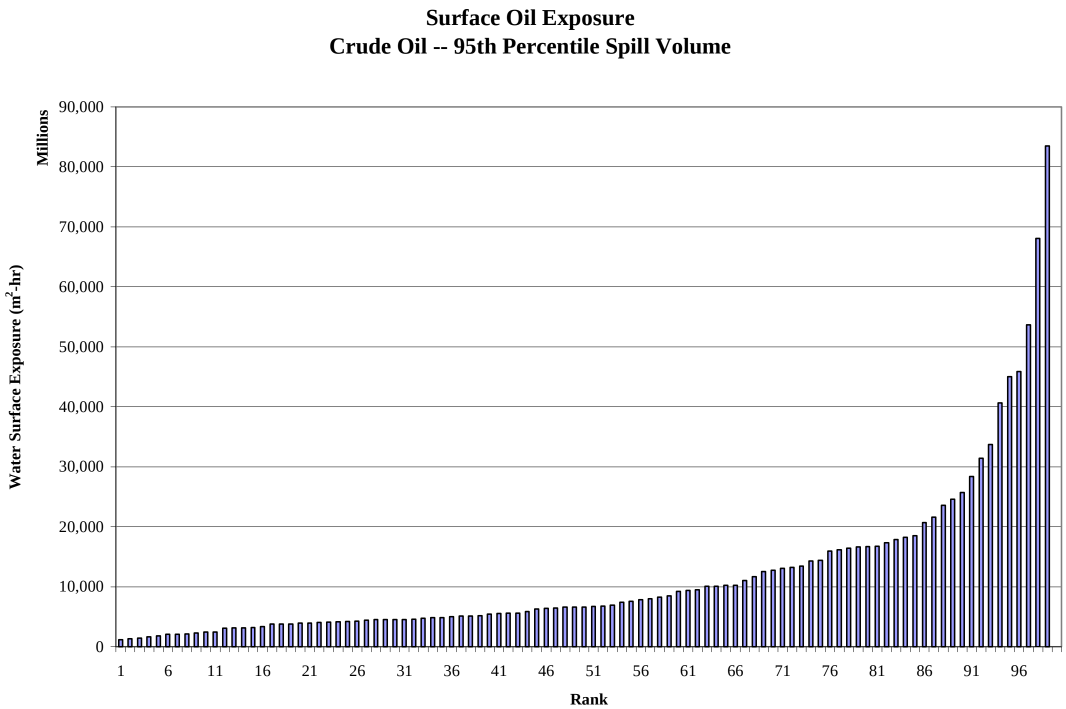

Figure 5 Water Surface Exposed to Floating Oil

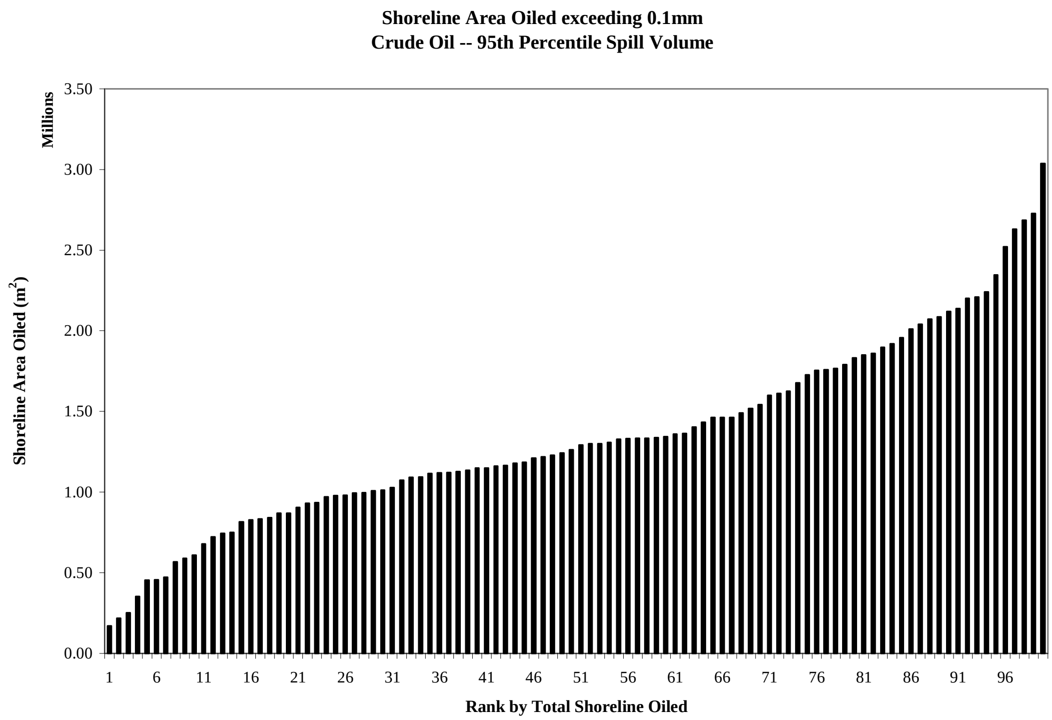

Figure 6 Shoreline Exposed to Oil >100g/m^2 (about 0.1mm Thick)

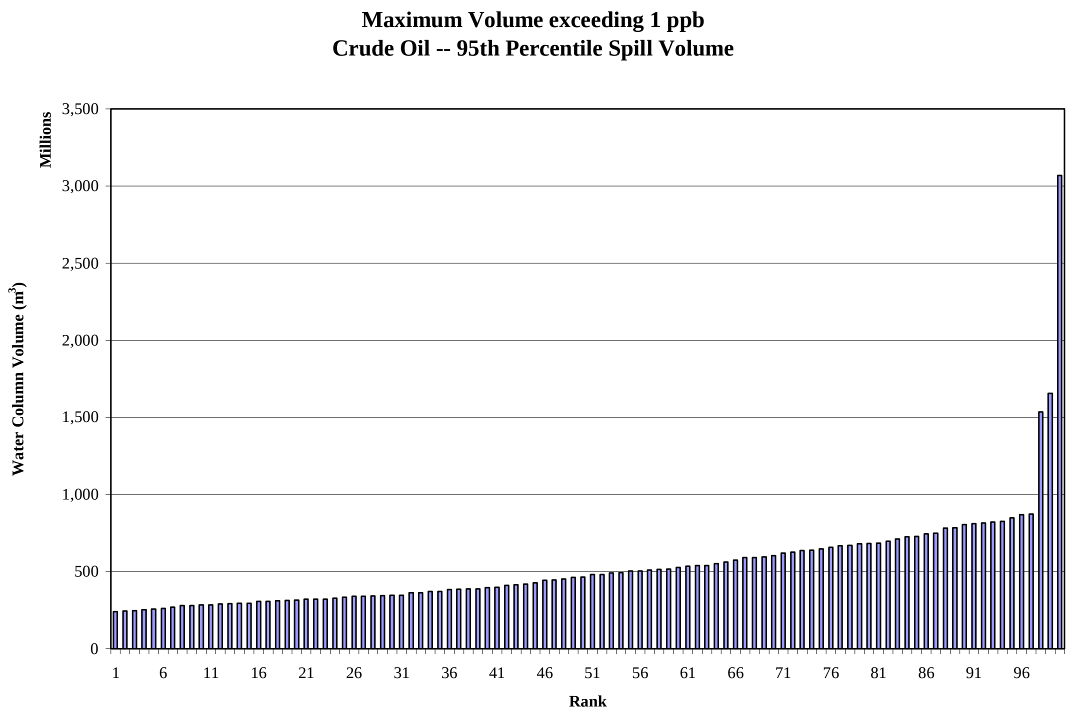

Figure 7 Water Volume Exposed to > 1 ppb of Dissolved Aromatic Concentration at Some Time after the Spill

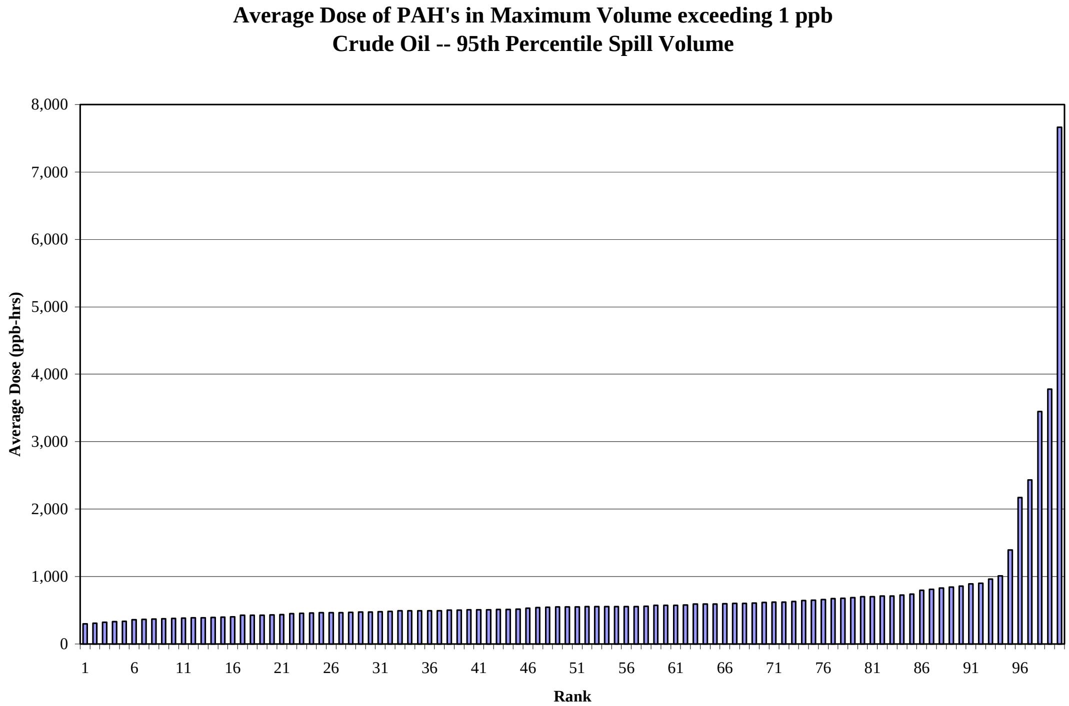

Figure 8 Exposure Dose of Dissolved Aromatics (ppb-hours) in the Water Volume Exposed to >1 ppb of Dissolved Aromatic Concentration at Some Time after the Spill

Table 7 contains the range of surface water exposure to floating hydrocarbons for spills of each type of fuel. Exposures would be greater than the listed range only during extreme events. The surface exposure of floating hydrocarbons for gasoline is relatively small and short-lived because gasoline is so volatile that as soon as it reaches the surface, it quickly evaporates. Therefore, the diesel and crude oil would have the most detrimental effects to the surface water based on exposure to floating hydrocarbons. This is reflected in the estimated impacts to wildlife and shorelines, response costs and socioeconomic impacts. The lower impact in the heavy fuel oil spills is because of the lower spill volumes, which are less than half the diesel volumes for each percentile volume. The crude oil spill volumes are about twice the diesel spill volumes, but diesel spreads faster and so covers more surface area per unit volume.

Table 7 Range of Surface Water and Shoreline Exposure to Oil

Oil Type	Surface Water >1 g/m^2 (m^2-hours)	Shoreline >100 g/m^2 (millions m^2)
Gasoline	200 - 6,000	0 - 0.3
Diesel	1,000 - 20,000	0.03 - 2
Crude oil	1,000 - 18,000	0.03 - 3
Heavy Fuel Oil	500 - 4,000	0.02 – 1.6

Table 7 summarizes the shoreline area exposed to hydrocarbons exceeding a threshold of 100 g/m^2 for each of the oils modeled. Diesel, crude oil and heavy fuel would be expected to oil the largest area of shoreline. Extreme events could cause exposure to as much as 1.4 to 2 million m^2. Gasoline would only be expected to oil as much as 300,000 m^2 in a worst case event. Gasoline and diesel would evaporate off the shoreline rapidly, while the crude and heavy fuel would remain on shore until it is cleaned up. (For detailed results, see French McCay et al, 2002).

For gasoline, diesel and crude, the water volume exposed to >1 ppb at some time after the spill is on the order of 10^9 m^3. For heavy fuel oil, where the spill volumes are smaller, the exposure volume is on the order of 10^7 m^3. The average dose in that volume is used as an index of exposure to determine the relative impact. In order to evaluate actual water column impact, the space- and time-varying concentrations need to be examined in sub-volumes of the exposed volume and compared to toxicity data. This is performed in the biological effects model (results discussed below).

The percent of spilled hydrocarbon mass reaching the sediments was evaluated. For gasoline, diesel and heavy fuel oil, the percentage is <1% for all runs. For crude, the percentage is <1% for most runs, but there are rare events where significant amounts of oil reach the sediment. These are high wind events causing high waves that entrain oil, resulting in high sedimentation in shallow water when the wind subsides.

For the heavy fuel and crude oil, environmental costs are largely driven by the impacts of surface oil, particularly by the shoreline cleanup costs. The wildlife and habitat impacts are generally proportional to shoreline oiling and cleanup costs. Thus, the 50^{th} and 95^{th} percentile runs were selected based on the frequency distribution of the shoreline cleanup costs. The order of model runs from lowest to highest impact is very similar for area of shore oiled by > >100 g/m^2 and cleanup costs, varying only by the differences in cleanup costs per unit area for different shore types (Etkin, 2002b).

For the diesel and gasoline spills, cleanup costs are much lower because there is much less oil that remains on the water surface and shorelines after the rapid evaporation period just after the spill. In addition, diesel and gasoline are much more easily entrained into the water and potentially cause more water column effect than the heavier oils. Thus, theoretically, the environmental costs are more driven by the NRDA costs for impacts to the fish and invertebrates in the water than would be the crude and heavy fuel oil scenarios. Using this reasoning, the index for water column effects, the dissolved aromatic dose (ppb-hours) in the volume of water where concentration exceeds 1 ppb at some time after the spill, was used to identify the 50^{th} and 95^{th} percentile runs to be examined further. The expectation was that water column impacts would be significant for the large spills, and these would dominate the NRDA costs. However, the results did not bear this hypothesis out, and the patterns are more complicated (as will be discussed below).

Figures 9 and 10 summarize the exposures to surface oil and dissolved aromatics for the 95^{th} percentile volume of crude oil and the 50^{th} percentile run for shoreline impacts. Thus, this run is representative for a 9949 MT spill of crude under mean environmental conditions (that have median consequences). In this particular run, the tides carry the oil into the south bay, as well as out of the bay. Shorelines alone these areas would be oiled.

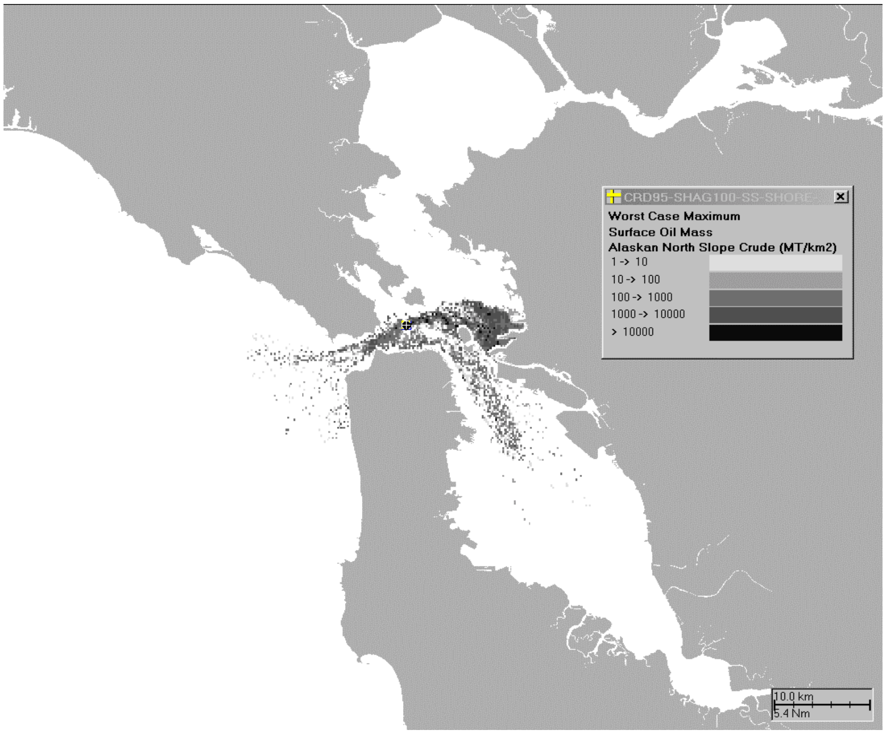

Figure 9 Water Surface Exposed to Floating Oil for Crude Oil, 95th Percentile in Volume, 50th Percentile Run

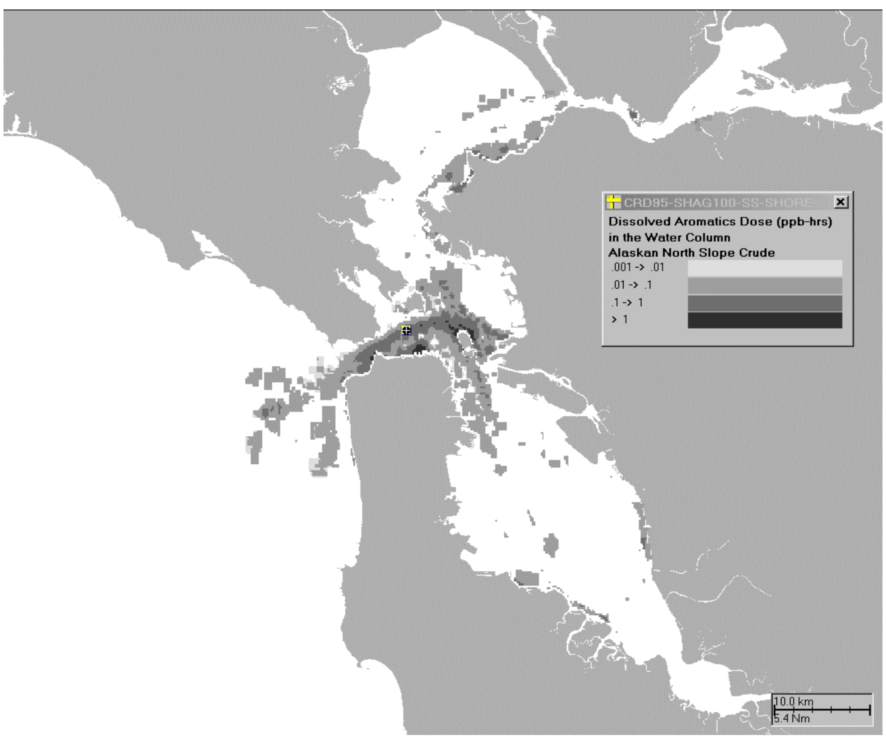

Figure 10 Water Column Exposure Dose of Dissolved Aromatic Concentration (ppb-

hours), 95^{th} Percentile in Volume, 50^{th} Percentile Run

The dissolved aromatic dose is very low over most of the exposed areas shown, < 1ppb-hour. The dissolved aromatic dose is plotted as a vertical average over the plume depth and in each grid cell. Concentrations and dosages are higher in smaller volumes than depicted in Figure 10, but this is captured in the distribution data plotted in Figures 7 and 8. These smaller volume exposures are evaluated in the biological effects model in the calculations of impacts.

The particular path of the spill trajectory is highly dependent on the tidal stage and winds at the time of the release. Variability in the fates is reflected in the results for those resources that are located in particular areas, such as the socioeconomic resources. Thus, some of the variability in the results reported by Etkin (2002a) can be explained by the variation in particular trajectory direction.

4.2 Biological Impacts

The majority of the estimated killed birds are waterfowl (diving ducks and grebes), seabirds (murres), and shorebirds (sandpipers). The species impacted most agree with experience in oil spill cases in and near San Francisco Bay. Murres are commonly the most impacted species and the focus of restoration efforts in compensation for spill injuries.

There is a large variability introduced by variation in the month of the spill. Table 8 summarizes the month of the year for each of the 24 individual scenarios run. The month has implications for temperature, which affects the rate of evaporation, but it is particularly significant to the biological impacts. The birds are highly variable in abundance by month of the year (Tables 4-5). Waterfowl (diving ducks, loons and grebes) are about 10 times more abundant in fall and winter than in spring-summer. Shorebirds are also more abundant in fall and winter. Outside San Francisco Bay, seabirds are 5 times as abundant in summer as in winter, whereas inside the bay seabird abundance does not vary much seasonally. Seabird abundance in the bay is the same order of magnitude as outside the bay in winter. The high seabird abundance outside the bay in summer is primarily due to the common murre and cormorants. Thus, summer spills exiting the bay and winter spills would impact the most birds.

Table 8 Spill Month for the 50^{th} and 95^{th} Percentile Runs

Percentile Volume	Percentile Run	Gasoline	Diesel	Crude Oil	Heavy Fuel Oil
95	50	May	Mar.	July	Mar.
95	95	Feb.	Dec.	July	Aug.
50	50	July	June	July	Nov.
50	95	Sept.	May	Nov.	Apr.
20	50	Jan.	Nov.	May	May
20	95	Feb.	Apr.	Apr.	July

This complicates the interpretation of the results. The wildlife abundances are typically the same within a season, winter being January-March, spring being April-

June, summer being July-September, and fall being October-December. However, given that different species are most abundant in different months of the year (Tables 4-5); it would be difficult to identify a single worst-case month for impacts to wildlife based on abundance. Waterfowl (diving ducks, loons, grebes) are more abundant in late fall and winter, while the impacts to murres are highest in summer if the spill is carried out of the bay on an out-going tide before coming ashore (because of the higher abundance outside the bay).

The results of the 24 individual model runs were used to construct probability distributions of wildlife impacts for all possible environmental conditions as follows. The water surface exposure (m^2-hours, as in Figure 5) and impacts for the individual model runs were used to calculate indices of wildlife oiled per m^2-hours surface oil exposure in subtidal (water) areas. The area of shoreline oiled (m^2, as in Figure 6) and number of shorebirds plus waders oiled for the individual model run provide an index of wildlife impacted per area of intertidal habitat oiled. The total wildlife impacted for each of the model runs is calculated from these indices and the degrees of exposure to floating and shoreline oil, generating a probability distribution for 100 potential environmental conditions that might occur after a spill of the specific volume and oil type.

If a scenario (i.e., spill volume, oil type, wind conditions, and current conditions) were to occur in a different month of the year, the impact to a species would change according to the ratio of abundance in the two months. In other words, the estimated wildlife kills are directly proportional to abundance. The probability distribution for other seasons is calculated using the ratios of abundance. Finally, a median and 95th percentile result is tabulated for each seasonal distribution. These are summarized in Tables 9-12.

Table 9 Estimated Wildlife Injuries for Gasoline Spills

	Percentile	Winter	Spring	Summer	Fall
20th Volume	50	1,896	287	398	1,829
50th Volume	50	3,883	3,232	10,052	6,673
95th Volume	50	9,629	1,660	2,476	9,651
20th Volume	95	9,260	1,385	1,900	8,910
50th Volume	95	20,185	17,522	55,186	35,345
95th Volume	95	46,755	7,350	10,240	45,902

Table 10 Estimated Wildlife Injuries for Diesel Spills

	Percentile	Winter	Spring	Summer	Fall
20th Volume	50	3,875	1,032	1,994	4,333
50th Volume	50	18,882	4,591	8,786	20,854
95th Volume	50	30,122	7,418	13,549	32,782
20th Volume	95	12,871	2,872	5,342	13,649
50th Volume	95	61,276	12,995	24,040	65,165
95th Volume	95	96,324	19,706	33,666	99,389

Table 11 Estimated Wildlife Injuries for Crude Spills

	Percentile	Winter	Spring	Summer	Fall
20th Volume	50	22,766	5,004	9,643	24,494
50th Volume	50	15,668	6,935	17,864	20,866
95th Volume	50	27,587	15,174	39,708	40,300
20th Volume	95	91,363	18,799	35,673	96,518
50th Volume	95	73,672	34,207	95,534	98,081
95th Volume	95	90,128	63,798	186,256	144,153

Table 12 Estimated Wildlife Injuries for HFO Spills

	Percentile	Winter	Spring	Summer	Fall
20th Volume	50	790	309	623	1,014
50th Volume	50	2,724	1,035	2,080	3,462
95th Volume	50	4,288	1,814	3,731	5,663
20th Volume	95	1,520	592	1,193	1,946
50th Volume	95	4,960	1,773	3,497	6,160
95th Volume	95	7,720	3,289	6,730	10,174

Figure 11 shows the wildlife impacts for the crude oil 95th percentile volume spill (the worst case examined) in summer for all 100 runs sampling environmental conditions. Analogous histogram distributions were constructed for other spill volumes, oil types, and seasons. These figures provide the range of consequences to wildlife for this spill volume, depending on month of the year and environmental conditions at the time of the spill.

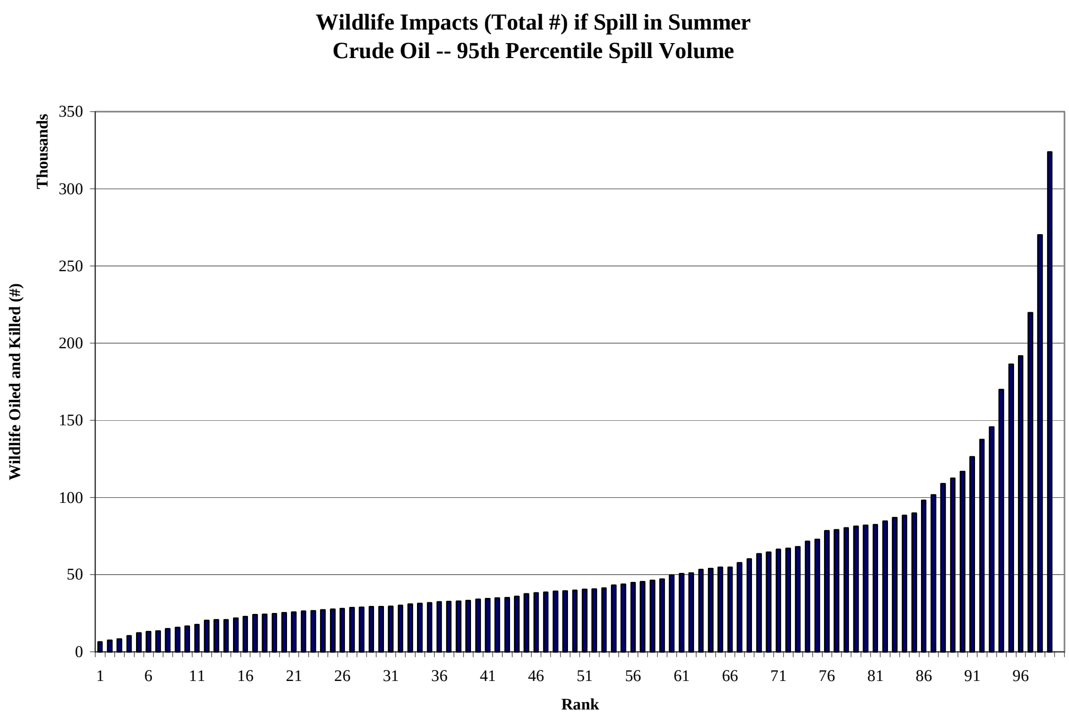

Figure 11 Range of Expected Wildlife impacts for Summer Spills of Crude (95th Percentile Volume)

In the wildlife impact results, there remains considerable variability due to the exact pathway of the spill. This explains those results in Tables 9-12 where larger spill volumes did not oil more wildlife. The spatial variability in abundance is more influential on the result than area of water surface swept. The major uncertainty on the estimates is related to the abundance assumed. If the pre-spill abundance were, for example, a factor two different, the model kill estimate would change by that same factor.

Table 13 summarizes the model-estimated fish and invertebrate impacts for the simulations. The majority of the estimated killed animals are squid and small pelagic fish, such as sea herring. Note again that if the pre-spill abundance were, for example, a factor two different, the model kill estimate would change by that same factor.

The only significant impacts to pelagic fish and invertebrates in the water, and demersal fish and invertebrates on the bottom and exposed to bottom water, were estimated to occur in the diesel and crude oil spills. The percent mortality of these organisms as a result of diesel and crude oil spills is estimated to be less than 10 percent in the volumes affected. The estimated impacts to water column organisms are very low, considering the large volumes of oil that is assumed released at 11-12m below the surface. However, the currents are very strong, the water depth is very deep such that the dilution volume is large, and the natural dispersion is very rapid. Thus, even though the initial concentrations of dissolved aromatics are high, they decrease rapidly, diluting into a large volume and minimizing the impact.

It should be noted that these fish and invertebrate impacts were calculated assuming all the species were of average sensitivity to dissolved aromatics. Some species will be much more sensitive, and impacts to those species would be higher. There would also likely be species less sensitive than average. As there are insufficient toxicity data available to quantify the degree of sensitivity to aromatics for all species in San Francisco Bay, there is considerable uncertainty around the results based on average sensitivity. Experience with past modeling efforts indicate the uncertainty in the injury estimate related to species sensitivity is on the order of a factor ten higher or lower (95% confidence range). As there is a mix of species sensitivity present, the uncertainty in the total fish and invertebrate injury would be less than a factor ten.

Table 13 Estimated Total Fish and Invertebrate Injuries

Percentile Volume	**Percentile Run**	**Gasoline**	**Diesel**	**Crude Oil**	**Heavy Fuel Oil**
95	50	0.01	857	1,630	309
95	95	0.15	1,995	1,112	78
50	50	0	0.08	203	0
50	95	0.01	548	43	0
20	50	0	0.3	0.03	0
20	95	0	47	0.8	0

5 Conclusions

Estimated impacts to birds ranged from a few hundred to nearly 200,000 birds, depending on the spill volume and environmental conditions that determines the locations and area swept by oil. There are several highly vulnerable species abundant in the area, including common murres, diving ducks, loons, grebes, and a variety of waders and shorebirds. Bird impacts were somewhat lower for the gasoline and heavy fuel oil spills examined (than for crude oil and diesel spills) because of the high volatility of the gasoline and the smaller potential spill volumes for the HFO.

In the central bay area that would be affected by spills resulting from groundings on the pinnacles, the water is very deep, currents are strong, and natural dispersion rates are high. Thus, the water column impacts of the spills examined were relatively low in consideration of the large volumes spilled and the assumption that the spill would occur at a depth of 11-12m (such that the toxic components would dissolve in the water column more than for a surface spill where they would preferentially evaporate). These water column impact results indicate that the dilution capacity of central San Francisco Bay is high, and that impacts to water column resources would be significant only in rare incidents and for sensitive species. This result, in combination with the relatively high bird impacts predicted (and seen in many spills), suggests that use of dispersants in this area would be of net environmental benefit in reducing wildlife and shoreline impacts.

The impacts vary considerably by the month of the release, as the abundance of the most impacted group, the birds, varies by up to a factor of 10 on a seasonal basis. The results are also highly influenced by the particular path of the oil (i.e., in-coming versus out-going tide and wind conditions when the oil is released). Thus, an analysis of potential impacts of spills needs to describe this variability based on uncertainty of the model inputs and conditions at the time of the spill. The stochastic modeling approach used here provides the range of possible impacts and a statistical quantification of the variability. The statistical description could be expanded to include other uncertainties in model inputs, as well as model algorithms and assumptions (i.e., in a larger Monte Carlo type design).

This work is significant as it demonstrates a statistically quantifiable method for estimating potential impacts that may be used in ecological risk assessment and cost-benefit analyses. The results of this study are being used by the Army Corps of Engineers San Francisco District in a cost-benefit analysis evaluating the trade-off of oil spill risk versus removal of rocks representing a hazard to shipping. The statistically-defined spill volumes and consequences provide an objective measure of the magnitude, range and variability of impacts to wildlife, aquatic organisms and shorelines for potential spills of four oil/fuel types shipped in the bay, each having distinct environmental fates and effects.

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