EVALUATION OF THE CONSEQUENCES OF VARIOUS RESPONSE OPTIONS USING MODELING OF FATE, EFFECTS AND NRDA COSTS OF OIL SPILLS INTO WASHINGTON WATERS

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ABSTRACT

Oil spill fate and effects modeling and analysis were performed to evaluate the implications of spill response options being considered by the Washington State Department of Ecology in their rulemaking related to oil spill preparedness (WA State Contingency Plan Rule). The impacts of potential spills in Washington's outer coast, sound and river environments were modeled varying response options and operational timing, including use of conventional mechanical containment and recovery operations; dispersant application with concurrent mechanical containment and recovery; and in-situ burning with concurrent mechanical containment and recovery. US Coast Guard federal response capability standards, current Washington State standards, and potential theoretical higher response capability standards were simulated for scenarios involving spills of crude oil, bunker fuel and diesel into Washington waters (in the Strait of Georgia, Strait of Juan de Fuca, outer coast, and lower and upper Columbia River). The modeling was performed in probabilistic mode, i.e., by randomly varying location along tanker routes, spill date, and time, and so environmental conditions during and after the release among potential conditions that would occur. The model results were analyzed to estimate mean, standard deviation (SD), and 5th, 50th and 95th percentile results for surface water and shoreline oiling, water column and sediment contamination, biological impacts, and natural resource damages (NRD). NRD costs were based on the Washington Compensation Schedule and Oil Pollution Act (OPA) NRD procedures involving compensatory restoration scaling and associated costs. Response costs and socioeconomic damages were evaluated in a companion study by D.S. Etkin (Environmental Research Consulting). The fates, impacts and NRD cost results for two scenarios are presented here: those for the outer coast spills assuming (1) only protective booming and (2) protective booming plus the mechanical removal up to Washington State standards. The results of these and other scenarios are being incorporated into a rulemaking process and cost-benefit analysis by the Department of Ecology.

KEYWORDS: *Oil Spill, Modeling, Response, Dispersants, Spill Impact, Natural Resource Damages, State of Washington*

INTRODUCTION

As part of their rulemaking related to oil spill preparedness (Washington State Contingency Plan Rule), the Washington State Department of Ecology (WDOE) needs to evaluate the implications of various spill response options being considered. Oil spill fate and effects modeling and analysis were performed to estimate the impacts of potential spills in Washington's outer coast, sound and river environments, assuming various response options and operational timing, including use of conventional mechanical containment and recovery operations; dispersant application with concurrent mechanical containment and recovery; and in-situ burning (ISB) with concurrent mechanical containment and recovery. US Coast Guard federal response capability standards, current Washington State standards, and potential theoretical higher response capability standards were simulated for scenarios involving spills of crude oil, bunker fuel and diesel into Washington waters in six geographic locations: Strait of Georgia, Strait of Juan de Fuca, Inner Strait/Puget Sound, outer coast, and lower and upper Columbia River. These locations were selected to be representative of potential spill sites along transportation routes. The upper Columbia River was used to evaluate implications of spills into large rivers of similar dimensions and river flow.

The SIMAP (Spill Impact Model Application Package) model (French McCay 2003, 2004), which originated from the Natural Resource Damage Assessment (NRDA) Model for Coastal and Marine Environments (NRDAM/CME) model [developed by Applied Science Associates (ASA) for use by the Department of the Interior in CERCLA NRDA type A regulations and for oil spill assessments under OPA, French et al. 1996], was used for this study. SIMAP is comprised of three-dimensional oil fate and biological effects models that access impacts and provide data to estimate NRD, response, and socioeconomic costs of spills in marine and freshwater environments. The model was run in stochastic mode to produce results and statistics for multiple model runs under various possible environmental conditions.

The model uses wind data, current data, and transport and weathering algorithms to calculate mass balance in various environmental compartments (water surface, shoreline, water column, atmosphere, sediments, etc.), surface oil distribution over time

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(trajectory), and concentrations of the oil components in water and sediments. SIMAP was used to evaluate exposure of aquatic habitats and organisms to whole oil and potentially toxic components from the fuels, resulting mortality and ecological losses.

Thirteen spill scenarios were run in stochastic mode using combinations of six spill locations, 3 oil types (crude, bunker C fuel, and diesel) and response combinations including protective booming, mechanical removal and dispersant use. For each scenario, the model was run numerous times, randomly sampling environmental conditions during and after the spill. For each stochastic scenario, the 5th, 50th and 95th percentile runs, in terms of environmental consequences, were examined in detail for NRDA, socioeconomic, and response costs. These 3 events were run with alternate response plans to evaluate the change in consequences resulting from different response implementations.

Specifications for the scenarios (amount, duration of release, etc.) were developed by the Department of Ecology based on Washington State planning standards, federal planning standards, and input from stakeholders. The spill locations were in most cases along shipping routes in Washington State waters. Spill sites for each individual run were randomized along the designated route for that scenario. (The outer coast scenario was at a single spill site.) The oil types selected were those typically shipped (Alaska North slope crude and diesel fuel) or used to power vessels (Bunker C). The spill volumes were selected to be a relatively large spill, but of a size that would be handled primarily by the state rather than the federal government. The crude oil and diesel spills were all 65,000 bbl, while the Bunker C spills were 25,000 bbl.

MODEL DESCRIPTION

Below are brief descriptions of the SIMAP fates and effects models. Detailed descriptions of the algorithms and assumptions in the model are in published papers (French McCay 2002, 2003, 2004). The model has been validated with more than 20 case histories, including the *Exxon Valdez* and other large spills (French and Rines, 1997; French McCay, 2003, 2004; French McCay and Rowe, 2004), as well as test spills (French et al., 1997).

The three-dimensional physical fates model estimates distribution (as mass and concentrations) of whole oil and oil components on the water surface, on shorelines, in the water column, and in sediments. Processes simulated include spreading (gravitational and by shearing), evaporation of volatiles from surface oil, transport on the surface and in the water column, randomized dispersion, emulsification, entrainment of oil as droplets into the water (natural and facilitated by dispersant), dissolution of soluble components, volatilization of dissolved hydrocarbons from the surface water, adherence of oil droplets to suspended sediments, adsorption of soluble and semi-soluble aromatics to suspended sediments, sedimentation, stranding on shorelines, and degradation. The algorithms and assumptions of the 3-d fates model are described in French McCay (2004).

The biological effects model (French et al., 1996; French McCay, 2003, 2004) estimates short term (acute) exposure of biota of various behavior types to floating oil and subsurface contamination (in water and subtidal sediments), resulting percent mortality, and sublethal effects on production (growth). For each wildlife behavior group, a portion of the animals in the area swept by surface oil over a threshold thickness (10 g/m^2) is assumed to die, based on probability of encounter with the oil on the water surface multiplied by the probability of mortality once oiled. Toxicity to aquatic biota in the water and subtidal sediments is estimated from dissolved aromatic concentrations and exposure duration, using laboratory-based bioassay data for oil hydrocarbon mixtures (French McCay, 2002). Losses are estimated by species or species group for fish, invertebrates and wildlife by multiplying percent loss by abundance.

MODEL INPUTS

Geographical data (habitat mapping and shoreline location) were obtained from existing Washington State Geographical Information System (GIS) databases and those based on Environmental Sensitivity Indices (ESI). Water depth was obtained from National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) soundings databases. Hourly wind speed and direction data over a long historical period (at least 10 years) were obtained from NOAA National Ocean Service weather buoys nearest the spill site(s). Wind driven surface drift was calculated within the oil spill model (based on Youssef, 1993; Youssef and Spaulding, 1993).

Tidal and other currents were modeled based on known water heights, using a hydrodynamic model based on physical laws (i.e., conserving mass and momentum). For the Strait of Juan de Fuca, outer coast and Columbia River scenarios, current data were generated using ASA's boundary fitted coordinate hydrodynamic model (BFHYDRO). The hydrodynamic model's governing equations and validation are described in detail in Muin and Spaulding (1997a, b) and Spaulding et al. (1999). Currents for the inner Straits and San Juan Islands scenarios were based on hydrodynamic model data from D.O. Hodgins (1998; Seaconsult Marine Research Ltd, Vancouver, Canada), who simulated currents in the Strait of Georgia.

Surface water temperature varied by month, based on data in French et al. (1996) for the area of the spill site. 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. The mean salinity value for the location of the spill site was used (French et al., 1996). Oil properties for Alaskan North Slope crude, bunker fuel and diesel were based on data in Environment Canada's Oil Property Catalogue (Jokuty et al. 1999).

Specifics of the spill response scenarios were developed by D. S. Etkin (Environmental Research Consulting; Etkin et al., 2005) based on state and federal planning standards and assumptions provided by WDOE. In all scenarios, including those where no mechanical removal was assumed, protective booming was included. The mechanical removal capacities were assumed to be one of three options (when included in the scenario), in increasing order of capacity: (1) US Coast Guard federal response capability standards, (2) current Washington State standards, and (3) a theoretical higher response capability. In the scenarios where dispersant use was included, the assumptions of the US Coast Guard federal response capability standards were used with the amount of equipment available set by the Washington State standards. Dispersant use was assumed to occur >3 nm offshore and was assumed effective when the thickness of the oil exceeded 13 microns and the wind speed was between 3 knots and 27 knots. In situ burning was assumed to be used with a wind speed of less than 25 knots; wave height of less than 3 feet, and current speed of less than 1 knot. Burning was assumed to occur >3 nm offshore and conducted at a rate of three 500-bbl/day burns daily. The minimum oil thickness assumed for ignition was 2 mm, which lowered to 1 mm once burning started. All response alternatives were assumed to only occur during daylight hours (8am to 6pm).

The NRDAM/CME (French et al., 1996) contains mean seasonal or monthly abundances for 77 biological provinces in US coastal and marine waters. The biological data for wildlife, fish, invertebrates and lower trophic levels in the province of the spill were used for the SIMAP simulations in the lower Columbia River (province 48 in the NRDAM/CME), outer coast (province 49 in the NRDAM/CME) and Straits/Puget Sound (province 51 in the NRDAM/CME) areas. The bird densities for NRDAM/CME province 49 were updated for common murre abundance using data from Thompson (1999), which surveyed marbled murrelets and common murres on the outer coast of Washington from the summer of 1997 to the winter of 1998-1999. The wading bird and shorebird densities for the Straits/Puget Sound were from NRDAM/CME province 51. However, the winter densities for diving bird species were updated from NRDAM/CME province 51 using Nysewander et al. (2001). For the upper Columbia River, biological data compiled by French et al. (1993a,b) were used. These data were compilations of typical fish and wildlife densities (by season) in Pacific Northwest rivers and wetlands.

RESULTS AND DISCUSSION

In evaluating the model results, we found that the assumptions based on state and federal planning standards for mechanical response were such that 50-70% of the spilled oil would be removed during response. This high recovery was not expected *a priori* because, in most spills in similar situations to those simulated, it is thought that on the order of 10% of the oil is cleaned up by on-water cleanup. As discussed in more detail in Etkin et al. (2005), the planning standards assume that responders will be able to use the equipment according to the manufacturer's specifications, that there would not be break-downs or other logistical problems, and that the weather would be cooperative. In addition, in the modeling we assumed that the responders would know where the oil was at all times and would be able to get to it to clean it up efficiently. In reality, the efficiency of the on-water cleanup goes down as the spill goes on because the oil becomes more scattered and thus harder to find, get to, and clean up. Thus, the mechanical recovery assumptions in the initial model runs were for an ideal response, given the equipment available based on federal, state, or the third level of standards. Moreover, the mechanical recovery based on the standards was so efficient that it left little to be dispersed chemically. Additional modeling and analysis assuming lower removal efficiency is on-going.

The results for two scenarios are presented here, those for the outer coast spills assuming (1) only protective booming and (2) protective booming plus the mechanical removal up to Washington State standards. The outer coast scenario was a 65,000 bbl spill at Duntz Rock, just northwest of Cape Flattery (Figure 1). The percent of the spilled oil mechanically removed averaged 65% (SD 10%) for scenario 2. Details of the model assumptions and results of these and other scenarios (as well as for the 5th, 50th and 95th percentile runs) are available in French McCay et al. (2004) and will be reported in other forums.

Figures 1 and 2, for no-removal and with-removal cases respectively, show the probability of oil greater than the thickness of sheen (0.01 µm) reaching different locations, based on 100 randomly-selected spill dates and times. The probability for a given grid cell (0.142 km^2 in area) represents the percentage of model runs where at least one "spillet" (Lagrangian element) representing any mass of oil (of at least sheen thickness) passes through the cell at any time after a spill. Note that if the mass is concentrated in patches much smaller than the area of the grid cell, as is often the case, the cell is still counted as a "hit". Thus, the gridded data are useful as indices of where exposure might occur, but do not represent the predicted distribution of oiling after any single spill.

Table 1 summarizes areas and lengths (mean, SD for 100 runs) affected by surface oil and shoreline oiling. The water surface area exposed to floating oil or sheen (counting 0.142 km^2 cells where some oil passed), the percentage of the oil coming ashore, and the shoreline area oiled by more than 0.01 g/m^2 averaged over shore segments (377 m long by 1 m wide), was significantly reduced when use of mechanical recovery was included in the simulations.

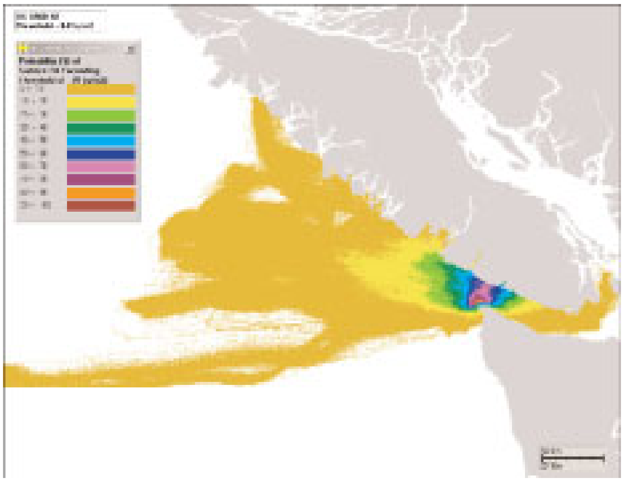

FIGURE 1. PROBABILITY (%) OF SURFACE FLOATING OIL EXCEEDING 0.01 G/M^2 (THE MINIMUM THICKNESS FOR SHEEN) FOR THE OUTER COAST SCENARIO WITH NO MECHANICAL REMOVAL.

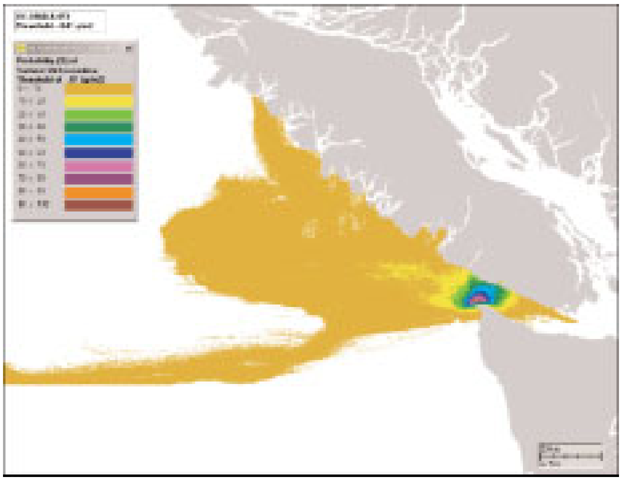

FIGURE 2. PROBABILITY (%) OF SURFACE FLOATING OIL EXCEEDING 0.01 G/M^2 (THE MINIMUM THICKNESS FOR SHEEN) FOR THE OUTER COAST SCENARIO WITH MECHANICAL REMOVAL PERFORMED TO WASHINGTON STATE STANDARDS UNDER IDEAL CONDITIONS.

For this offshore scenario in deep water with high rates of natural dispersion, most of the biological effects would be to birds (seabirds and waterfowl), with little impact expected on subtidal fish and invertebrates (Table 1). Intertidal invertebrates would be affected by oil coming ashore. The majority of the marine mammals affected would be sea otters, with most of the remaining impacts to harbor seals. The spill size for this scenario is 1/4 the size of the *Exxon Valdez* in an area with similar wildlife species and abundance. Government estimates of the impact of the *Exxon Valdez* were 3500-5500 sea otters, 200 seals, and 260,000-580,000 birds (French McCay 2004). The on-water response using mechanical removal (based on state standards) would reduce the wildlife impact substantially if fully implemented and if all floating oil could be tracked and reached with personnel and equipment with no logistical constraints.

NRDA costs were calculated according to guidance in the 1990 Oil Pollution Act NRDA regulations (published in January of 1996

Table 1. Summary of results for outer coast scenarios: mean (standard deviation) for 100 runs.

Index of Exposure or Impact	No Mechanical Recovery	With Mechanical Recovery
Water surface area (km^2) oiled by > 0.01 g/m^2 (sheen or thicker oil) at some time after the spill	2,553 (2,099)	1,283 (1,884)
Water surface area (km^2) oiled by > 10.0 g/m^2 at some time after the spill (enough to affect wildlife)	1,707 (1,497)	429 (687)
Percent of spilled oil coming ashore (%)	5.9 (5.2)	1.1 (1.5)
Shoreline length (km) oiled by > 0.01 g/m^2 (where cleanup would occur)	97 (66)	33 (27)
Shoreline length (km) oiled by > 100 g/m^2 (heavily oiled shorelines)	88 (61)	12 (14)
Maximum percent of spilled hydrocarbon mass in the water column at any time after the spill (%)	2.5 (2.1)	1.1 (1.5)
Total number of birds oiled (thousands)	154 (120)	51 (55)
Total number of mammals oiled	41 (32)	14 (15)
Total impact (kg) to subtidal fish and invertebrates	3 (0)	3 (0)
Total impact (kg) to intertidal invertebrates (clams)	150 (281)	31 (132)
Compensatory restoration area (acres) assuming wetland (saltmarsh) creation	4,712 (3,658)	1,590 (1,676)
Total NRDA restoration costs (in millions of 2004$), assuming wetland (saltmarsh) creation	883 (685)	298 (314)
Compensatory restoration area (acres) assuming seagrass bed creation	2,944 (2,286)	993 (1,047)
Total NRDA restoration costs (in millions of 2004$), assuming seagrass bed creation	352 (273)	119 (125)
Total NRDA costs (in millions of $), using the WA Compensation Schedule	64.3 (0.75)	59.8 (1.27)

by NOAA), using compensatory restoration costs based on Habitat Equivalency Analysis (HEA). Scaling methods were developed for use in the *North Cape* case, as described in French McCay and Rowe (2003). These methods have also been used in several other cases, as well as in successful claims for 23 cases submitted by the Florida Department of Environmental Protection to the US Coast Guard, National Pollution Fund Center (French McCay et al., 2003). The NRDA costs (Table 1) were based on creation of saltmarsh or seagrass beds large enough to provide production of food that would translate to new production of species at the same trophic levels (and so equivalent ecologically) as the injured resources. The area of saltmarsh required for compensation is 1.6 times the area of seagrass bed, and the total costs for saltmarsh compensation are 2.5 times those for seagrass bed. However, it is likely that saltmarsh would be the restoration option selected by NRD trustees because it is more likely to be successfully implemented, given the difficulties in establishing successful seagrass beds.

The Washington Compensation Schedule, as described in the State of Washington's Chapter 173-183 WAC (i.e., the Washington Chapter of regulations), was also applied to the model results. The Compensation Schedule is designed to be a simplified procedure for small spills. Thus, for spills the size of those considered here, the OPA procedures using restoration costs are more likely to be used for NRDA. However, we have included the Compensation Schedule results for comparison.

CONCLUSION

This work demonstrates a statistically quantifiable method for estimating potential impacts and financial consequences that may be used in ecological risk assessment and cost-benefit analyses. The statistically-defined consequences provide an objective measure of the magnitude, range and variability of impacts to wildlife, aquatic organisms and shorelines, and of damages that could be claimed by (US) federal and state natural resource trustees.

The mechanical removal assumptions, based on state and federal planning standards, indicate that it is theoretically possible to remove 50-70% of the spilled oil if the responders have perfect knowledge of the locations of floating oil and if they could reach that oil quickly and remove it without break-downs, delays or other similar problems. Clearly, this high recovery rate cannot be expected as the weather and other logistics would not normally be cooperative, and the oil would become more and more scattered over time making it harder to find and clean up, particularly in an offshore area such as the example shown here. Additional modeling and analyses incorporating more likely recovery efficiencies are on-going and will provide additional insight to this problem.

BIOGRAPHY

Deborah French McCay received her bachelor's degree in Zoology from Rutgers in 1974 and her Ph.D. in Biological Oceanography from the University of Rhode Island in 1984. She is a Principal at Applied Science Associates (Narragansett, RI, USA), where she specializes in quantitative assessments and modeling of aquatic ecosystems and populations, oil and chemical transport and fates, toxicity, exposure and the bioaccumulation of pollutants by biota, along with the effects of this contamination. These models have been used for impact, risk, and natural resource damage assessments, as well as for studies of the biological systems.

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