FINAL

M/V Ever Reach Spill of 30 September 2002 in Charleston Harbor, SC: Modeling of Physical Fates and Biological Injuries

by

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SUMMARY

Oil spill modeling was performed for the 30 September 2002 spill into Charleston Harbor, SC, from the container ship *M/V Ever Reach*. Figure S-1 is a map of the spill-affected area with the ship's path and observed shoreline oiling. The objectives were to provide (1) an assessment of the pathways and fate of the oil, and thus estimate exposure to the water surface, shoreline and other habitats, water column, and sediments; and (2) an estimate of injuries to wildlife (birds, marine mammals, sea turtles) and subtidal aquatic organisms (water column and benthic biota, exposed by the water pathway and subtidal sediment contamination) that can be used to scale compensatory restoration. Observations and data collected during and after the spill were used as much as possible as input to and to calibrate the model. Where data from the event were not available, historical information was used to make the assessment as site-specific as possible.

The analysis was performed using the model system SIMAP (Spill Impact Model Analysis Package). The physical fates model in SIMAP estimates the distribution of oil (as mass and concentrations) on the water surface, on shorelines, in the water column and in the sediments, accounting for spreading, evaporation, transport, dispersion, emulsification, entrainment, dissolution, volatilization, partitioning, sedimentation, and degradation. The biological effects model 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 (somatic 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 column and subtidal sediments is estimated from dissolved aromatic concentrations and exposure duration, using laboratory-based bioassay data for oil hydrocarbon mixtures. Losses are estimated by species or species group for fish, invertebrates and wildlife by multiplying percent loss by abundance. The model has been validated using simulations of over 20 spill events where data are available for comparison.

The model uses incident specific 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 (trajectory), and concentrations of the oil components in water and sediments. Geographical data (habitat mapping and shoreline location, Figure S-2) were obtained from existing Geographical Information System (GIS) databases based on Environmental Sensitivity Indices (ESI). Water depth is available from National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) soundings databases. Hourly wind speed and direction data during and after the spill was obtained from a nearby meteorological station. Tidal and other currents were modeled based on known water heights, using a hydrodynamic model based on physical laws, and that conserves mass and momentum.

Specifications for the scenario (date, timing, amount, duration of release, etc.) were based on information obtained and distributed during the response by NOAA HAZMAT, the US Coast Guard, state responders and trustees, and the Responsible Party (RP). The spill was 12,500 gal (= 46.4 MT) of intermediate fuel oil (IFO 380). It appears to have been caused by grounding on a submerged dredge pipe in the Cooper River, which occurred as the vessel came into port early on 30 September 2002. Based on the distribution of oil observed (Figure S-1) after the spill and modeling results, the release must have been protracted: as the ship was traveling from the grounding site (32^{o} 51.167' N, 79^{o} 56.195' W) into Berth 1 NC Terminal (05:35 to 07:18 hours), and again as the ship left the harbor later the same day (left berth at 19:00 hours, passed harbor entrance about 20:30 hours, path in Figure S-1). Oiling in the harbor and outside along Morris and Folly Islands cannot be accounted for assuming oil was released only at or up-river of the submerged dredge site. Considerable oil must have been released in the lower harbor and outside in offshore waters. The leak apparently stopped while the ship was at the berth, as the U.S. Coast Guard did not observe any oil around the ship while in port. (Hydrostatic pressure would retain oil in the hull while the ship was stationary, but when the ship moved, lower pressure over the hull surface and turbulence would draw oil out of the ship.)

The surface oil trajectory agreed with observations from over-flights, mapping of shoreline oil (from SCAT surveys and other observations), and other field records, and was thus considered the best simulation of the event. The model replicates well the overall movement of the oil. The model conserves oil mass, estimates losses to evaporation, and so the surface oil area estimates are realistic estimates of the oil mass on the water at any given time.

A total of 18-23 brown pelicans were observed in the field as moderately or heavily oiled, with 30 other pelicans showing spots or oil stain. Tri-State treated 21 of the oiled pelicans (1 adult and 20 juveniles) and released them. Other oiled birds observed were: 1 great blue heron, several egrets, 1 double-crested cormorant, and 15 ruddy turnstones. Aquatic bird injuries were estimated using the model from the area swept by enough surface oil to oil a bird above a threshold dose level for effects. Tables S-1 and S-2 list the model-estimated direct kill of wildlife for the best fates model simulation, along with the observed oiled birds. The estimated numbers are probabilities, and thus may be fractions of an animal. The model estimate of the total birds oiled is 175, including 75 brown pelicans, 7.3 black skimmers, 3.4 terns, 3.3 gulls, 16.4 wading birds, 69 shorebirds, and fractions of waterfowl and raptors (estimated as probabilities). The estimate numbers of sea turtles and dolphins oiled were insignificant, and the injury assumed zero. The number of oiled pelicans estimated by the model is 75, as opposed to the 18-23 observed as significantly oiled. This difference is in part accounted for in that the model estimates injuries to pelicans that are distributed around the harbor and in the rivers, and not just those concentrated in areas of heavy oiling at Crab Bank (which were the ones observed). The colony at Crab Bank was explicitly modeled, and 70 birds were estimated oiled there, in addition to 5 pelicans distributed around the area. Oiled skimmers, terns, and shorebirds would be unlikely to be observed or captured for cleaning. Note that if the pre-spill abundance were, for example, a factor two different, the model kill estimate would change by that same factor. Thus, the model estimates and the field data agree within the uncertainty of both estimates.

Table S-2 also lists the total injury interim loss, which is the sum (annually) of the numbers killed that would still be alive each year after the spill, as #-years, using standard demographic modeling and discounting the future losses at 3% annually. The interim loss includes the direct kill of birds and the first generation of their progeny. To express the injury in units that could be used to scale restoration, which is likely to be based on increased production of fledglings, the interim loss of mixed ages is divided by the bird-years gained per fledgling to estimate the number of fledglings required in compensation. The interim loss was translated to the equivalent number of age 0 animals (fledglings) at the time of the spill (2002) and if they were to be replaced in the year 2006 (i.e., discounted for 4 years of delay before restoration, a possible time-frame for restoration to be implemented). Scaling for restoration accomplished in other years than 2006 can be easily calculated by discounting the 2002 fledgling equivalents by 3% each year of delay after 2002. The majority of the injury is due to seabirds (mostly pelicans) and shorebirds, with a smaller loss of waders. The raptor and waterfowl injuries would be compensated by less than one fledgling each (in 2006).

The best estimate of total injury to subtidal fish and invertebrates is 0 kg. Subsurface concentrations of oil hydrocarbons and dissolved aromatics did not exceed 1 ppb in any water volume >140 m^3 (the resolution of the model grid for the subsurface plume) at any time after the spill. Thus, the exposure to water column and bottom-dwelling organisms in subtidal habitats was not significantly toxic and no significant impacts to these organisms from acute exposure to oil would be expected.

Injuries to intertidal biota other than birds were not included in the modeling assessment. The field-collected data (sediment and oyster tissue samples) from intertidal areas contaminated by the spill may be used to evaluate potential injuries there from exposure to oil hydrocarbons. Table S-3 lists the areas of intertidal habitat oiled to varying degrees in the (best) model simulation. The threshold 0.1 mm (~100 g/m^2) is the minimum (dose) in the model for impact to waders and shorebirds in the intertidal areas. Mortality of the vegetation in marshes occurs above about 14 mm of oil, according to literature reviewed in French et al. (1996a). In the model simulations, none of the wetlands exceeded 14 mm thick oil. Figure S-3 shows the areas oiled. Over-laid on the map are locations of intertidal oyster reefs along the Cooper River, in Charleston Harbor, and near Folly Beach. When the majority of the oil mass came ashore, 95% of the PAHs remained in the oil. Thus, the PAH content of the shoreline oil was about 2%, inferring 1 g/m^2 of total hydrocarbons (THC) is equivalent to about 0.02 g PAH/m^2. Assuming the oil was mixed into the top 1 cm of sediment, a sediment porosity of 40%, and a sediment dry weight of 2.6 g/cm^3, 1 g THC/m^2 is equivalent to 64 μg THC/g of dry sediment (64 ppm). The PAH concentration in dry sediment that is equivalent to 1 g THC/m^2 is 1.3 μg PAH/g dry sediment (1.3 ppm). The intertidal contamination predicted by the model can be broadly compared to observations based on sampling. However, detailed comparisons to sample stations are inappropriate, as the model's resolution does not address the patchy nature of the actual contamination on shore.

The accuracy of the biological injury assessment depends primarily on the accuracy of (1) the fates model results, (2) the assumed toxicity values, and (3) the biological abundance data input to the model. Since the wind and current data input to the model are reasonably accurate, the fates model simulation agrees well with observations after the spill and uncertainty associated with the fates model assumptions is relatively low. With more accurate wind data (more spatial detail), the fates model and bird mortality results would be more accurate, but the estimated losses would change by much less than an order of magnitude. Because species and life stages vary considerably in their sensitivity to aromatics in oil, the injury was quantified for the range of possible toxicity values, including for sensitive species. Even for the most sensitive species where bioassay data are available, subtidal fish and invertebrate injury from acute exposure is not indicated or likely, given the spill scenario and environmental conditions after the spill. For birds, the biomass losses are directly proportional to the pre-spill abundance assumed in the model inputs. Thus, a change (or uncertainty) in abundance is directly translated to a proportional change (uncertainty) in the quantified injury.

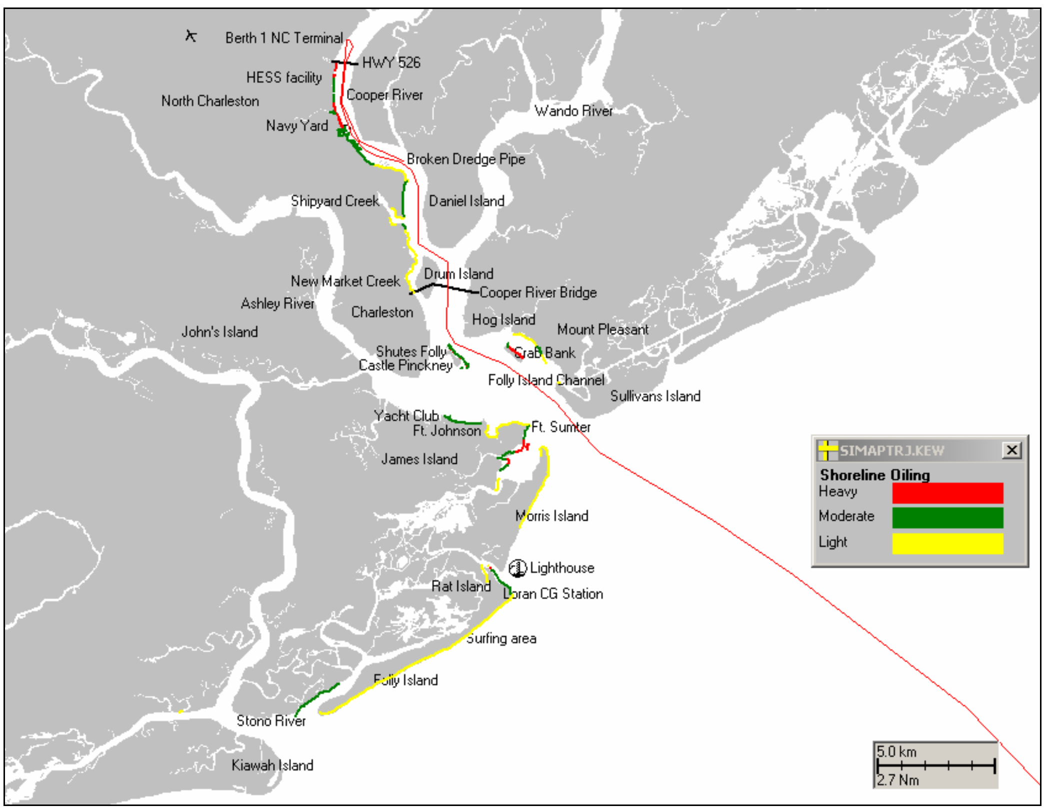

Figure S-1. Map of Charleston Harbor area, the *Ever Reach*'s path and observed shoreline oiling after the spill.

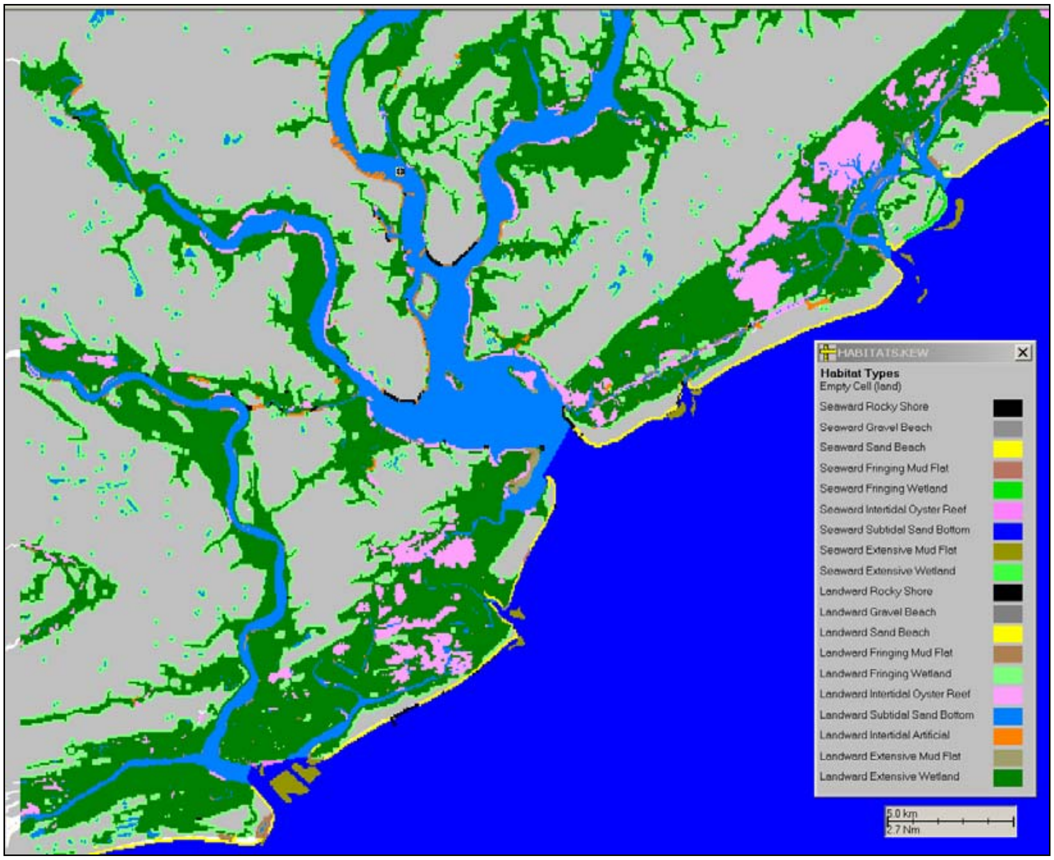

Figure S-2. Habitat grid used in modeling in the area affected by the spill.

Table S-1. Estimated injuries to birds, marine mammals and sea turtles for the best simulation of the spill. The model estimate is a probability, and thus may be a fraction of an animal. Observations of oiled birds are also listed for comparison.

Species	Model (#)	Observed (#)
Waterfowl (ducks, geese)	0.06	
Black skimmer	7.28	
Black tern	0.61	
Bonaparte’s gull	0.00	
Brown pelican	75.20	48-53
Caspian tern	0.16	
Common tern	2.04	
Double-crested cormorant	1.07	1
Forster's tern	0.04	
Gull-billed tern	0.47	
Herring gull	0.10	
Laughing gull	0.56	
Least tern	0.04	
Ring-billed gull	2.60	
Royal tern	0.05	
Sandwich tern	0.01	
Black-crowned night-heron	0.02	
Clapper rail	0.05	
Great egret	12.0	several
Great blue heron	4.0	1
Green heron	0.16	
Little blue heron	0.01	
Tricolored heron	0.07	
Snowy egret	0.05	
Wood stork	0.03	
American oystercatcher	0.91	
Black-bellied plover	0.35	
Dunlin	0.99	
Greater yellowlegs	0.02	
Marbled godwit	0.37	
Ruddy turnstone	60.0	15
Semipalmated plover	2.44	
Short-billed dowitcher	2.99	
Willet	0.71	
Bald eagle	0.01	
Osprey	0.13	
Loggerhead turtle	-	

Table S-2. Summary of estimated injuries to birds, marine mammals and sea turtles for the best simulation of the spill. The model estimate is a probability, and thus may be a fraction of an animal. Observations of oiled birds are also listed for comparison.

Group Totals	Model (#)	Observed (#)	Interim Loss (# -years)	# Fledgling Equivalents (in 2002)	# Fledgling Equivalents (in 2006)
Waterfowl	0.06	-	0.1	0.1	0.1
Seabirds	89.2	49-54	556	384	433
Wading birds	16.4	approx. 4	31	36	40
Shorebirds	68.8	15	531	260	293
Raptors	0.14	-	1.0	0.5	0.6
Marine mammals (dolphins)	0	-	0	-	-
Sea turtles	0	-	0	-	-
Total birds	**174.6**	**68-73**	**1120**	**681**	**766**

Table S-3. Area (m2) of intertidal zone, by shore type, contaminated by oil of various thicknesses (1 mm thick oil ~ 1000 g/m^2 ~64 ppm total hydrocarbons, THC, ~ 1300 ppm of PAH) in the best model simulation.

Total Hydrocarbons	**>1000 g/m^2**	**>100 g/m^2**	**>10 g/m^2**	**> 1 g/m^2**	**>0.1 g/m^2**
Oil Thickness	**>1 mm**	**>0.1 mm**	**>0.01 mm**	**>0.001 mm**	**>0.0001 mm**
THC concentration (µg TPH/g dry sediment)	**> 64 mg/g**	**> 6400 µg/g**	**> 640 µg/g**	**> 64. µg/g**	**> 6.4 µg/m^2**
PAH concentration (ppm)	**> 1300 ppm**	**> 130 ppm**	**> 13 ppm**	**> 1.3 ppm**	**> 0.13 ppm**
PAH concentration (µg PAH/g dry sediment)	**> 1300 µg/g**	**> 130 µg/g**	**> 13 µg/g**	**> 1.3 µg/g**	**> 0.13 µg/m^2**
Shore Type:					
Rocky shoreline	140	2,737	2,737	2,737	2,737
Gravel beach	211	772	772	772	772
Sand beach	702	6,317	6,317	6,317	6,317
Mud flat	702	2,456	2,456	2,456	2,456
Wetland	772	2,737	2,737	2,737	2,737
Oyster reef	0	2,035	2,035	2,035	2,035
Artificial shoreline	2,527	6,387	6,387	6,387	6,387
Total	5,053	23,442	23,442	23,442	23,442

Table S-4. Area (acres) of intertidal zone, by shore type, contaminated by oil of various thicknesses (1 mm thick oil ~ 1000 g/m2 ~64 ppm total hydrocarbons, THC, ~ 1300 ppm of PAH) in the best model simulation.

Total Hydrocarbons	**>1000 g/m^2**	**>100 g/m^2**	**>10 g/m^2**	**> 1 g/m^2**	**>0.1 g/m^2**
Oil Thickness	**>1 mm**	**>0.1 mm**	**>0.01 mm**	**>0.001 mm**	**>0.0001 mm**
THC concentration (µg TPH/g dry sediment)	**> 64 mg/g**	**> 6400 µg/g**	**> 640 µg/g**	**> 64. µg/g**	**> 6.4 µg/m^2**
PAH concentration (ppm)	**> 1300 ppm**	**> 130 ppm**	**> 13 ppm**	**> 1.3 ppm**	**> 0.13 ppm**
PAH concentration (µg PAH/g dry sediment)	**> 1300 µg/g**	**> 130 µg/g**	**> 13 µg/g**	**> 1.3 µg/g**	**> 0.13 µg/m^2**
Shore Type:					
Rocky shoreline	0.03	0.68	0.68	0.68	0.68
Gravel beach	0.05	0.19	0.19	0.19	0.19
Sand beach	0.17	1.56	1.56	1.56	1.56
Mud flat	0.17	0.61	0.61	0.61	0.61
Wetland	0.19	0.68	0.68	0.68	0.68
Oyster reef	0.00	0.50	0.50	0.50	0.50
Artificial shoreline	0.62	1.58	1.58	1.58	1.58
Total	1.25	5.79	5.79	5.79	5.79

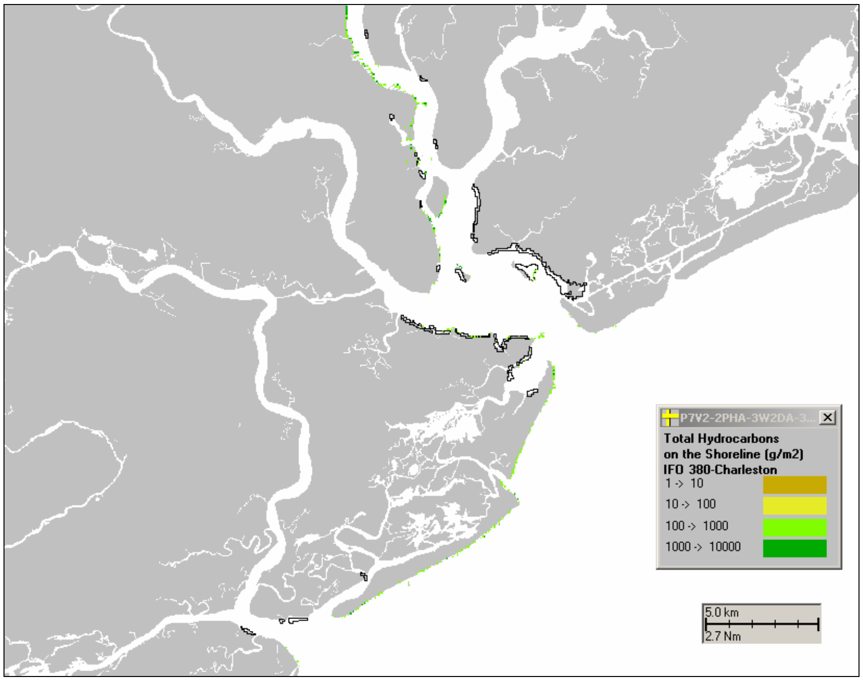

Figure S-3. Total hydrocarbons on shorelines predicted by the (best) model simulation. The polygons over-laid on the map are locations of oyster reefs that are along the shore of the Cooper River, in Charleston Harbor, and near Folly Beach, i.e., that were oiled or near areas oiled in the model simulation. (Note: Figure S-2 shows the location of all oyster reefs in the model grid.)

1. INTRODUCTION

Oil spill modeling was performed for the 30 September 2002 spill into Charleston Harbor, SC, from the container ship *M/V Ever Reach*. The modeling provides (1) an assessment of the pathways and fate of the oil, and thus estimate exposure to the water surface, shoreline and other habitats, water column, and sediments; and (2) an estimate of injuries to wildlife (birds, mammals, sea turtles) and subtidal aquatic organisms (i.e., water column and benthic biota, exposed by the water pathway and subtidal sediment contamination). This report describes the data inputs for and results of the modeling. Inputs include habitat and depth mapping, winds, currents, other environmental conditions, chemical composition and properties of the source oil, specifications of the release (amount, timing, etc.), toxicity parameters, and biological abundance. Some inputs have significant influence on the modeling results. Sensitivity analysis was performed by varying critical input data.

Model results are displayed by a Windows graphical user interface (SIMAP Viewer) that animates the trajectory and concentrations over time. The model simulation outputs are provided with the SIMAP Viewer so that the details may be examined at any scale (zoom window). The figures included here (in the appendices) are selected snapshots taken from that output. Appendix A.1 shows the spill location and nearby areas. Place names on the map are used in this report to describe observations and model results. Appendices A.2 and A.3 show the shoreline and habitat types, and water depths in the model domain.

The spill was 12,500 gal (= 46.4 MT) of intermediate fuel oil (IFO 380). It appears to have been caused by grounding on a submerged dredge pipe in the Cooper River, which occurred as the vessel came into port early on 30 September 2002. Based on the distribution of oil observed after the spill and modeling results, the release must have been protracted: as the ship was traveling from the grounding site (79^{o} 56.195' W, 32^{o} 51.167' N) into Berth 1 NC Terminal (05:35 to 07:18 hours), and again as the ship left the harbor later the same day (left berth at 19:00 hours, passed harbor entrance about 20:30 hours). Oiling in the harbor and outside along Morris and Folly Islands cannot be accounted for assuming oil was released only at or up-river of the submerged dredge site. Considerable oil must have been released in the lower harbor and outside in offshore waters. The leak apparently stopped while the ship was at the berth, as the U.S. Coast Guard did not observe any oil around the ship while in port. (Hydrostatic pressure would retain oil in the hull while the ship was stationary, but when the ship moved, lower pressure over the hull surface and turbulence would draw oil out of the ship.)

Figures in Appendix B show observations made on oil movements and the extent of oil contamination. From an over-flight done between 07:30 and 09:00 on 2 October 2003, the shoreline of the Navy pier was heavily oiled, as was the eastern coastlines of Shutes Folly and Crab Bank (Figure B.1-1). This oiling was still observed on the mornings of 3 October and 4 October (Figures B.1-2 and B.1-3). The SCAT observations from 2 October are similar to those from the over-flight on that same day, however, with some more oiling on the shore side of Mount Pleasant, heavy oiling along Ft. Johnson, and some light oiling on Morris Island (Figure B.2-1). On the morning of 3 October, the

SCAT team observed small tar balls (approximately 2 cm in diameter) in the wrack line and estimated 1% oil coverage on North Folly Beach. As the SCAT team moved south on Folly Beach, they noticed an increase in the size of tar balls (up to the size of a quarter) and estimated oil coverage to be 10% (Figure B.2-2; Situation Update, http://spills.incidentnews.gov). These observations were used to calibrate the fates model to the spill conditions.

Section 2 describes the physical fates and biological effects model used for this analysis. Section 3 describes the model input data and assumptions. Results of the physical fates model are described in Section 4. Section 5 describes the biological impacts and injury quantification results. References cited are in Section 6. Appendices provide input data and model results, in tables, maps and other figures.

2. MODEL DESCRIPTION

The analysis was performed using the model system developed by Applied Science Associates (ASA) called SIMAP (Spill Impact Model Analysis Package). SIMAP includes (1) an oil physical fates model, (2) interfacing to a hydrodynamics model for simulation of currents, (3) a biological effects model, (4) an oil physical, chemical and toxicological database, (5) environmental databases (winds, currents, salinity, temperature), (6) geographical data (in a GIS), (7) a biological database, (8) a response module to analyze effects of response activities, (9) graphical visualization tools for outputs, and (10) exporting tools to produce text format output.

SIMAP originated 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 in the early 1990s for the US Department of the Interior for use in Natural Resource Damage Assessment (NRDA) regulations under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). 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). This technical development involved several in-depth peer reviews, as described in the Final Rule.

SIMAP has undergone considerable development since completion of the NRDAM/CME. Additions and modifications to prepare SIMAP were made to increase model resolution, allow modification and site-specificity of input data, allow incorporation of temporally varying current data, evaluate subsurface releases and movements of subsurface oil, track multiple chemical components of the oil, enable stochastic modeling, and facilitate analysis of results. The consideration of the impacts of subsurface oil is important, particularly in the evaluation of impacts on aquatic organisms. Surface floating oil primarily impacts wildlife and intertidal biota, and not aquatic biota in subtidal habitats. At higher wind speeds than about 12 knots, oil will entrain into the water column, unless it has become too viscous to do so after weathering and the formation of mousse. Once oil is entrained in the water in the form of small droplets, monoaromatics (MAHs) and polynuclear aromatic hydrocarbons (PAHs) dissolve into the water column. The dissolved MAHs and PAHs are the most bioavailable and toxic portion of the oil. The dissolution rate is very sensitive to the droplet size (because it involves mass transfer across the surface area of the droplet), and the amount of hydrocarbon mass dissolved is a function of the mass entrained and droplet size distribution. These are in turn a function of soluble hydrocarbon content of the oil, the amount of evaporation of these components before entrainment, oil viscosity (which increases as the oil weathers and emulsifies), oil surface tension (which may be reduced by surfactant dispersants), and the energy in the system (the higher the energy the smaller the droplets). Large droplets (greater than a few hundred microns in diameter) resurface rapidly, and so dissolution from those is also inconsequential.

Thus, the fate of MAHs and PAHs in surface oil is primarily volatilization to the atmosphere, rather than to the water. If wind speeds exceed 12 knots, entrainment of the surface oil into the water becomes significant. If oil is entrained before it has weathered and lost the lower molecular weight aromatics to the atmosphere, dissolved MAHs and PAHs in the water can reach concentrations where they can affect water column organisms or bottom communities (French McCay and Payne, 2001).

Below are brief descriptions of the fates and effects models implemented in SIMAP. 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 designed to verify the model (French et al., 1997).

2.1 Physical Fates Model

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. Oil fate processes included are spreading (gravitational and by shearing), evaporation from slicks, transport, randomized dispersion, emulsification, entrainment (natural and facilitated by dispersant), dissolution, 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, and degradation.

Oil is a mixture of hydrocarbons of varying physical, chemical, and toxicological characteristics. Thus, oil hydrocarbons have varying fates and impacts on organisms. In the model, oil is represented by component categories, and the fate of each tracked separately. The "pseudo-component" approach (Payne et al., 1984, 1987; French et al., 1996a; Jones 1997; Lehr et al. 2000) is used, where chemicals in the oil mixture are grouped by physical-chemical properties, and the resulting component category behaves as if it were a single chemical with characteristics typical of the chemical group.

The most toxic components of oil to aquatic organisms are low molecular weight aromatic compounds (monoaromatic and polynuclear aromatic hydrocarbons, MAHs and PAHs), which are both volatile and soluble in water. Their acute toxic effects are by narcosis, where toxicity is related to the octanol-water partition coefficient (K_{ow}), a measure of hydrophobicity. The more hydrophobic the compound, the more toxic, but the less soluble and so the less exposure there is to aquatic organisms. Compounds of $\log(K_{ow})>5.6$ are considered insoluble and so unavailable to aquatic biota (French McCay, 2002). Thus, impact is the result of a balance between bioavailability (exposure) and toxicity once exposed. French McCay (2002) contains a full description of the oil toxicity model in SIMAP.

Because of these considerations, the SIMAP fates model focuses on tracking the lower molecular weight aromatic components divided into chemical groups based on volatility, solubility, and hydrophobicity. In the model, the oil is treated as eight components (defined in Table 2-1). Six of the components (all but the two non-volatile residual components) evaporate at rates specific to the pseudo-component. Solubility is strongly correlated with volatility, and the solubility of aromatics is higher than aliphatics of the same volatility, with the MAHs the most soluble, the 2-ring PAHs semi-soluble, and the 3-ring PAHs slightly soluble Mackay et al. (1992a,b,c,d). Both the solubility and toxicity of the non-aromatic hydrocarbons are much less than for the aromatics and dissolution (and water concentrations) of non-aromatics is safely ignored. Thus, dissolved concentrations are calculated only for each of the three soluble aromatic pseudo-components.

This number of components provides sufficient accuracy for the evaporation and dissolution calculations, particularly given the time frame (minutes) over which dissolution occurs from small droplets and the rapid resurfacing of large droplets (see discussion above). The alternative of treating oil as a single compound with empirically-derived rates (e.g., Mackay et al, 1980; Stiver and Mackay, 1984) does not provide sufficient accuracy for impact analyses because the impacts to water column organisms are caused by MAHs and PAHs, which have specific properties that differ from the other volatile and soluble compounds. Use of more pseudo components does not improve accuracy, as the major constituents of concern are well characterized (sufficiently similar in properties within the pseudo-component group of chemicals) by the modelled component properties used in SIMAP. The model has been validated both in predicting dissolved concentrations and resulting toxic effects, supporting the adequacy of the use of this number of pseudo-components (French McCay, 2003).

Table 2-1. Definition of four distillation cuts and the eight pseudo-components in the model (monoaromatic hydrocarbons, MAHs; benzene + toluene + ethybenzene + xylene, BTEX; polynuclear aromatic hydrocarbons, PAHs).

Characteristic	**Volatile and and Highly Soluble**	**Semi-volatile and Soluble**	**Low Volatility and Slightly Soluble**	**Residual (non-volatile and insoluble)**
Distillation cut	1	2	3	4
Boiling Point (^{o}C)	< 180	180 - 265	265 - 380	>380
Molecular Weight	50 - 125	125 - 168	152 - 215	> 215
Log(K_{ow})	2.1-3.7	3.7-4.4	3.9-5.6	>5.6
Aliphatic pseudo-components: Number of Carbons	volatile aliphatics: C4 – C10	semi-volatile aliphatics: C10 – C15	low-volatility aliphatics: C15 – C20	non-volatile aliphatics: > C20
Aromatic pseudo-component name: included compounds	MAHs: BTEX, MAHs to C3-benzenes	2 ring PAHs: C4-benzenes, naphthalene, C1-, C2-naphthalenes	3 ring PAHs: C3-, C4-naphthalenes, 3-4 ring PAHs with log(K_{ow}) < 5.6	$\geq$4 ring aromatics: PAHs with log(K_{ow}) > 5.6 (insoluble)

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; French McCay 2004). The residual fractions in the model are composed on non-volatile and insoluble compounds that remain in the "whole oil" that spreads, is transported on the water surface, strands on shorelines, and disperses into the water column as oil droplets or remains on the surface as tar balls. This is the fraction that composes black oil, mousse, and sheen.

The schematic in Figure 2-1 shows oil fate processes simulated in the model in open water. The algorithms are described in French McCay (2004). Lagrangian elements (spillets) are used to simulate the movements of oil components in three dimensions over time. Surface floating oil, subsurface droplets, and dissolved components are tracked in separate spillets. Transport is the sum of advective velocities by currents input to the model, surface wind drift, vertical movement according to buoyancy, and randomized turbulent diffusive velocities in three dimensions. The vertical diffusion coefficient is computed as a function of wind speed in the wave-mixed layer. The horizontal and deeper water vertical diffusion coefficients are model inputs.

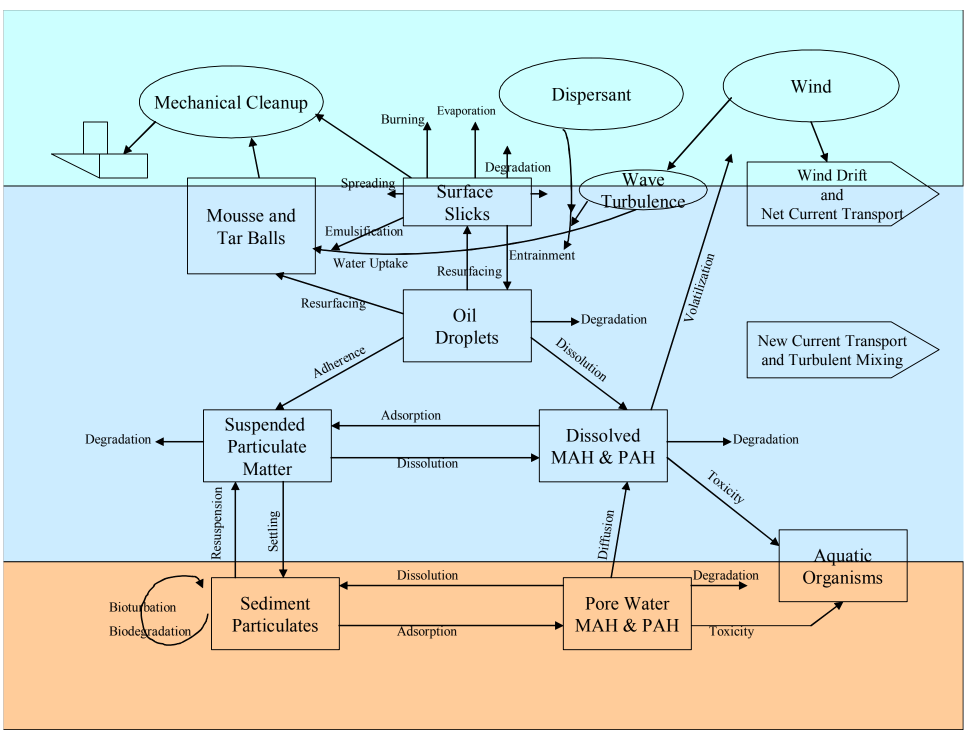

Figure 2-1. Simulated oil fates processes in open water

The oil (whole and as pseudo-components) separates into different phases or parts of the environment, i.e., surface slicks; emulsified oil (mousse) and tar balls; oil droplets suspended in the water column; dissolved lower molecular weight components (MAHs and PAHs) in the water column; oil droplets adhered and hydrocarbons adsorbed to suspended particulate matter in the water; hydrocarbons on and in the sediments; dissolved MAHs and PAHs in the sediment pore water; and hydrocarbons on and in the shoreline sediments and surfaces. The physical fates model creates output files recording the distribution of a spilled substance in three-dimensional space and time. The quantities recorded are:

- area covered by oil and thickness on the water surface ("swept area");
- volumes in the water column at various concentrations of dissolved aromatics;
- volumes in the water column at various concentrations of total hydrocarbons in suspended droplets;
- total hydrocarbon concentrations and dissolved aromatic concentrations in surface sediment;
- lengths and locations of shoreline impacted and volume of oil ashore in each segment.

The dissolved aromatic hydrocarbon concentration in the water column is calculated from the mass in the Lagrangian elements, as follows. Concentration is contoured on a three-dimensional Lagrangian grid system. This grid (of 200 X 200 cells in the horizontal and 5 vertical layers) is scaled each time step to just cover the volume occupied by aromatic particles, including the dispersion around each particle center. This maximizes the resolution of the contour map at each time step and reduces error caused by averaging mass over large cell volumes. Distribution of mass around the particle center is described as Gaussian in three dimensions, with one standard deviation equal to twice the diffusive distance ($2D_xt$ in the horizontal, $2D_zt$ in the vertical, where D_x is the horizontal and D_z is the vertical diffusion coefficient, and t is particle age). The plume grid edges are set at one standard deviation out from the outer-most particle. These data are used by the biological effects model to evaluate exposure, toxicity and impacts.

2.2 Biological Effects Model

The biological exposure model 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. The biological effects model estimates losses resulting from acute exposure after a spill (i.e., losses at the time of the spill and while acutely toxic concentrations remain in the environment) in terms of direct mortality and lost production because of direct exposure or the loss of food resources from the food web. Losses are estimated by species or species group for fish, invertebrates (i.e., shellfish and non-fished species) and wildlife (birds, mammals, sea turtles). Lost production of aquatic plants (microalgae and macrophytes) and lower trophic levels of animals are also estimated.

The area potentially affected by the spill is represented by a rectangular grid with each grid cell coded as to habitat type. The habitat grid is also used by the physical fates model to define the shoreline location and type, as well as habitat and sediment type. A habitat is an area of essentially uniform physical and biological characteristics that is occupied by a group of organisms that are distributed throughout that area. A contiguous grouping of habitat grid cells with the same habitat code represents an ecosystem in the biological model. The density of fish, invertebrates and wildlife, and rates of lower trophic level productivity, are assumed constant for the duration of the spill simulation and evenly distributed across an ecosystem. While biological distributions are known to be highly variable in time and space, data are generally not sufficient to characterize this patchiness. Oil is also patchy in distribution. The patchiness is assumed to be on the same scale so that the intersection of the oil and biota is equivalent to overlays of spatial mean distributions.

Mobile fish, invertebrates and wildlife are assumed to move at random within each ecosystem during the simulation period. This is a reasonable assumption for the period of the simulation (generally a few weeks). Benthic organisms may also remain stationary on or in the bottom. Planktonic stages, such as pelagic fish eggs, larvae, and juveniles (i.e., young-of-the-year during their pelagic stage(s)), move with the currents.

Habitats include open water, oyster reef, wetland, sea grass, and shoreline environments. Habitat types are defined by depth, proximity to shoreline(s), bottom/shore type, dominant vegetation type, and the presence of invertebrate reefs. With respect to proximity to shoreline(s), habitats are designated as landward or seaward. Landward portions are the harbor, rivers, and inlets. The seaward portion is the open ocean (coastal continental shelf). This designation allows different biological abundances to be simulated in landward and seaward zones of the same habitat type (e.g., open water with sand bottom).

2.2.1 Wildlife

In the model, surface slicks (or other floating forms such as tar balls) of oils and petroleum products impact wildlife (birds, marine mammals, sea turtles). For each of a series of surface spillets, the physical fates model calculates the location and size (radius of circular spreading spillet) as a function of time. The area swept by a surface spillet in a given time step is calculated as the quadrilateral area defined by the path swept by the spillet diameter. This area is summed over all time steps for the time period the spillet is present on the water surface and separately for each habitat type where the oil passes. Spillets sweeping the same area of water surface at the same time are superimposed. The total area swept over a threshold thickness by habitat type is multiplied by the probability that a species uses that habitat (0 or 1, depending upon its behavior) and a combined probability of oiling and mortality. This calculation is made for each surface-floating spillet and each habitat for the duration of the model simulation.

A portion of the wildlife in the area swept by the slick over a threshold thickness is assumed to die, based on probability of encounter with the slick multiplied by the probability of mortality once oiled. The probability of encounter with the slick is related to the percentage of the time an animal spends on the water or shoreline surface. The probability of mortality once oiled is nearly 100% for birds and fur-covered mammals (assuming they are not successfully treated) and much lower for other wildlife. The products of the two probabilities for various wildlife behavior groups are in Table 2-2. Estimates for the probabilities are derived from information on behavior and field observations of mortality after spills (reviewed in French et al., 1996a). The threshold is

10 micron (~10g/m^2) thick oil, based on data and calculations in French et al. (1996a). The wildlife mortality model has been validated with more than 20 case histories, including the *Exxon Valdez* and other large spills, verifying that these values are reasonable (French and Rines, 1997; French McCay 2003, 2004; French McCay and Rowe, 2004).

Area swept is calculated for the habitats occupied by each of the behavior groups of wildlife listed in Table 2-2. Species or species groups are assigned to behavior groups to evaluate their loss. Wildlife mortality is directly proportional to abundance per unit area and the percent mortalities in Table 2-2.

Table 2-2. Combined probability of encounter with the slick and mortality once oiled, if present in the area swept by a slick exceeding a threshold thickness. Area swept is calculated for the habitats occupied.

Wildlife Group	Probability	Habitats Occupied
Dabbling waterfowl	99%	Intertidal and landward subtidal
Nearshore aerial divers	35%	Intertidal and landward subtidal
Surface seabirds	99%	All intertidal and subtidal
Aerial seabirds	5%	All intertidal and subtidal
Wetland wildlife (waders and shorebirds)	35%	Wetlands, shorelines, seagrass beds
Cetaceans	0.1%	Seaward subtidal
Sea turtles	1%	All intertidal and subtidal
Surface birds in seaward only	99%	All seaward intertidal and subtidal
Surface diving birds in seaward only	35%	All seaward intertidal and subtidal
Aerial divers in seaward only	5%	All seaward intertidal and subtidal
Surface birds in landward only	99%	All landward intertidal and subtidal
Surface diving birds in landward only	35%	All landward intertidal and subtidal
Aerial divers in landward only	5%	All landward intertidal and subtidal
Surface diving birds in water only	35%	All subtidal
Aerial divers in water only	5%	All subtidal

2.2.2 Fish and Invertebrates

In the model, aquatic biota (e.g., fish, invertebrates) are affected by dissolved aromatic concentrations in the water or sediment. This rationale is supported by the fact that soluble aromatics are the most toxic constituents of oil (Neff *et al.*, 1976; Rice *et al.*, 1977; Tatem *et al.*, 1978; Neff and Anderson, 1981; Malins and Hodgins, 1981; National Research Council, 1985, 2002; Anderson, 1985; French McCay 2002). Exposures in the water column are short in duration. Therefore, effects there are the result of acute toxicity. In the sediments, exposure may be both acute and chronic, as the concentrations may remain elevated for longer periods of time.

The model evaluates mortality and sublethal effects of dissolved aromatic concentrations in the water or sediment. 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 which 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 2-2). Percent mortality is a log-normal function of concentration, with the LC50 the center of the distribution.

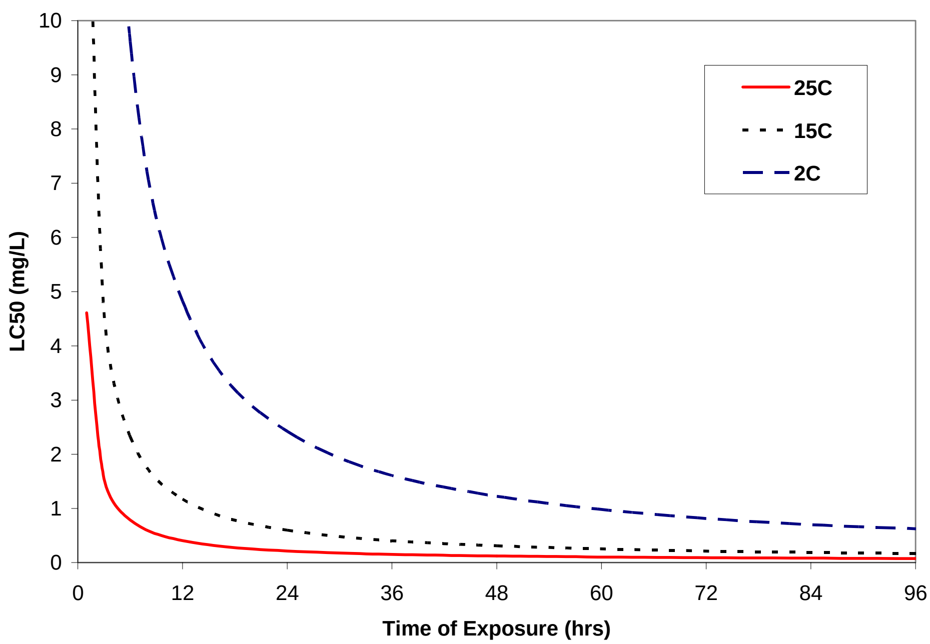

Figure 2-2. LC50 of dissolved PAH mixtures from oil, as a function of exposure duration and temperature.

The oil toxicity model in SIMAP utilizes the accepted toxic units approach for organic compounds whose primary acute effect is narcosis, which include MAHs and PAHs. The acute toxic effects of narcotic chemicals are additive (Swartz et al., 1995; French et al., 1996a; DiToro et al., 2000; DiToro and McGrath, 2000; French McCay, 2002). The approach is being used by the US Environmental Protection Agency (EPA) in the development of PAH water and sediment quality criteria (DiToro et al., 2000; DiToro and McGrath, 2000). French McCay (2002) provides estimates of $LC50_\infty$ for MAH and PAH mixtures in fuel and crude oils for spills under different environmental conditions. Figure 2-2 plots LC50s for total dissolved PAHs for species of average sensitivity under turbulent conditions ($LC50_\infty = 50$ µg/L) for a range of exposure durations and temperatures. The $LC50_\infty$ for 95% of species fall in the range 6-400 µg/L (ppb). This oil toxicity model has been validated using laboratory oil bioassay data (French McCay, 2002).

In SIMAP, $LC50_\infty$ for the dissolved aromatic mixture of the spilled oil is input to the model. For each of a series of aquatic biota behavior groups, the model evaluates exposure duration, and corrects the LC50 for time of exposure and temperature to calculate mortality (Figure 2-2). The oil toxicity model is described in detail in French McCay (2002).

Movements of biota, either active or by current transport, are accounted for in determining time and concentration of exposure. Lagrangian elements are used to represent schools or groups of animals. The elements move or remain stationary according to the behavior of the animal type, and concentration and duration of exposure are recorded. Exposures are integrated over space and time by habitat type (open water, reef, or wetland in offshore or nearshore waters) to calculate a total percentage killed. The behavior groups, representing species or stages within species, are:

1) planktonic (move with currents),
2) demersal and stationary (on the bottom exposed to near bottom water),
3) benthic (in the sediments and stationary),
4) demersal fish and invertebrates (on the bottom exposed to near bottom (within 1 m) water and moving slowly),
5) small pelagic fish and invertebrates (moving randomly and slowly in the water column), and
6) large pelagic fish and invertebrates (moving randomly and rapidly in the water column).

Mortality is calculated as percent loss in specified areas. The percent mortality of the exposure group is multiplied by abundance at the time exposed and in the habitat type to calculate the species' mortality as numbers or biomass (kg).

Lost production of lower trophic level plants and animals (not explicitly modeled as individual species) is also integrated in space and over time using EC50s, the effective concentration to reduce growth to 50% of normal, to parameterize a log-normal function of the same form as the mortality function. Total production loss (g dry weight) is summed over time and space. Production losses of lower trophic levels are typically very small because of their short generation times and quick recovery after a spill. They have not been measured in the field because the impact is less than natural variability.

2.3 Validation of the Biological Effects Model

The biological effect model has been validated using simulations of over 20 spill events where data are available for comparison (French and Rines, 1997; French McCay, 2003, 2004; French and Rowe, 2004). In most cases (French and Rines, 1997; French McCay, 2004; French and Rowe, 2004) only the wildlife impacts could be verified because of limitations of the available observational data. However, in the *North Cape* spill simulations, both wildlife and water column impacts (lobsters) could be verified (French McCay, 2003).

2.4 Quantification of Fish and Invertebrate Injury as Lost Production

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 is estimated and added to the direct kill injury. The total injury is the total production foregone. 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 present year.

Interim losses are injuries sustained in future years (pending recovery to baseline abundance) resulting from the direct kill at the time of the spill. Interim losses potentially include:

- Lost future uses (ecological and human services) of the killed organisms themselves;
- Lost future (somatic) growth of the killed organisms (i.e., production foregone, which provides additional services);
- Lost future reproduction, which would otherwise recruit to the next generation.

The approach here is that the injury includes the direct kill and its future services, plus the lost somatic growth of the killed organisms, which would have provided additional services. Because the impact on each species, while locally significant, is relatively small compared to the scale of the total population in the area, it is assumed that density-dependent changes in survival rate are negligible, i.e., changes in natural and fishing mortality of surviving animals do not compensate for the killed animals during the natural life span of the animals killed.

It is also assumed that the injuries were not large enough to significantly affect future reproduction and recruitment in the long term. It is assumed that sufficient eggs will be produced to replace the lost animals in the next generation. The numbers of organisms affected, while locally significant, are relatively small portions of the total reproductive stock. Given the reproductive strategy of the species involved to produce large numbers of eggs, of which only a few survive, it is assumed that density-dependent compensation for lost reproduction occurs naturally.

The services provided by the injured organisms are measured in terms of production, i.e., biomass (kg wet weight) directly lost or not produced. Among other factors, services of biological systems are related to the productivity of the resources, i.e., to the amount of food produced, the usage of other resources (as food and nutrients), the production and recycling of wastes, etc. Particularly in aquatic ecosystems, the rate of turnover (production) is a better measure of ecological services than standing biomass (Odum, 1971). Thus, the sum of the standing stock killed (which resulted from production previous to the spill) plus lost future production is a more appropriate scaler, as opposed to standing stock alone (as number or kg), for measuring ecological services.

This injury estimation method was developed and used previously in the injury quantification for the *North Cape* spill of January 1996 (French McCay et al., 2003). The method makes use of the population model in the NRDAM/CME and SIMAP. Injuries are calculated in three steps:

1. The direct kill is quantified by age class using a standard population model used by fisheries scientists.
2. The net (somatic) growth normally to be expected of the killed organisms is computed and summed over the remainder of their life spans (termed lifetime production).
3. Future interim losses are calculated in present day values using discounting at a 3% annual rate.

The normal (natural in local waters) survival rates per year and length-weight by age relationships are used to construct a life table of numbers and kg for each annual age class. Lifetime production is estimated as the sum of the net (somatic) growth normally to be expected of the killed individual over the remainder of its life span. The age-class specific weight gain per year times percent expected to be left alive by the end of that year is summed over all years to calculate total lifetime production. Growth in future years is discounted 3% annually. Equations for these calculations are in French McCay et al. (2003).

It should be noted that compensation is needed for lost production of each of the individual species injured, and that losses are additive. Restoration for a prey species killed will compensate for that prey killed and all the services that prey would have provided in the future to its predators and other resources. The predators that would eat that prey but were directly killed were produced before the spill from *different* prey individuals as food. Thus, the predator's production loss must be compensated in addition to the prey animals directly killed. This may be accomplished by providing additional prey production to compensate for the direct predator loss.

Discounting at 3% per year is included to translate losses in future years (interim loss) to present-day values. The discounting multiplier for translating value n years after the spill to present value is calculated as $(1+d)^{-n} = 1/(1+d)^{n}$, where d=0.03. Thus, the losses in future years have a discounted value in the present. In this report, all discounting is calculated based on the number of years from the year of the spill. The present day is considered the year of the spill.

2.5 Quantification of Wildlife Injury (Interim Loss)

The interim loss of wildlife (in this case, birds) is calculated from the number of oil-killed birds using standard demographic modeling. The interim loss includes the direct loss, expressed as the number of bird-years lost that is attributable to the killed birds themselves, and the loss of fledgling production those birds would have produced. The lost fledglings are also translated to number of bird-years lost using the same demographic model. One generation of fledglings is assumed lost because of the spill's effects.

The direct loss is the sum over all years into the future of the number of birds that would have otherwise been alive each year following the spill, counting each year of life as one bird-year, until all animals would have died in the absence of the spill. The calculation is based on the following, using annual age classes. The number reaching age *t* in years (N_t) is the number at the previous annual age class (N_{t-1}) times the annual survival rate for that age class:

$$N_t = N_{t-1}\, e^{(-Z_t)}$$

where Z_t is the age-specific annual instantaneous natural mortality rate, which is related to the annual survival rate for age *t* (S_t) by the following:

$$S_t = e^{(-Z_t)}$$

The equations used to calculate the direct interim loss in bird-years (D_L) are:

$$D_L = \sum_i \sum_y \ (N_{i,y}\, S_{i+y}) / (1+d)^y$$

$$N_{i+1,y+1} = N_{i,y}\, S_{i+y} = N_{i,y}\, e^{[-(Z_{i+y})]}$$

where $N_{i,y}$ is the number of age class i expected to have remained alive at the beginning of year y after the spill, S_{i+y} is the expected portion of age class i surviving from age i+y to i+y+1, W_{i+y} is the weight per individual for age class i at y years after the spill, Z_{i+y} is instantaneous annual mortality rate (for age i+y), and *d* is the discount rate ($d = 0.03$: NOAA 1997). For first year birds, S_1 is corrected for the age of the bird at the spill date, i.e., survival rate is assumed constant from the date of fledging to their first birthday after hatching.

The equations used to calculate the interim loss for fledglings the kill birds would have otherwise produced, in bird-years (F_L) are:

$$F_L = \sum_{i} \sum_{y} \left(N_{i,y} S_{i+y} R_{i+y} F_{i+y} \right) / (1+d)^{y}$$

where R_{i+y} is the number of fledglings produced per bird at age $i+y$ and F_{i+y} is the number of bird-years per fledgling discounted by the number of years after the spill when they would have been produced, $i+y$. F_{i+y} is calculated as:

$$F_{i+y} = \sum_{n=i+y}^{\infty} \left(S_{i+y} \right) / (1+d)^{n}$$

The total interim loss (T_L), in bird-years, is the sum of the direct loss and the lost fledgling production:

$$T_L = D_L + F_L$$

These bird-years (T_L) are of mixed age classes. The interim loss T_L is translated to the equivalent number of fledglings (F_P) needed in compensation, as a likely restoration objective would be to produce additional fledglings to add to the population. The calculation of F_P is as follows:

$$F_P = T_L / F_G$$

where F_G is the number of bird-years per fledgling produced, calculated as:

$$F_G = \sum_{i} \left(S_i \right) / (1+d)^{i}$$

Thus, the injury is quantified as lost bird-years of mixed age classes (T_L) and translated to the number of fledglings that would produce that same number of bird-years (F_P). Replacement of F_P birds at the age of fledging would compensate for the injury resulting from the oil-induced mortality of all ages of birds and their fledgling production foregone.

3. MODEL INPUT DATA

3.1 Geographical and Model Grid

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 is generated from a digital coastline using the ESRI Arc/Info compatible Spatial Analyst program. The cells are then coded for depth and habitat type. Note that the model identifies the shoreline using this grid. Thus, in model outputs, the coastline map is only used for visual reference; it is the habitat grid that defines the actual location of the shoreline in the model.

The digital shoreline, shore type, and habitat mapping were obtained from the Environmental Sensitivity Index (ESI) Atlas database compiled for the area by Research Planning, Inc. (RPI). These data are distributed by NOAA Hazmat (Seattle, WA). GIS data for intertidal oyster reefs were complied from ESI data and ground-truthed data from the 1980's (Michael Yianopoulos, SCDNR, pers. comm., December 2003). The oyster reef data were also compared to a map of SCDNR GIS coverages of oyster beds in the Charleston Harbor area from 1995 provided by Tom Moore (NOAA) and Howard Schnabolk (NOAA RC in Charleston). In some locations, oyster reefs were present one survey and not in the others, but all surveys were included in the mapping of the habitat grid. The gridded habitat type data are shown in Appendix A.2. The grid scale resolution is indicated in Table A.2-1 of Appendix A.2.

As noted above, within a grid, habitats are designated as landward or seaward. Landward portions are the harbor, rivers, and inlets. The seaward portion is the open ocean (coastal continental shelf). This designation allows different biological abundances to be simulated in landward and seaward zones of the same habitat type (e.g., open water with sand bottom). The biological database is coded to landward or seaward by species (see French et al., 1996a, c).

Ecological habitat types (Table 3-1) are broadly categorized into two zones: intertidal and subtidal. Intertidal habitats are those above spring low water tide level, with subtidal being all water areas below that level. Intertidal areas may be extensive, such that they are wide enough to be represented by an entire grid cell at the resolution of the grid. These are typically either mud flats or wetlands, and are coded 20 (seaward mudflat), 21 (seaward wetland), 50 (landward mudflat) or 51 (landward wetland). All other intertidal habitats are typically much narrower than the size of a grid cell. Thus, these fringing intertidal types (indicated by F in Table 3-1) have typical (for the region, French et al., 1996a) widths associated with them in the model. Boundaries between land and water are fringing intertidal habitat types. On the waterside of fringing intertidal grid cells, there may be extensive intertidal grid cells if the intertidal zone is extensive. Otherwise, subtidal habitats border the fringing intertidal.

Table 3-1. Classification of habitats. Seaward (Swd) and landward (Lwd) system codes are listed. (Fringing types indicated by (F) are only as wide as the intertidal zone in that province. Others (W = water) are a full grid cell wide and must have a fringing type on the land side.)

Habitat Code (Swd, lwd)	Zone	Ecological Habitat	F or W
1,31	Intertidal	Rocky Shore	F
2,32		Gravel Beach	F
3,33		Sand Beach	F
4,34		Fringing Mud Flat	F
5,35		Fringing Wetland (Saltmarsh)	F
6,36		Macrophyte Bed	F
7,37		Mollusk Reef	F
8,38		Coral Reef	F
9,39	Subtidal	Rock Bottom	W
10,40		Gravel Bottom	W
11,41		Sand Bottom	W
12,42		Silt-mud Bottom	W
13,43		Wetland (Subtidal of Saltmarsh)	W
14,44		Macroalgal (Kelp) Bed	W
15,45		Mollusk Reef	W
16,46		Coral Reef	W
17,47		Seagrass Bed	W
18,48	Intertidal	Man-made, Artificial	F
19,49		Ice Edge	F
20,50		Extensive Mud Flat	W
21,51		Extensive Wetland (Saltmarsh)	W

The intertidal habitats were assigned based on the shore types in digital Environmental Sensitivity Index (ESI) maps distributed by NOAA HAZMAT (CD-ROM). This data was gridded using the ESRI Arc/Info compatible Spatial Analyst program. Open water areas were defaulted to sand bottom, as open water bottom type has no influence on the model results. Where data are missing, shore types are defaulted as in Table 3-2. Habitats inside Charleston Harbor, the rivers, and other coastal inlets were designated as landward, and open coastal water as seaward.

Table 3-2. Default fringing intertidal habitat type, given adjacent subtidal or extensive intertidal habitat type.

Subtidal or Extensive Intertidal Habitat	Fringing Intertidal Habitat
Seagrass Bed (47)	Sand Beach (33)
Subtidal Sand Bottom (41)	Sand Beach (33)
Extensive Mudflat (50)	Fringing Mudflat (34)
Extensive Wetland (51)	Fringing wetland (35)

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. Hydrographic survey data consist of large numbers of individual depth soundings. The depth soundings were gridded using the ESRI Arc/Info compatible Spatial Analyst program. The gridded depth data are shown in Appendix A.3.

3.2 Environmental Data

The model uses hourly wind speed and direction for the time of the spill and simulation. The model can use multiple wind files, spatially interpolating between them to determine local wind speed and direction. Two wind data sets are available for the area and time of the spill. Standard meteorological data were acquired from the National Data Buoy Center (http://www.ndbc.noaa.gov/station_page.phtml?station=fbis1), "Station FBIS1 - Folly Beach, SC" (32.68^{o}N, 79.89^{o}W). Wind data were also obtained for Charleston International Airport (32.9 ^{o} N, 80.033^{o} W). Hourly mean wind speed and direction for 30 September to October 31 2002 were compiled in the SIMAP model input file format. Wind speed and direction data are in Appendix C.

Surface water temperature was 23^{o}C during the week after the spill (NOAA CO-OPS, http://co-ops.nos.noaa.gov). The same temperature is assumed for both the water surface and the air immediately above the water. Water temperature affects evaporation rate, and so surface oil volume, but not the trajectory of the spill. The effect of water temperature within the range of a few degrees Celsius is insignificant.

Salinity is assumed to be the mean value for South Carolina inlets, based on data compiled in French et al. (1996b). The salinity value assumed in the model runs has little influence on the fate of the oil, as salinity is used to calculate water density (along with temperature), which is used to calculate buoyancy, and none of the oils evaluated have densities near that of the water.

Suspended sediment is assumed 11.7 mg/L, based on Department of Health and Environmental Control (SCDHEC) data (David Graves, pers. comm., January 2004). A concentration of 10 mg/L is typical for coastal waters (Kullenberg, 1982). The sedimentation rate is set at 1 m/day. The low suspended sediment concentration indicates little adsorption and settling of oil occurred and so the sinking rate has no significant affect on the model trajectory. Sedimentation of oil and PAHs becomes significant at about 100 mg/L suspended sediment concentration. There is no evidence that high suspended sediment concentrations occurred during the spill.

The horizontal diffusion (randomized mixing) coefficient is assumed as 1 m^2/sec, and the range from 0.1-10 m^2/sec was examined in sensitivity analyses. The vertical diffusion (randomized mixing) coefficient is assumed 0.0001 m^2/sec. These are reasonable values for coastal waters based on empirical data (Okubo and Ozmidov, 1970; Okubo, 1971) and modeling experience. The vertical diffusion coefficient used kept the relatively shallow water column well mixed, and so variation of this parameter had no significant impact on the results. Thus, only variation of the horizontal diffusion coefficient was examined.

3.3 Currents

3.3.1 Tidal and Other Currents

Currents have significant influence on the trajectory and oil fate, and are critical data inputs. Wind-driven, tidal and background (river flow) currents were included in the modeling analysis. The local surface wind drift is calculated within the oil spill model (as described in the next section). The tidal currents and river-flow currents are input to the oil fates and biological effects models from a current file that is prepared for this purpose.

Current data were generated using ASA's boundary fitted coordinate hydrodynamic model (BFHYDRO) which produces applicable hydrodynamic data sets suitable for use in the SIMAP model system. The hydrodynamic model's governing equations and validation are described in detail in Spaulding (1984), Muin (1993), Muin and Spaulding (1997a, b), Spaulding et al. (1999a), and Sankaranarayanan and Spaulding (2003). The boundary-fitted grid is a mesh of quadrilateral cells of varying size and included angles, which is capable of handling variable geometry and flow regimes. The boundary fitted coordinate system in BFHYDRO uses 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 may be resolved, along with the larger, without being penalized by an excessive grid size (number of cells).

The boundary-fitted method uses a set of coupled quasi-linear elliptic transformation equations to map an arbitrary horizontal multi-connected region from physical space to a rectangular mesh structure in the transformed horizontal plane. The 3-dimensional conservation of mass and momentum equations, with approximations suitable for estuaries (Muin and Spaulding, 1997a, b) that form the basis of the model, are then solved in this transformed space. In addition, an algebraic transformation is used in the vertical to map the free surface and bottom onto coordinate surfaces. The resulting equations are solved using an efficient semi-implicit finite difference algorithm.

The hydrodynamic model (BFHYDRO) has been validated in numerous applications, including in Muin and Spaulding (1997a, b), Spaulding et al. (1999a), and Sankaranarayanan and Spaulding (2003) where the governing equations are described. Applications that have been validated include: for San Francisco Bay (Sankaranarayanan and French McCay, 2003a); for the Narragansett Bay system (Swanson et al., 1998; Spaulding et al., 1999b; Kim and Swanson, 2001); for Bay of Fundy (Sankaranarayanan and French McCay, 2003b); the Savannah River (Mendelsohn et al., 1999), and Charleston Harbor, SC (Peene et al., 1997; Yassuda et al., 2000a,b; Mendelsohn et al., 2001).

In that Charleston Harbor and nearby coastal waters are highly energetic and predominantly well-mixed, BFHYDRO was applied in the two-dimensional mode, thus providing vertically-averaged currents. Known physical conditions were input to the model grid at the edges, termed "open boundaries". These inputs are described as "forcing factors". The forcing factors used were water height, available from tidal height data, and river flow. Salinity driven (i.e., density driven) flows, were not considered for the present analysis. Forcing factors due to wind stress on the water surface were included in the wind drift calculation in the oil fates model.

Tidal currents are driven by a mix of forces with semi-diurnal and diurnal periodicity, causing the elevations of successive high and low tides to be unequal. The major 6 constituents are M2, S2, N2, K1, O1, and P1, where the letter and number codes for the tidal constituents are standard terminology based on harmonic analysis of tidal height data (Defant, 1961), with the number indicating the approximate frequency of the sinusoidal cycle per day (1 is diurnal and 2 is semi-diurnal). The letter indicates the sinusoidal periodicities included in the component. M2 and S2 are pure lunar and solar components, respectively. All the others are mixtures of signals resulting from various periodic changes in the position of the sun and moon relative to the earth. For more information, see Defant (1961) or similar oceanographic text book.

The model grid is shown in Appendix D.1 (Figure D.1-1). Tidal forcing was accomplished by defining the water height over time at the model grid boundaries. The forcing was specified for each tidal constituent. The current vectors for each constituent were computed for each model grid cell and time step based on physical laws (conservation of mass and momentum). Current vectors for non-tidal flows (i.e., river) were computed in an analogous manner. In the oil spill model, the various tidal constituent and non-tidal current vectors were summed to determine the actual transport of oil components and plankton in the particular grid cell and time step of interest.

Appendix D.2 contains current vector plots for selected representative times after the spill. An animation of the current vectors, as well as current speed contour maps, may be seen using the SIMAP Viewer.

3.3.2 Wind-driven Surface Currents

Local wind-driven surface currents are calculated within the SIMAP fates model, based on local wind speed and direction. Surface wind drift of oil has been observed in the field to be 1-6% (average 3-4%) of wind speed in a direction 0-30 degrees to the right (in the northern hemisphere) of the down-wind direction (ASCE, 1996). In restricted waters with little fetch, such as in the spill area, the angle tends to be near zero, while in open waters the angle develops to be 20^{o}-30^{o} to the right of down wind.

Wind drift speed and angle were studied in detail by Youssef and Spaulding (Youssef, 1993; Youssef and Spaulding, 1993, 1994). Wind drift speed is a percentage of wind speed over the water, highest at low wind speed and decreasing as wind speed increases. The range of drift speed for winds up to 20 kts (averaged over time) is 2-4% of wind speed. At 10 kts or less, which prevailed during the spill event, the percent of wind speed is about 3.5-4% at the water surface, decreasing to 2% at 0.1m below the surface. The angle to the right of down wind is highest at low wind speed, on the water surface ranging from about 20^{o}-30^{o} at 10 kts or less. The drift speed decreases, and the drift angle increases, deeper into the water column.

Youssef and Spaulding (Youssef, 1993; Youssef and Spaulding, 1993, 1994) developed a set of equations to describe the percent of wind speed and angle as functions of wind speed and depth in the water. This algorithm has been incorporated into SIMAP. The wind drift is applied to the upper 5 meters of the water column. The SIMAP algorithm was validated with observations of the drift of floating fuel and bitumen in open ocean surface water after an intentional (test) Orimulsion spill (French et al., 1997). This Youssef and Spaulding algorithm was used in some model runs for surface wind drift. However, the best fit to the shoreline oiling observations was obtained assuming a constant 3.5% of wind speed and 0^{o} angle (see results, below).

3.4 Oil Properties and Toxicity

The spilled oil consisted of Intermediate Fuel Oil (IFO 380), a heavy fuel oil. Physical and chemical data were taken from the Environment Canada catalogue of crude oil and oil product properties (Whiticar et al., 1992; Jokuty et al, 1996), except as available from measurements on the source oil (provided by the responsible party, measured by Battelle). Fuel density was assumed 0.98 g/cm^3 (API = 12.888), which is lighter than seawater water, and so the (pure) fuel floated. The viscosity (40,470 cp) of typical heavy fuel is high, which slows entrainment into the water column to a very low rate. Variation of these two parameters within the typical range for heavy fuels would have no significant effect on the results. Surface tension was assumed 32.6 dyne/cm. Minimum oil slick thickness for spreading oil was assumed 1mm, based on McAuliffe (1987).

PAH concentrations were measured in the source oil by Battelle. MAH concentrations were based on data in Wang et al. (1995). For heavy fuel oil spills, MAHs do not have a significant impact on aquatic organisms for the following reasons. MAH concentrations are <3% in fresh fuel oils. MAHs are soluble, and so some becomes bioavailable (dissolved). MAH compounds are also very volatile, and will volatilize (from the water surface and water column) very quickly after a spill. The threshold for toxic effects for these compounds is about 500 ppb for sensitive species (French McCay, 2002). MAHs evaporate faster than they dissolve, such that toxic concentrations are not reached. The small concentrations of MAHs in the water will quickly be diluted to levels well below toxic thresholds immediately after a spill. Thus, while the assumed values for MAHs are approximate, this has little influence on model results.

The percentage of PAHs in the oil has a significant influence on the model results. Thus, the LC50s assumed were for PAH concentrations in the water. French McCay (2002) estimated an LC50 for PAH mixtures of 50 ppb for typical heavy fuels at infinite exposure time and for the average species. Ninety-five percent of species have LC50s between 6 and 400 μg/L (ppb). In the assessment, a worst case was evaluated to determine if injuries in subtidal habitats would be expected for any species. Thus, all species were assumed to be of high sensitivity to dissolved hydrocarbons, i.e., LC50 = 6 ppb. The model corrected this LC50 to temperature and duration of exposure for each group of organisms exposed.

From analysis of the source oil by Battelle, the total PAH content is 1.64% (mean of two source oil sample measurements). Of the total, 1.38% is of 2 to 3-ring PAHs with log(Kow)$\leq$5.6, which are the acutely toxic components. Table E-3 of Appendix E lists the fraction of the oil represented by each pseudocomponent used in the model runs.

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., 1996a,b), shore holding capacity 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., 1996a). These data are used here (Table 3-3). The shore width (intertidal zone width where oiling would occur) was assumed 1 m.

Table 3-3. Maximum surface oil thicknesses for various beach types as a function of oil viscosity (from French et al., 1996a, based on Gundlach, 1987).

	Oil Thickness (mm) by Oil Type		
Shore Type	Light (<30 cSt)	Medium (30-2000 cSt)	Heavy (>2000 cSt)
Rocky shore	1	5	10
Gravel beach	2	9	15
Sand beach	4	17	25
Mud flat	6	30	40
Wetland	6	30	40
Artificial	1	2	2

3.6 Scenario

The spill was estimated as involving 12,500 gal (= 46.4 MT) of intermediate fuel oil (IFO 380). It appears to have begun after the ship grounded on a submerged dredge pipe in the Cooper River, which occurred as the vessel came into port early on 30 September 2002. The ship reached the dredge pipe (32 ^{o} 51.167' N, 79^{o} 56.195' W) at 05:35 AM on 30 September. Based on the distribution of oil observed after the spill and modeling results, the release must have been protracted: as the ship was traveling from the grounding site into Berth 1 NC Terminal (05:35 to 07:18 hours), and again as the ship left the harbor later the same day (left berth at 19:00 hours, passed harbor entrance about 20:30 hours). Oiling in the harbor and outside along Morris and Folly Islands cannot be accounted for assuming oil was released only at or up-river of the submerged dredge site (see results). The leak apparently stopped while the ship was at the berth, as the US Coast Guard (USCG) did not observe any leaking while the *Ever Reach* was docked. The oil apparently leaked again as the ship was underway leaving the harbor. Hydrostatic pressure would retain oil in the hull while the ship was stationary, but when the ship moved, lower pressure over the hull surface and turbulence would draw oil out of the ship.

The ship's log and the responsible party provided waypoints and times for the ship's movements, as listed in Table E-2 of Appendix E. Figures E-1 and E-2 plot the path of the ship inbound and outbound, respectively. The path of the ship between waypoints was assumed to follow the harbor channel, and the times between known points were interpolated assuming constant speed between waypoints.

The oil was assumed to be released from the water surface. While the crack in the hull was underwater, the oil is buoyant in seawater and so floats to the surface rapidly. The volume spilled was assumed to released evenly in time during the inbound trip (30% of the volume from 05:35 to 07:18 hours) and the outbound trip (70% from 19:00 to 22:19 hours), with no leakage while docked at the berth. Appendix E contains tables of model inputs for the SIMAP physical fates model.

The model simulations did not include accounting for on-water or shoreline oil removal activities. While these activities did occur, estimates of the actual amount of oil removed are not available. Removal of oil from shorelines would not affect the magnitude of injuries calculated by the model because cleanup occurred after the birds were exposed (in the model). Removal of oil from the water surface would not have a significant affect the injuries calculated, because most of this skimming activity occurred in the area of the Navy base where little oiling of birds occurred.

3.7 Biological Abundances

Wildlife species include aquatic birds, marine mammals and sea turtles. The model inputs may include two types of abundance data: (1) distributed average densities (#/km^2) in appropriate habitats, and (2) total number at specific locations located in the GIS database (e.g., at colony sites). Section 2.2 describes the assignment of each species to a set of habitats that it uses and that are assumed for the distributed densities. Those densities are assumed uniformly distributed across its preferred habitats. Thus, the habitat grid defines the habitat map, and so the distributed density of each species. Added to this are the total number of animals at specific point locations (colonies).

Fish and invertebrates are also input as average density by species (or group) per unit area in assigned habitats. The NRDAM/CME (French et al., 1996c) contains mean seasonal or monthly densities for 77 biological provinces in US coastal and marine waters. Data for province 21, for South Carolina coastal waters, were used (summarized in Appendix G). Fish and invertebrate density varies by landward open water, seaward open water, and structured habitat (i.e., wetlands, oyster reefs, Table 3-1). In the NRDAM/CME (French et al., 1996c), the abundances are for fished stocks and the biomass includes those animals greater than the age of recruitment to fishing. In the biological effects model the age/size distribution is computed from fishery modeling parameters (natural and fishing instantaneous mortality rates, length as a function of age, and weight-length relationships), such that the mortality is calculated for all age classes from age 1 year up (and assuming the various age classes live in the same habitat in that age structure).

Young-of-the-year mortality is quantified separately. The biological database includes number of age 1-year (365 day old) individuals per km^2. The young-of-the-year abundances in the NRDAM/CME (French et al., 1996c) were calculated from the spawning stock and life history information as to where those animals would live for each month of their first year of life. The numbers are those needed to recruit to the stock at age one year in order to maintain a stable population size. Thus, young-of-the-year mortality is for only those that would have survived their first year if not for the spill. Assumed densities of young-of-the-year are in Appendix G.

3.7.1 Wildlife Densities

Data for the distributed bird densities were derived from various surveys that occurred in the Charleston Harbor area. The four main data sources included 1) USGS Breeding Bird Survey (BBS) for sites near Charleston Harbor (Sauer et al. 2003); 2) 2002-2003 nesting bird counts from Tom Murphy (South Carolina Department of Natural Resources) for Crab Bank and Castle Pinckney on Shutes Folly; 3) 2000-2002 International Shorebird Survey (Brian Harrington, Manomet Center for Conservation Sciences), and 4) existing data in the NRDAM/CME (French et al. 1996c) from Portnoy et al. 1981, Haney and McGillivery (1985), and Johnsgard (1990). Table 3-4 summarizes the distributed bird density estimates and assumptions of species seasonality and presence that were used in modeling.

The USGS Breeding Bird Survey (BBS) is a roadside survey conducted during the peak nesting season (Sauer et al. 1997), which is primarily during June, although for some southern states it occurs during May as the breeding season is earlier than other areas of the US. Each route is 24.5 miles (39.4 km) with a total of fifty stops located at 0.5 mile (0.8 km) intervals. At each stop, the observer records all birds heard or seen within 0.25

miles (0.4 km). The Kiawah Island route (SC-801, funded by the town of Kiawah, South Carolina) was used to estimate the abundance of seabirds, waders and raptors that would be present at the time of the spill (September-October 2002). GIS was used to calculate the area of habitat for each species that was within 0.4 km of every stop along the route. This area, the ratio of breeders to non-breeders estimated by French et al. (1996c), and the assumption that the resident and breeding species would still be present in September-early October were used to calculate the density of seabirds, waders and raptors that would be in the spill area during the fall.

The John's Island BBS route (SC-001) was used to estimate the density of waterfowl, as no waterfowl species were counted in the Kiawah route (SC-801). Unlike with the Kiawah Island survey, the exact route for John's Island was not available. Therefore, the suitable habitat area (water or wetlands) was assumed to be ½ of the survey route, as a maximum possible area (assuming the road used for the survey follows the shores of water bodies, with terrestrial habitat on the opposite side of the road). This leads to density estimates for waterfowl species that are minimum estimates. Using the same area estimate, the densities of waterfowl for two other BBS surveys (Walterboro and Adam's Run), show that there is little variability in waterfowl abundance between sites (Table 3-5). The assumed habitat area for John's Island and the ratio of breeders to non-breeders (French et al. 1996) were used to calculate the density of waterfowl that would be in the spill area during the fall.

Nest count data for 2002-2003 at Crab Bank and Castle Pinckney (on Shutes Folly, Tom Murphy, pers. comm., Sept. 2003) were used to estimate osprey and brown pelican abundance within the lower Charleston Harbor. There are about 15 pairs of osprey observed to nest in the lower harbor. They nest in the spring (March-April), and migrate out in October (Tom Murphy, pers. comm., Sept. 2003). In 2002-2003, a mean of 430 pairs of pelicans nested in the harbor area (at Crab Bank and Castle Pinckney). Multiplying these estimates by the estimated ratio of total birds per breeding pair (from French et al., 1996), there were an estimated 42 osprey and 1672 pelicans in the population associated with the lower harbor area. While those birds would have been concentrated at the nest sites during nesting season, they would have been more dispersed but still within the local area by September 30. As both species prefer estuarine waters, it is assumed they remained primarily in the lower harbor. The area of the lower harbor estimated using GIS (72.7 km^2) was used to calculate a (distributed) density of osprey and pelicans that would be present during the time of the spill.

Considerable uncertainty exists with the distributed density estimates, primarily in the calculation of area these species use as habitat. For instance, the estimate for brown pelican in the lower harbor from Tom Murphy's data (Tom Murphy, pers. comm., Sept. 2003), is greater than that of brown pelican on Kiawah Island in the BBS Survey (Sauer et al. 2003) by a factor of two (Table 3-6), although this difference is likely attributable to differences in habitat. For osprey, the abundance estimate from the BBS Kiawah Island survey is a factor of eight greater than that calculated from Tom Murphy's data (Table 3-6). Because of this variability, we have used the lower harbor density estimates for species where sufficient data were available, using the Kiahah Island densities for other species.

In addition to pelicans distributed in the general area of Charleston Harbor, Tri-State observed 200 pelicans concentrated on Crab Bank and 10 on nearby Hog Island (Figure A.1-1) during the week following the spill. The concentration of pelicans at the colony sites were input to the model, along with the distributed density derived as described above, but with 210 pelicans subtracted from the 1672 in the local population before calculating the distributed density. The model evaluated whether each colony site was hit, and calculated the percentage of the pelicans oiled based on the probability described in Section 2.2.1 (35%, Table 2-2, which amounts to 70 birds if the Crab Bank area was oiled in the simulation and 3.5 birds if the Hog Island area was oiled).

The International Shorebird Survey (ISS), specifically the Pitt Street, Mount Pleasant site (on Shem Creek just north of Crab Bank in the lower harbor) for September to November 2000-2002 (Brian Harrington, Manomet Center for Conservation Sciences, pers. comm., April 13, 2004), was used to calculate the distributed density of shorebirds that would be present at the time of the spill. From an aerial photo of the Pitt Street vicinity, the area surveyed was estimated as 0.30 km^2. Table 3-7 is a comparison of the Pitt Street site with the smaller Folly Road, James Island site (0.07 km^2). This comparison shows the high level of variability between sites. The Pitt Street was chosen as a more accurate representation of shorebirds that would be present in Charleston Harbor during the period of the spill.

3.7.2 Wildlife Life History Data

Wildlife life history parameters are required to calculate the interim loss for the injury quantification. Tables 3-8 to 3-12 list the population parameters used and their sources. The most abundant species present in each group was used to estimate the interim losses, and so the population parameters were for those species. The number of fledglings produced per adult (greater than the age of first reproduction) per year is based on the age distribution indicated by the survivorship schedule and the assumption that all mature adults nest each year.

The data for pelicans were primarily based on a life history review by Hingtgen et al. (1985), which was used to develop a Habitat Suitability Index (HSI) model to the eastern brown pelican. The average number of brown pelican fledglings produced per nest in SC from 1970 to 1982 was 1.1 (observed in nest counts by Wilkinson, 1982), and half this was used as the fledging rate per adult ($\geq$ 4 yrs old) in the population.

For the other species groups, the data in French et al. (1996c) were used. These values were developed to be generally applicable to spills throughout the US, and were based on literature review for each species or species group using information for populations throughout North America. The notes in Table 3-13, from French et al. (1996c), describe the sources of the data.

Table 3-4. Summary of the distributed density data used for waterfowl, seabirds, waders, shorebirds and raptors.

Species Name	$\#/km^2$ for fall	Species seasonality from Forsythe (1998)	Presence Basis	Source
Mallard	0.001	Winter Visitor	Observed in BBS survey in summer	BBS Survey for Johns Island (1982-1996)
Canada goose	0.02	Winter Visitor	Observed in BBS survey in summer	BBS Survey for Johns Island (1982-1996)
Hooded merganser	0.00	Winter Visitor	Observed in BBS survey in summer	BBS Survey for Johns Island (1982-1996)
Pied-billed grebe	0.00	Permanent Resident	Not observed in survey	BBS Survey for Kiawah Island (1966-2002)
Double-crested cormorant, seaward	0.00	Permanent Resident	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Double-crested cormorant, landward	2.00	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Herring gull	0.11	Summer Visitor	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Ring-billed gull	2.78	Summer Visitor	Assumed still present in fall	Forsythe 1972
Laughing gull, seaward	0.27	Summer Resident	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Laughing gull, landward	12.07	Summer Resident	Assumed still present in fall	BBS Survey for Kiawah Island (1966-2002)
Bonaparte’s gull	0.00	Winter Visitor		NRDAMCME: Haney and McGillivery (1985)
Wilson's phalarope	present	Transients	Not observed in fall surveys	Forsythe (pers. obs.)
Black skimmer, seaward	1.08	Permanent Resident	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Black skimmer, landward	2.51	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Least tern, seaward	0.00	Summer Resident	Not observed in fall survey	NRDAMCME: Haney and McGillivery (1985)
Least tern, landward	1.33	Summer Resident	Assumed still present in fall	BBS Survey for Kiawah Island (1966-2002)
Common tern	2.18	Transient	Uncommon	NRDAMCME: Haney and McGillivery (1985)
Forster's tern, seaward	0.01	Permanent Resident	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Forster's tern, landward	1.16	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island
Royal tern, seaward	0.01	Permanent Resident	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Royal tern, landward	1.49	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Caspian tern	0.17	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)

Species Name	#/km^2 for fall	Species seasonality from Forsythe (1998)	Presence Basis	Source
Black tern	0.65	Transient	Common in Aug-Sept	NRDAMCME: Haney and McGillivery (1985)
Sandwich tern, seaward	0.01	Summer Resident	Observed in fall in survey	NRDAMCME: Haney and McGillivery (1985)
Sandwich tern, landward	0.00	Summer Resident	Not observed in survey	BBS Survey for Kiawah Island (1966-2002)
Gull-billed tern	0.50	Summer Resident	Assumed still present in fall	BBS Survey for Kiawah Island (1966-2002)
Brown pelican, seaward	0.22	Permanent Resident	Observed in fall in survey	NRDAMCME: Portnoy et al. 1981
Brown pelican, landward	20.25	Permanent Resident	Assume same density all year	Tom Murphy counts, pers com Sept 2003
Great blue heron	1.04	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Tricolored heron	1.56	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Little blue heron	0.17	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Green heron	3.73	Summer Resident	Assumed still present in fall	BBS Survey for Kiawah Island (1966-2002)
Black-crowned night-heron	0.43	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Yellow-crowned night-heron	0.09	Summer Resident	Assumed still present in fall	BBS Survey for Kiawah Island (1966-2002)
Great egret	4.59	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Snowy egret	1.30	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Clapper rail	1.22	Permanent Resident	Assume same density all year	BBS Survey for Kiawah Island (1966-2002)
Wood stork	0.61	Summer Resident	Assumed still present in fall	BBS Survey for Kiawah Island (1966-2002)
Willet	17.01	Permanent Resident	Assume same density all year	International Shorebird Survey, 2000-2002
Killdeer	0.00	Permanent Resident	Assume same density all year	International Shorebird Survey, 2000-2002
American Oystercatcher	21.73	Permanent Resident	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Black-bellied Plover	8.50	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002

Species Name	#/km² for fall	Species seasonality from Forsythe (1998)	Presence Basis	Source
Semipalmated Plover	58.58	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Piping plover	0.00	Winter Visitor	Not observed in Manomet survey	International Shorebird Survey, 2000-2002
Wilson's Plover	present	Summer Resident	Not observed in fall surveys	International Shorebird Survey, 2000-2002
Greater Yellowlegs	0.47	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Spotted Sandpiper	0.00	Transient, winter visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Whimbrel	0.00	Transient, winter visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Marbled Godwit	8.98	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Ruddy Turnstone	4.72	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Semipalmated Sandpiper	0.00	Transient	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Western Sandpiper	0.00	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Least Sandpiper	0.00	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Dunlin	23.62	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Short-billed Dowitcher	71.81	Winter Visitor	area for Pitt Street, Mt Pleasant	International Shorebird Survey, 2000-2002
Osprey	0.57	Summer Resident	Assumed still present in fall	Tom Murphy counts, pers com Sept 2003
Bald eagle	0.05	Permanent Resident	Assume same density all year	NRDAMCME: Johnsgard (1990)
Marsh wren	present	Permanent Resident	Not observed in fall surveys	Forsythe (pers. obs.)

Table 3-5. Comparison of waterfowl density estimates based on data for three sites in BBS Survey that are located in relatively close proximity to Charleston Harbor. Data for John's Island was used for modeling.

Species Name	USGS BBS, Adam's Run (1966 – 2002) #/km^2	USGS BBS, Walterboro (1966 – 2002) #/km^2	USGS BBS, Johns Island (1982 – 1996) #/km^2
Mallard	0.000	0.002	0.001
Canada goose	0.047	0.075	0.022
Hooded merganser	0.005	0.002	0.002

Table 3-6. Comparison of seabird, wader and raptor distributed density estimates based on data from 2 data sources [Tom Murphy, SCDNR (pers. comm. Sept. 2003) and USGS BBS Survey for Kiawah Island (Sauer et al. 2003)].

Species Name	Tom Murphy (SCDNR), per comm., Sept 2003 #/km^2	USGS BBS, Kiawah Island, 1966-2002 monthly mean #/km^2
Pied-billed grebe		0.00
Double-crested cormorant, landward		2.00
Laughing gull, landward		12.06
Black skimmer, landward		2.51
Least tern, landward		1.33
Forster's tern, landward		1.16
Royal tern, landward		1.50
Sandwich tern, landward		0.00
Gull-billed tern		0.50
Brown pelican, landward	20.25	10.27
Great blue heron		1.04
Tricolored heron		1.56
Little blue heron		0.17
Green heron		3.73
Black-crowned night-heron		0.43
Yellow-crowned night-heron		0.09
Great egret		4.59
Snowy egret		1.30
Clapper rail		1.21
Willet		0.16
Killdeer		0.05
Osprey	0.57	4.42

Table 3-7. Comparison of shorebird data for two sites in International Shorebird Survey. Density estimates (#/km^2) for Pitt Street, Mount Pleasant were used in modeling.

Species	Pitt Street, Mt. Pleasant 2000-2002	Pitt Street, Mt. Pleasant 2000-2002	Folly Rd, James Island 2000-2002	Folly Rd, James Island 2000-2002
Units	**Mean Count**	**#/km^2**	**Mean Count**	**#/km^2**
Black-bellied Plover	2.57	8.50	27.07	348.35
Wilson's Plover	0.00	0.00	0.00	0.00
Semipalmated Plover	17.71	58.58	43.33	557.70
Piping Plover	0.00	0.00	0.00	0.00
American Oystercatcher	6.57	21.73	0.00	0.00
Greater Yellowlegs	0.14	0.47	0.07	0.86
Lesser Yellowlegs	0.00	0.00	0.00	0.00
Spotted Sandpiper	0.00	0.00	0.20	2.57
Whimbrel	0.00	0.00	0.13	1.72
Marbled Godwit	2.71	8.98	0.00	0.00
Ruddy Turnstone	1.43	4.72	2.07	26.60
Red Knot	0.00	0.00	0.00	0.00
Sanderling	0.00	0.00	0.00	0.00
Semipalmated Sandpiper	0.00	0.00	3.93	50.62
Western Sandpiper	0.00	0.00	18.27	235.09
Least Sandpiper	0.00	0.00	11.67	150.15
Dunlin	7.14	23.62	0.33	4.29
Short-billed Dowitcher	21.71	71.81	20.27	260.83
Long-billed Dowitcher	0.00	0.00	0.00	0.00
Wilson's Snipe	0.00	0.00	0.00	0.00
Willet	5.14	17.01	6.27	80.65
Killdeer	0.00	0.00	0.07	0.86

Table 3-8. Life history parameters assumed for waterfowl based on Canada goose (the most abundant species).

Parameter	Value	Reference
Survival: fledging to age 1 year	0.239	French et al. (1996c)
Month of year when hatch	6	French et al. (1996c)
Months age at fledging	2	French et al. (1996c)
Age of young-of-the-year (yr) at spill date	0.333	(calculated)
Survival spill to age 1	0.318	(calculated)
Annual survival (>1 yr)	0.546	French et al. (1996c)
# Fledglings /adult /yr	1.4	French et al. (1996c)
Age first reproduce (yrs)	3	French et al. (1996c)
Weight (kg/bird)	5	French et al. (1996c)

Table 3-9. Life history parameters assumed for seabirds based on eastern brown pelican (the most abundant species).

Parameter	Value	Reference
Survival: fledging to age 1 year	0.275	Hingtgen et al. (1985); Schreiber and Mock, 1988
Month of year when hatch	5	Hingtgen et al. (1985)
Months age at fledging	3	Hingtgen et al. (1985)
Age of young-of-the-year (yr) at spill date	0.417	(calculated)
Survival spill to age 1	0.366	(calculated)
Annual survival (>1 yr)	0.840	Hingtgen et al. (1985)
# Fledglings /adult /yr	0.55	Wilkinson (1982)
Age first reproduce (yrs)	4	Hingtgen et al. (1985)
Weight (kg/bird)	3.5	Hingtgen et al. (1985)

Table 3-10. Life history parameters assumed for wading birds based on herons and egrets, generally (as described in French et al., 1996c).

Parameter	Value	Reference
Survival: fledging to age 1 year	0.320	French et al. (1996c)
Month of year when hatch	5	French et al. (1996c)
Months age at fledging	2	French et al. (1996c)
Age of young-of-the-year (yr) at spill date	0.417	(calculated)
Survival spill to age 1	0.450	(calculated)
Annual survival (>1 yr)	0.660	French et al. (1996c)
# Fledglings /adult /yr	0.84	French et al. (1996c)
Age first reproduce (yrs)	2	French et al. (1996c)
Weight (kg/bird)	1.3	French et al. (1996c)

Table 3-11. Life history parameters assumed for shorebirds based on sandpipers, generally (as described in French et al., 1996c).

Parameter	Value	Reference
Survival: fledging to age 1 year	0.470	French et al. (1996c)
Month of year when hatch	5	French et al. (1996c)
Months age at fledging	1	French et al. (1996c)
Age of young-of-the-year (yr) at spill date	0.417	(calculated)
Survival spill to age 1	0.618	(calculated)
Annual survival (>1 yr)	0.800	French et al. (1996c)
# Fledglings /adult /yr	0.87	French et al. (1996c)
Age first reproduce (yrs)	1	French et al. (1996c)
Weight (kg/bird)	0.03	French et al. (1996c)

Table 3-12. Life history parameters assumed for raptors based on osprey (the most abundant species).

Parameter	Value	Reference
Survival: fledging to age 1 year	0.380	French et al. (1996c)
Month of year when hatch	5	French et al. (1996c)
Months age at fledging	2	French et al. (1996c)
Age of young-of-the-year (yr) at spill date	0.417	(calculated)
Survival spill to age 1	0.508	(calculated)
Annual survival (>1 yr)	0.820	French et al. (1996c)
# Fledglings /adult /yr	0.76	French et al. (1996c)
Age first reproduce (yrs)	3	French et al. (1996c)
Weight (kg/bird)	1.9	French et al. (1996c)

Table 3-13. Sources for life history parameters assumed.

Species Group	Notes on Sources
Geese	Annual survival rates are means of data provided by Ogilvie (1978) and Bellrose (1980), including for Canada and snow geese. Hunting mortalities, hatchlings per adult, fledglings per adult, and age of reproduction are from Bellrose (1980) for Canada geese. Month hatched, age fledged and maximum age are from Ogilvie (1978). Mean weight is a mean of data for Canadian geese from Johnsgard (1978) and Bellrose (1980)
Herons and egrets	Values are means of available data for herons and egrets. Survival is from Ryder (1978). Hatchlings per adult is from English (1978). Fledglings per adult is a mean from English (1978), Konerman et al. (1978) and Frederick and Collopy (1989). Month hatched is from Bayer (1978) and English (1978). Age fledged is from Ehrlich et al. (1988). Age of reproduction is from Bayer (1978). Maximum age is from Ryder (1978). Mean weight for great blue herons, great egrets and black-crowned night-herons is from Hoffman (1978)
Sandpipers and plovers	First year survival is from Boyd (1962), Jacobs (1986) and Evans and Pienkowski (1984). Adult survival is from these sources plus Evans (1991). Hatchings per adult is from Evans and Pienkowski (1984). Fledglings per adult is from Safriel (1975). Month hatched is from Bent (1962). Age fledged is from Ehrlich et al. (1988). Age of reproduction and maximum age are from Oring et al. (1983). Mean weight is from Page et al. (1979)
Osprey	Survival rates and mean weight are from Newton (1979) and Henney (1986). Hatchlings per adult is from the Audubon Society of RI (1990). Fledglings per adult is from the Audubon Society of RI (1990), Newton (1979) and Henney (1986). Month hatched is from Bent (1937) and age fledged is from Bent (1937) and Ehrlich et al. (1988). Age of reproduction is from Bent (1937) and Henney (1986). Maximum age is from Newton (1979)

4. FATES MODEL RESULTS

The SIMAP model quantifies, in space and over time:

- 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 (which causes most aquatic toxicity) in three dimensions over time
- Total hydrocarbons and aromatics in the sediments over time

The fates model output at each time step includes:

- oil thickness (microns or g/m^2) on water surface,
- oil thickness (microns or g/m^2) on shorelines,
- subsurface oil droplet concentration (ppb), as total hydrocarbons,
- dissolved aromatic concentration in water (ppb),
- total hydrocarbon loading on sediments (g/m^2), and
- dissolved aromatics concentration in sediment pore water (ppb).

Model results are displayed by a Windows graphical user interface that animates the trajectory and concentrations over time. The figures included in the appendices are summaries of that output. The full model outputs of all model runs are available on CD and may be viewed with the SIMAP Viewer software, which is the model interface that displays the output data.

With the SIMAP Viewer, one can view the model results for all times steps of the model simulations. The maps show total hydrocarbons on and in the water, and dissolved aromatic concentrations in the water, after the spill. Concentrations in the water are calculated for a grid (200 X 200 cells horizontally, 5 layers vertically) sized to just cover the plume at the time of the output. The Viewer provides animated maps showing the vertical maximum concentration, the vertical mean concentration, or the concentrations in a selected layer. The Viewer also produces cross-sections showing subsurface concentrations. The user's manual for the SIMAP Viewer provides instructions on the use of the software.

Modeling of the trajectory and fate of the oil was performed using SIMAP, varying uncertain parameters to evaluate sensitivity to those assumptions. The calculations were made with a time step of 5 min. The model was run for 10 days, during which time all the oil came ashore or dispersed at sea. The following model inputs were varied to determine which provided the best fit to the observations.

- The horizontal turbulent diffusion coefficient (0.1, 1, 5, or 10 m^2/sec)
- Wind drift was either 3.5% of wind speed and angle = 0^o, or calculated using the model (see section 3.3.2)

- The spill was assumed instantaneous from one location, the location of the submerged dredge, or along the path and with the timing described in Section 3.6.

The fates model results of surface oil were visually compared to observed surface oil locations (e.g., from over-flights), scat reports, and other field data, as available. Surface oil distribution from over-flights and other observations are summarized in Appendix B. Quantitative observations of the surface oil distribution in the field are not available. Thus, quantitative comparisons to the model simulations could not be made. The model conserves oil mass, estimates losses to evaporation, and so the surface oil area estimates are realistic estimates of the oil mass on the water at any given time.

Appendix F contains figures for the best simulation (base case), i.e., that simulation best agreeing with observed oil locations and shoreline oiling. Appendix F.1 shows the mass balance of oil. The graph shows, as a function of time since the release start, percent of total mass spilled on the water surface, in the water column, on shorelines, in the sediment, in the atmosphere, and degraded. Initially all of the oil is on the surface. After 3 hours the majority of the surface oil from the 30 September morning's release (during the inbound trip) has come ashore (85.5%). Also at this time 14% of the oil has evaporated, no oil is entrained in the water column and 0.1% of the oil has degraded. Just after the second phase of the release during the outbound trip (at 17 hours after the spill start), 46% of the oil is floating and 46% is ashore. By 48 hours (05:35 on 2 October), 19% remains floating, 62% is ashore, and 13% has evaporated. The remaining floating oil is mainly at sea at this time, and over the next week it disperses.

Quantitative measurements of mass cleaned up are not available. Thus, cleanup was not included in the model simulations. Inclusion of shoreline cleanup would have no effect on the biological model results, as birds are exposed to oil as it comes ashore in the model. The model does not include effects of oiling that might have occurred at a later time (e.g., weeks after the spill).

Appendix F.2 shows the model trajectory, i.e., the path of the oil and locations where shorelines were oiled to some degree. The model replicates well the overall movement and timing of the oil from the spill path to the Navy piers, Crab Bank, Shutes Folly and Folly Beach. Once the majority of the spill was outside the harbor, it traveled in a westerly direction towards Folly Beach. Close to the source of the release, oil would have appeared as dark brown sheen with occasional patches of thicker oil. As the oil approached the Folly Beach area, the oil spread out and weathered. Very little would have been visible on the water as it would be tar balls and sheen by the time it reached shore.

Appendix F.3 shows the amount of oil accumulated on shorelines and sediments for the (base case) simulation, as mass of total hydrocarbons per unit area (averaged in each habitat grid cell). The area of shoreline that was oiled with greater than 100 g/m^2 (1mm) is estimate in the model simulation as 2,316 m^2 for rocky shore; 772 m^2 for gravel beach; 6,527 m^2 for sand beach; 2,597 m^2 for mud flat; 2,737 m^2 for wetland; 2,106 m^2 for oyster reef, and 6,387 for artificial/man made shoreline. No shoreline cleanup was simulated in the model. Thus, oil simply accumulates and remains on the shore.

Appendix F.3 also summarizes the sensitivity analysis results for oil contamination. The shoreline oiled by each simulation is plotted. The variation of the horizontal diffusion coefficient affected the amount of shoreline oiled; more shoreline was oiled if the value was higher. However, if too much horizontal diffusion was assumed, the result was too much oiling on the left descending bank of the Cooper River, which was not observed. Use of the model drift algorithm did not result in the correct distribution of oiling on Folley's Island. The assumption of 3.5% of wind speed and 0^o angle provided the best overall fit to the shoreline oiling observations.

The case where all the oil was assumed released instantaneously at the submerged dredge site does not fit the observations at all (Figure F.3-7). The river currents are not sufficiently strong to move the oil down into the harbor and to outside coastal areas by the time it was observed there. A similar pattern (absence of oil in the lower harbor and offshore) would result if oil were released only at and up-river of the submerged dredge in the model.

Appendix F.4 shows the surface distribution of oil. For slicks on the water surface, 1 μm ~ 1 g/m^2. Table 4-1 gives approximate thickness ranges for surface oil of varying appearance. Dull brown sheens are about 1 g/m^2 thick. Rainbow sheen is about 200-800 mg/m^2 and silver sheens are 50-800 mg/m^2 thick (NRC, 1985). Crude and heavy fuel oil > 1mm thick appears as black oil. Floating oil will not always have these appearances, however, as weathered oil would be in the form of scattered floating tar balls and tar mats where currents converge.

Table 4-1. Oil thickness (microns ~ g/m^2) and appearance on water (NRC, 1985).

Minimum	Maximum	Appearance
0.05	0.2	Colorless and silver sheen
0.2	0.8	Rainbow sheen
1	4	Dull brown sheen
10	100	Dark brown sheen
1000	10000	Black oil

Figure F.4-1 shows the maximum amount of surface oil (g/m^2) passing through each model grid cell at any time after the spill, averaged over the area of the grid cell. As indicated in Section 2.2, the threshold for impacts to wildlife is 10 μm (10 g/m^2). Note that the evaluation of surface oil impacts is made using the output of the fates model that retains the patchy and time-varying oil distribution information. The map of mean g/m^2 of floating oil in each grid cell (Figure F.4-1) only provides a summary of the path of the oil for illustrative purposes.

Subsurface concentrations of oil hydrocarbons and dissolved aromatics did not exceed 1 ppb in any water volume >140 m^3 (the resolution of the model grid for the subsurface plume) at any time after the spill. Focused runs with this high resolution were made to evaluate the potential for toxic concentrations to occur in the top 1m of the water column. The thinnest layer examined was the top 0.2m of the water column, just under the floating oil. No concentrations exceeding 1 ppb were estimated for any cell of horizontal dimension 20m by 35m. The mass balance (Table F-2 in Appendix F.1) shows that the amount of soluble aromatics dissolved during the spill was very small, much less than 1% of the total soluble (and volatile) aromatic fraction. Most of the soluble/volatile aromatics evaporated from the floating oil on the water surface and off the oiled shorelines. Thus, the exposure to water column and bottom-dwelling organisms in subtidal habitats was not significant and no acute toxicity induced impacts to these organisms would be expected.

5. ASSESSMENT OF INJURIES

5.1 Wildlife

Appendix B.4 contains a table summarizing the oiled birds observed in the field after the spill. A total of 18-23 brown pelicans were observed moderately or heavily oiled, with 30 other pelicans showing spots or oil stain. Tri-State treated 21 of the oiled pelicans (1 adult and 20 juveniles) and released them. Other oiled birds observed were: 1 great blue heron, several egrets, 1 double-crested cormorant, and 15 ruddy turnstones.

Table 5-1 lists the model-estimated impacts to wildlife for the best fates model simulation, along with the observed oiled birds. The estimated numbers are probabilities, and thus may be fractions of an animal. The majority of the 99 estimated killed birds are brown pelicans (75) and black skimmers (7). Others estimated oiled are 3.4 terns, 3.3 gulls, 1 cormorant, 1 wading bird, 9 shorebirds and 0.1 osprey. The number of oiled pelicans estimated by the model is 75, as opposed to the 48-53 observed. This difference is in part accounted for in that the model estimates injuries to pelicans that are distributed around the harbor and in the rivers, and not just those concentrated in areas of heavy oiling at Crab Bank (which were the ones observed). The colony at Crab Bank was explicitly modeled, and 70 birds were estimated oiled there, in addition to 5 pelicans distributed around the area. Oiled skimmers, terns, and shorebirds would be unlikely to be observed or captured for cleaning. Note that if the pre-spill abundance were, for example, a factor two different, the model kill estimate would change by that same factor. Thus, the model estimates and the field data agree within the uncertainty of both estimates.

The estimate of sea turtle injury is 0.12 adult (loggerhead) turtles, and is therefore not significant. Sea turtles of any age group would be very unlikely to be impacted by a spill in this location and no oiled sea turtles were observed.

Cetaceans (dolphins), while in the area impacted by the spill, were estimated to have a very low probability of oiling in the model simulations. The model results include <0.005 dolphin. This result is a probability and as no marine mammals were observed affected by the spill, the injury to marine mammals is assumed zero.

Tables 5-2 and 5-3 list the model results for all the scenarios run. It may be seen that the seabird and osprey (0.1 bird) injuries are not sensitive to the variation in the horizontal diffusion coefficient. However, the amount of shoreline oiling and the resulting wader and shorebird injuries vary with the horizontal diffusion coefficient. As the value used for the best simulation gives agreement with the observed shoreline oiling, the results in Table 5-1 are the best estimates. The injuries are somewhat sensitive to the model drift, but again, the best simulation is that that best fits the shore oiling observations.

After performing the modeling, it was recognized that 1 great blue heron, 3 great egrets and 15 ruddy turnstones were observed oiled, but the model estimates were much lower than this (Tables 5-1 to 5-3), likely due to underestimation of the pre-spill abundance. Thus, the actual injury was at least these values. In recognition that not all oiled birds would have been observed after the spill, the likely number of birds of these species oiled was higher. We assume a multiplier of 4 times the observed oiled birds to estimate total oiled birds of these species. Thus, the final injury estimates of great blue heron, great egrets, and ruddy turnstones are 4, 12, and 60, respectively, as reflected in Tables S-1 and S-2 of the summary section. Thus, the estimated numbers of birds oiled in the spill are as listed in Tables S-1 and S-2. The results in Table S-2 are repeated in Table 5-4, along with the estimates of the interim loss.

The interim loss was estimated using the methods described in Section 2.5. The direct loss, indirect loss of fledglings, and total interim loss, as bird-years per bird killed, are discounted in future years at 3% annually and represent mixed age classes. The total lost bird years of mixed ages is the bird-years per bird killed times the number killed. The number of fledgling equivalents are calculated in order to express the injury in a single age class, that most likely to be used to scale the restoration. The number of fledglings needed for compensation of the spill's injuries is given in year 2002 numbers (assuming restoration were to occur in that year of the spill) and in year 2006 numbers (the appropriate number if the restoration were in 2006. The appropriate number to use in the scaling is that used as the units for the restoration scale calculation.

Table 5-1. Estimated injuries to birds, marine mammals and sea turtles for the best simulation of the spill. The model estimate is a probability, and thus may be a fraction of an animal. Observations of oiled birds are also listed for comparison.

Species	Model (#)	Observed (#)
Canada goose	0.01	
Hooded merganser	0.05	
Mallard	0	
Black skimmer	7.28	
Black tern	0.61	
Bonaparte's gull	0.00	
Brown pelican	75.20	48-53
Caspian tern	0.16	
Common tern	2.04	
Double-crested cormorant	1.07	1
Forster's tern	0.04	
Gull-billed tern	0.47	
Herring gull	0.10	
Laughing gull	0.56	
Least tern	0.04	
Ring-billed gull	2.60	
Royal tern	0.05	
Sandwich tern	0.01	
Black-crowned night-heron	0.02	
Clapper rails	0.05	
Great egret	0.19	Several (3)
Great blue heron	0.04	1
Green heron	0.16	
Little blue heron	0.01	
Tricolored heron	0.07	
Snowy egret	0.05	
Wood stork	0.03	
Yellow-crowned night-heron	0.00	
Am. oystercatcher	0.91	
Black-bellied plover	0.35	
Dunlin	0.99	
Greater yellowlegs	0.02	
Marbled godwit	0.37	
Piping plover	0.00	
Ruddy turnstone	0.20	15
Semipalm. sandpiper	0.00	
Semipalmated plover	2.44	
Short-billed dowitcher	2.99	
Willet	0.71	

Species	Model (#)	Observed (#)
Bald eagle	0.01	
Osprey	0.13	
Bottlenose Dolphin	0.00	
Striped dolphin	0.00	
Loggerhead turtle	0.12	
Ridley turtle	0.00	
Group Totals:		
Waterfowl	0.06	-
Seabirds	89.24	49-54
Wading birds	0.61	approx. 4
Shorebirds	8.98	15
Raptors	0.14	-
Marine mammals (dolphins)	0	-
Sea turtles	0.12	-
Total birds	**99.15**	**68-73**

Table 5-2. Total oiled wildlife (#) by category in alternate scenario runs performed in the sensitivity analysis. The best simulation is that with 3.5% of wind speed, 0^o angle, and horizontal diffusion of 1.0 m^2/sec.

Wind Drift	**3.5%, 0^o**	**3.5%, 0^o**	**3.5%, 0^o**	**3.5%, 0^o**	**Model calculated**	**Model calculated**
Horizontal Diffusion	**1.0 m^2/s**	**10.0 m^2/s**	**5.0 m^2/s**	**0.1 m^2/s**	**1.0 m^2/s**	**10.0 m^2/s**
Waterfowl	0.06	0.06	0.06	0.06	0.05	0.05
Seabirds	89.24	89.96	90.65	90.15	87.61	86.80
Wading birds	0.61	0.86	0.90	0.40	0.75	0.88
Shorebirds	8.98	12.62	13.13	5.85	10.95	12.8
Raptors	0.14	0.14	0.14	0.12	0.15	0.14
Cetaceans	0.00	0.00	0.00	0.00	0.00	0.00
Sea turtles	0.12	0.12	0.12	0.12	0.09	0.09

Table 5-3. Estimated oiled wildlife (#) by species in alternate scenario runs performed in the sensitivity analysis. The best simulation is that with 3.5% of wind speed, 0^o angle, and horizontal diffusion of 1.0 m^2/sec. [In the species name, lwd indicates the landward density, and swd indicates the seaward density.]

Wind Drift	**3.5%, 0^o**	**3.5%, 0^o**	**3.5%, 0^o**	**3.5%, 0^o**	**Model calculated**	**Model calculated**
Horizontal Diffusion	**1.0 m^2/s**	**10.0 m^2/s**	**5.0 m^2/s**	**0.1 m^2/s**	**1.0 m^2/s**	**10.0 m^2/s**
Canada goose	0.01	0.01	0.02	0.01	0.02	0.01
Hooded merganser	0.05	0.05	0.05	0.05	0.04	0.04
Mallard	0.00	0.00	0.00	0.00	0.00	0.00
Black skimmer, lwd	0.47	0.47	0.50	0.46	0.53	0.46
Black skimmer, swd	6.81	6.68	6.86	6.82	5.20	5.25
Black tern	0.61	0.60	0.61	0.61	0.47	0.47
Bonaparte’s gull	0.00	0.00	0.00	0.00	0.00	0.00
Brown pelican, Crab Bank	70.00	70.00	70.00	70.00	70.00	70.00
Brown pelican, lwd	3.81	3.80	4.00	3.74	4.29	3.70
Brown pelican, swd	1.39	1.36	1.40	1.39	1.06	1.07
Caspian tern	0.16	0.15	0.16	0.16	0.12	0.12
Common tern	2.04	2.01	2.06	2.04	1.58	1.59
Double-crested cormorant lwd	1.06	1.06	1.12	1.04	1.20	1.03
Double-crested cormorant swd	0.01	0.01	0.01	0.01	0.01	0.01
Forster's tern, lwd	0.03	0.03	0.03	0.03	0.04	0.03
Forster's tern, swd	0.01	0.01	0.01	0.01	0.01	0.01
Gull-billed tern	0.47	0.46	0.47	0.47	0.36	0.36
Herring gull	0.1	0.10	0.10	0.10	0.08	0.08
Laughing gull, lwd	0.32	0.32	0.34	0.32	0.37	0.31
Laughing gull, swd	0.24	0.24	0.25	0.24	0.19	0.19
Least tern, lwd	0.04	0.04	0.04	0.04	0.04	0.03
Ring-billed gull	2.6	2.56	2.63	2.60	2.02	2.03
Royal tern, lwd	0.04	0.04	0.04	0.04	0.05	0.04
Royal tern, swd	0.01	0.01	0.01	0.01	0.01	0.01
Sandwich tern, swd	0.01	0.01	0.01	0.01	0.01	0.01
Black-crowned night-heron	0.02	0.03	0.03	0.01	0.02	0.03

Wind Drift	3.5%, 0°	3.5%, 0°	3.5%, 0°	3.5%, 0°	Model calculated	Model calculated
Horizontal Diffusion	**1.0 m^2/s**	**10.0 m^2/s**	**5.0 m^2/s**	**0.1 m^2/s**	**1.0 m^2/s**	**10.0 m^2/s**
Clapper rails	0.05	0.07	0.07	0.03	0.06	0.07
Great egret	0.19	0.27	0.28	0.12	0.23	0.27
Great blue heron	0.04	0.06	0.06	0.03	0.05	0.06
Green heron	0.16	0.22	0.23	0.10	0.19	0.22
Little blue heron	0.01	0.01	0.01	0.00	0.01	0.01
Tricolored heron	0.07	0.09	0.10	0.04	0.08	0.09
Snowy egret	0.05	0.08	0.08	0.04	0.07	0.08
Wood stork	0.03	0.04	0.04	0.02	0.03	0.04
Yellow-crowned night-heron	0	0.01	0.01	0.00	0.00	0.01
Am. oystercatcher	0.91	1.27	1.32	0.59	1.10	1.29
Black-bellied plover	0.35	0.50	0.52	0.23	0.43	0.51
Dunlin	0.99	1.38	1.44	0.64	1.20	1.40
Greater yellowlegs	0.02	0.03	0.03	0.01	0.02	0.03
Marbled godwit	0.37	0.53	0.55	0.24	0.46	0.53
Piping plover	0	0.00	0.00	0.00	0.00	0.00
Ruddy turnstone	0.2	0.28	0.29	0.13	0.24	0.28
Semipalm. sandpiper	0	0.00	0.00	0.00	0.00	0.00
Semipalmated plover	2.44	3.43	3.57	1.59	2.98	3.48
Short-billed dowitcher	2.99	4.21	4.38	1.95	3.65	4.27
Willet	0.71	1.00	1.04	0.46	0.86	1.01
Bald eagle	0.01	0.01	0.01	0.01	0.01	0.01
Osprey	0.13	0.13	0.14	0.12	0.14	0.13
Bottlenose Dolphin	0	0.00	0.00	0.00	0.00	0.00
Striped dolphin	0	0.00	0.00	0.00	0.00	0.00
Loggerhead turtle	0.12	0.12	0.12	0.12	0.09	0.09
Ridley turtle	0	0.00	0.00	0.00	0.00	0.00

Table 5-4. Estimated total birds killed by oil and interim loss calculations (based on the methods described in Section 2.5).

Measure of Interim Loss	Waterfowl	Seabirds	Wading Birds	Shorebirds	Raptors
Direct kill by oiling (#)	0.06	89.24	16.38	68.78	0.14
Direct loss of bird-years/bird killed (discounted) (D_L/ $N_{i,0}$)	0.91	4.01	1.59	3.32	3.63
Lost fledgling production: Bird-years/bird killed (discounted) (F_L/ $N_{i,0}$)	0.11	2.23	0.30	4.41	3.36
Total bird-years/bird killed (of mixed ages, discounted) (T_L/ $N_{i,0}$)	1.02	6.23	1.89	7.72	6.99
Bird-years/fledgling (discounted) (F_G)	0.49	1.45	0.86	2.04	1.81
Number of fledglings to restore per bird killed (fledgling equivalents of a killed bird) (F_P/ $N_{i,0}$)	2.07	4.31	2.18	3.78	3.86
Total lost bird-years (of mixed ages) (T_L)	0.06	556	30.9	531	2.4
Number of fledgling equivalents (F_P, # fledglings to be restored, assumed in 2002)	0.12	384	35.8	260	1.3
Number of fledgling equivalents (# of fledglings to be restored, assumed in 2006)	0.14	433	40.3	293	1.5

5.2 Fish and Invertebrates in Subtidal Habitats

Table 5-5 lists the losses of fish and invertebrates for the best, as well as alternate, simulation(s) of the spill. Losses include the direct kill plus the calculated production foregone, which is the future growth of the killed animals, had there not been a spill. In the simulation for this case, the concentrations of toxic aromatics in the water and sediments did not exceed thresholds for effects. Thus, there are no fish or invertebrate injuries.

Table 5-5. Estimate of injury to fish and invertebrates.

Fishery species	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Total small pelagic fish	0	0	0	0
Total large pelagic fish	0	0	0	0
Total demersal fish	0	0	0	0
Total demersal invertebrates	0	0	0	0
Total mollusks	0	0	0	0
Total all species	0	0	0	0

5.3 Intertidal Habitats

Tables 5-6 and 5-7 list the areas of intertidal habitat oiled to varying degrees in the (best) model simulation. The threshold 0.1 mm (~100 g/m^2) is the minimum (dose) in the model for impact to waders and shorebirds in the intertidal areas. Mortality of the vegetation in marshes occurs above about 14 mm of oil, according to literature reviewed in French et al. (1996a). In the model simulation, none of the wetlands exceeded 14 mm thick oil. Figure 5-1 shows the areas oiled. Over-laid on the map are locations of oyster reefs along the Cooper River, in Charleston Harbor, and near Folly Beach.

When the majority of the oil mass came ashore, 95% of the PAHs remained in the oil. Thus, the PAH content of the shoreline oil was about 2% of total hydrocarbons. This infers 1 g/m^2 of total hydrocarbons on the shoreline is equivalent to about 20 mg PAH/m^2. Assuming the oil was mixed into the top 1 cm of sediment, 1 g/m^2 of total hydrocarbons (THC) on the shoreline is equivalent to 10^{-4} g THC/cm^3 of wet sediment. Assuming a sediment porosity of 40% (i.e., 40% water and 60% sediment) and a sediment dry weight of 2.6 g/cm^3, 1 cm^3 of wet sediment contains 1.56 g dry sediment. Thus, 1 g THC/m^2 is equivalent to 64 μg THC/g of dry sediment (64 ppm). The PAH concentration in dry sediment that is equivalent to 1 g THC/m^2 is 1.3 μg PAH/g dry sediment (1.3 ppm). The intertidal contamination predicted by the model can be broadly compared to observations based on sampling. However, detailed comparisons to sample stations are inappropriate, as the model's resolution does not address the patchy nature of the actual contamination on shore.

Table 5-6. Area (m^2) of intertidal zone, by shore type, contaminated by oil of various thicknesses (1 mm thick oil ~ 1000 g/m^2 ~64 ppm total hydrocarbons, THC, ~ 1300 ppm of PAH) in the best model simulation.

Total Hydrocarbons	**>1000 g/m^2**	**>100 g/m^2**	**>10 g/m^2**	**> 1 g/m^2**	**>0.1 g/m^2**
Oil Thickness	**>1 mm**	**>0.1 mm**	**>0.01 mm**	**>0.001 mm**	**>0.0001 mm**
THC concentration (µg TPH/g dry sediment)	**> 64 mg/g**	**> 6400 µg/g**	**> 640 µg/g**	**> 64. µg/g**	**> 6.4 µg/m^2**
PAH concentration (ppm)	**> 1300 ppm**	**> 130 ppm**	**> 13 ppm**	**> 1.3 ppm**	**> 0.13 ppm**
PAH concentration (µg PAH/g dry sediment)	**> 1300 µg/g**	**> 130 µg/g**	**> 13 µg/g**	**> 1.3 µg/g**	**> 0.13 µg/m^2**
Shore Type:					
Rocky shoreline	140	2,737	2,737	2,737	2,737
Gravel beach	211	772	772	772	772
Sand beach	702	6,317	6,317	6,317	6,317
Mud flat	702	2,456	2,456	2,456	2,456
Wetland	772	2,737	2,737	2,737	2,737
Oyster reef	0	2,035	2,035	2,035	2,035
Artificial shoreline	2,527	6,387	6,387	6,387	6,387
Total	5,053	23,442	23,442	23,442	23,442

Table 5-6. Area (acres) of intertidal zone, by shore type, contaminated by oil of various thicknesses (1 mm thick oil ~ 1000 g/m^2 ~64 ppm total hydrocarbons, THC, ~ 1300 ppm of PAH) in the best model simulation.

Total Hydrocarbons	**>1000 g/m^2**	**>100 g/m^2**	**>10 g/m^2**	**> 1 g/m^2**	**>0.1 g/m^2**
Oil Thickness	**>1 mm**	**>0.1 mm**	**>0.01 mm**	**>0.001 mm**	**>0.0001 mm**
THC concentration (µg TPH/g dry sediment)	**> 64 mg/g**	**> 6400 µg/g**	**> 640 µg/g**	**> 64. µg/g**	**> 6.4 µg/m^2**
PAH concentration (ppm)	**> 1300 ppm**	**> 130 ppm**	**> 13 ppm**	**> 1.3 ppm**	**> 0.13 ppm**
PAH concentration (µg PAH/g dry sediment)	**> 1300 µg/g**	**> 130 µg/g**	**> 13 µg/g**	**> 1.3 µg/g**	**> 0.13 µg/m^2**
Shore Type:					
Rocky shoreline	0.03	0.68	0.68	0.68	0.68
Gravel beach	0.05	0.19	0.19	0.19	0.19
Sand beach	0.17	1.56	1.56	1.56	1.56
Mud flat	0.17	0.61	0.61	0.61	0.61
Wetland	0.19	0.68	0.68	0.68	0.68
Oyster reef	0.00	0.50	0.50	0.50	0.50
Artificial shoreline	0.62	1.58	1.58	1.58	1.58
Total	1.25	5.79	5.79	5.79	5.79

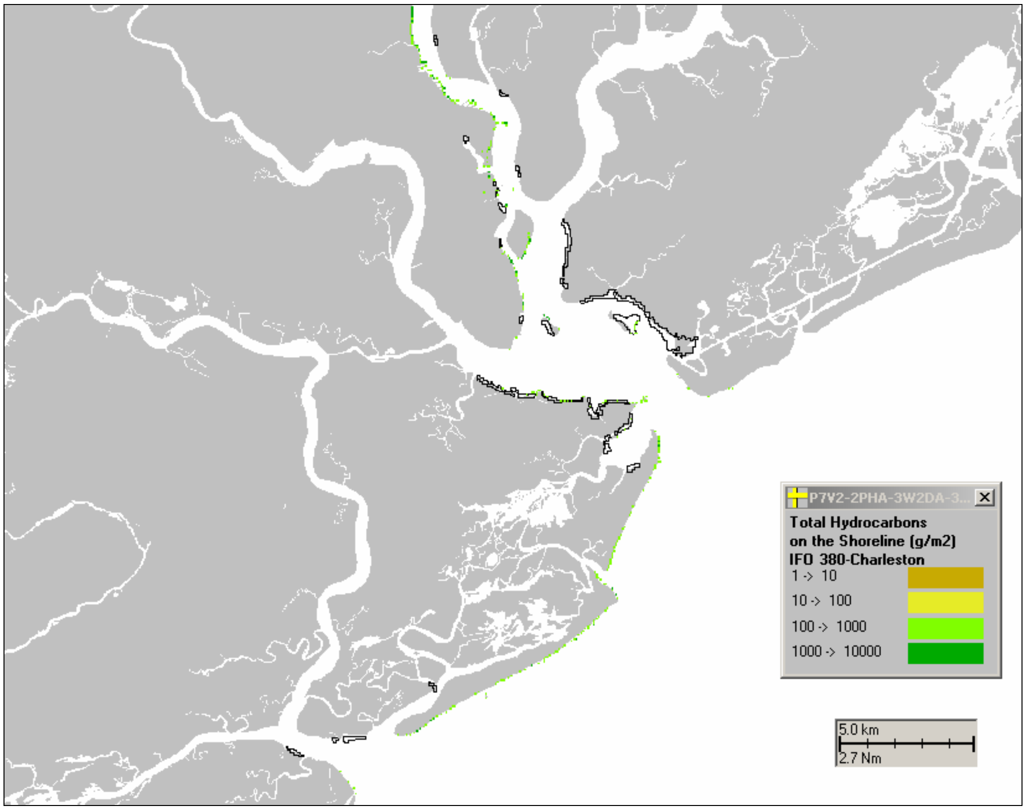

Figure 5-1. Total hydrocarbons on shorelines predicted by the (best) model simulation. The polygons over-laid on the map are locations of oyster reefs along the Cooper River, in Charleston Harbor, and near Folly Beach.

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APPENDIX A: GEOGRAPHICAL DATA AND MAPS

This appendix contains maps of the areas affected by the spill and the model habitat and depth grids used in the simulations.

A.1 Maps of the Vicinity of the Spill

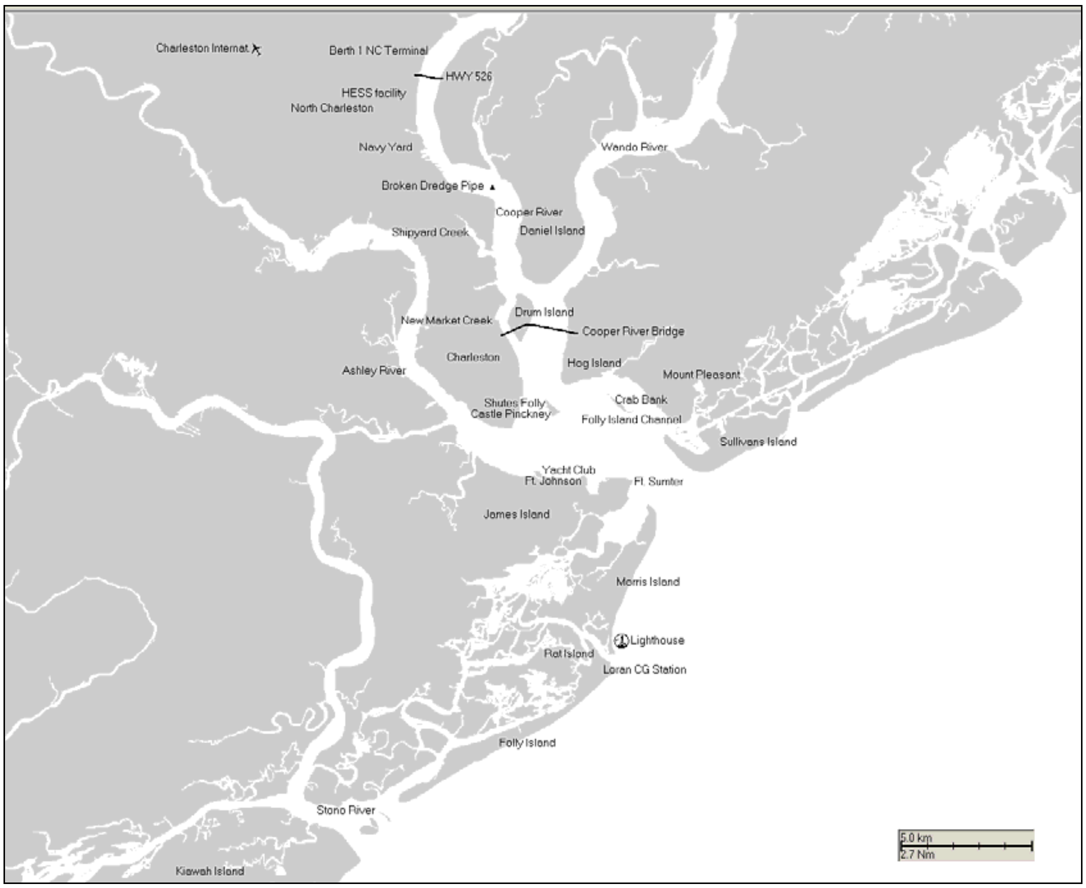

Figure A.1-1. Map of Charleston Harbor and its surrounding vicinity.

Figure A.1-2. Closer view of Charleston Harbor including areas that were impacted by the spill.

A.2 Gridded Habitat Mapping

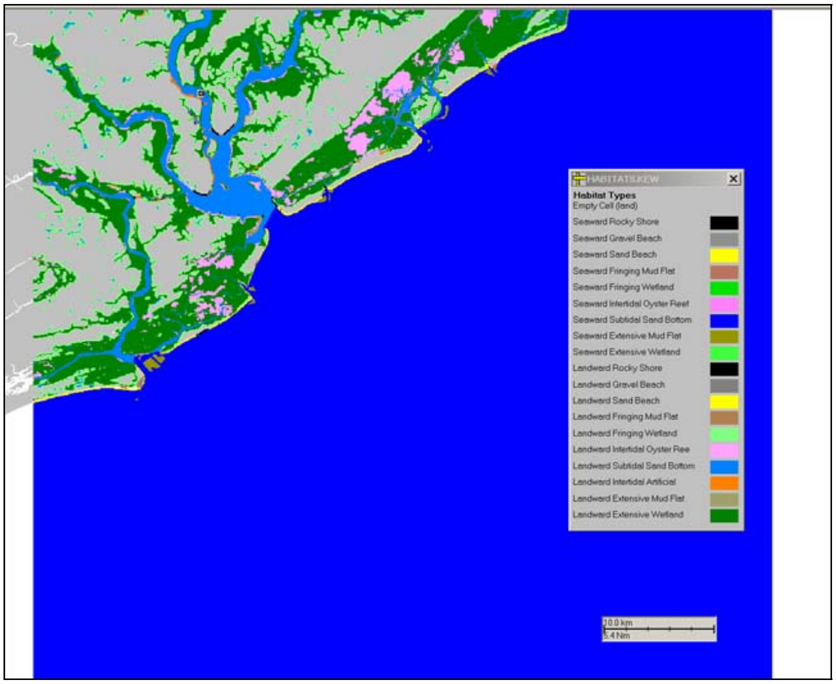

Figure A.2-1. Habitat grid used in modeling (full view).

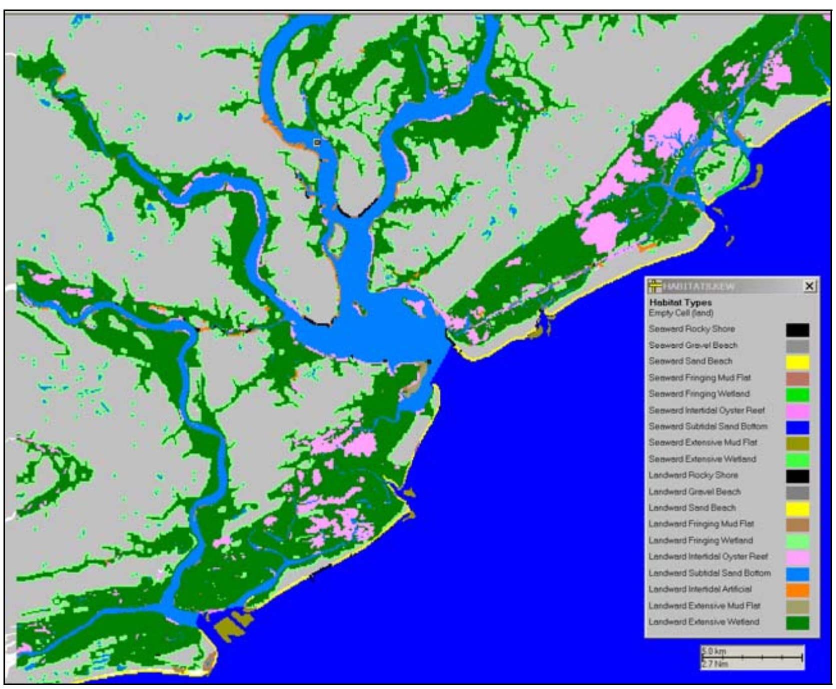

Figure A.2-2. Closer view of habitat grid used in modeling.

The location and dimensions of habitat grid are listed in Table A.2-1.

Table A.2-1. Location and dimensions of the habitat grid cells.

Characteristic	**Value**
Grid W edge (^{o}longitude)	80.100853 ^{o}W
Grid S edge (^{o}latitude)	32.367374 ^{o}N
Cell size (^{o}longitude)	0.000688
Cell size (^{o}latitude)	0.000688
Cell size (m) west-east	64.50
Cell size (m) south-north	76.37
# cells west-east	1,094
# cells south-north	807
Water cell area (m^2)	4,926
Shore cell length (m)	70.2
Shore cell width	1.0

A.3 Gridded Water Depth Data

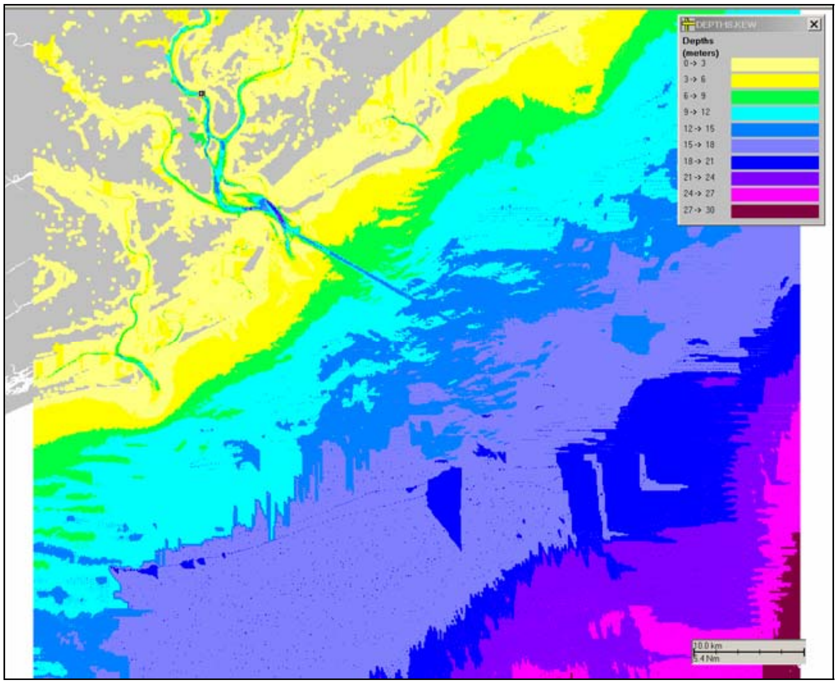

Figure A.3-1. Depth grid used in modeling (full view).

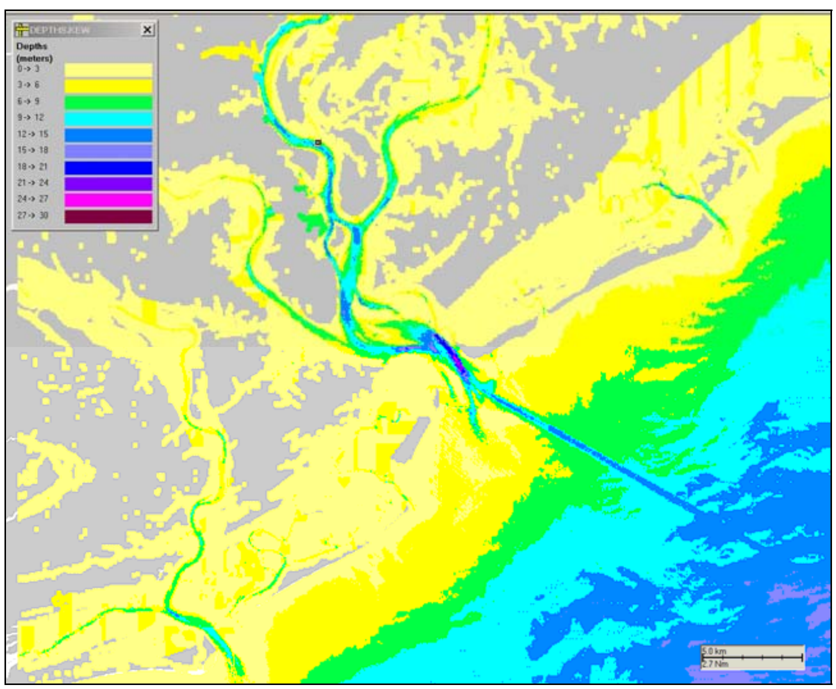

Figure A.3-2. Closer view of depth grid used in modeling.

APPENDIX B: OBSERVATIONS OF OIL CONTAMINATION AND RESPONSE ACTIVITIES

B.1 Observations of Oil Movements

The figures in this appendix are summaries of over-flights made by NOAA HAZMAT (2002), which were made the mornings of 2,3 and 4 October 2002. The over-flights depicted shoreline oiling, oil slicks on the water surface, and some subsurface oil.

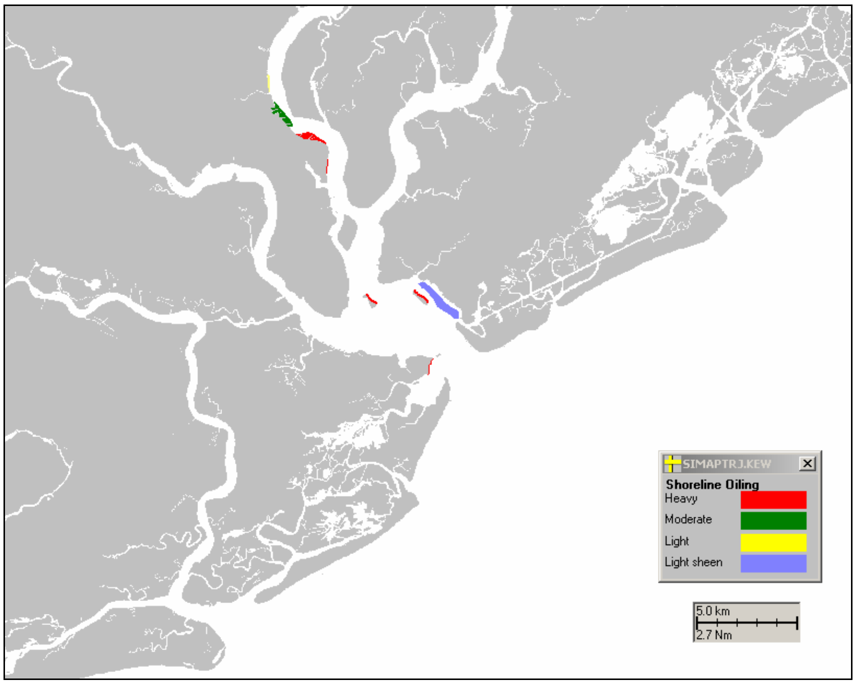

Figure B.1-1. Overflight for 2 October 2002 for 07:30 – 09:00 hours.

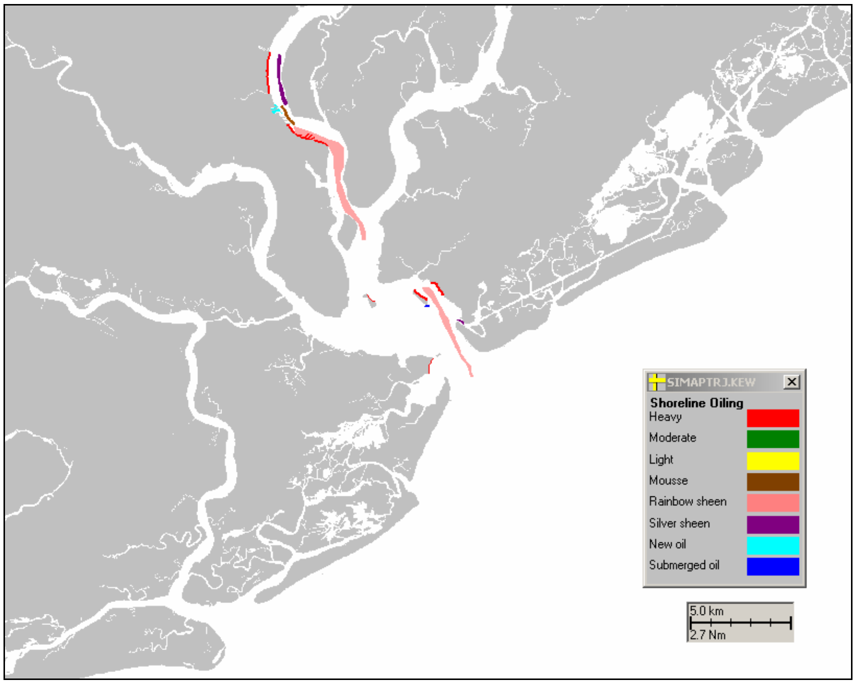

Figure B.1-2. Overflight for 3 October 2002 for 08:00 – 09:00 hours.

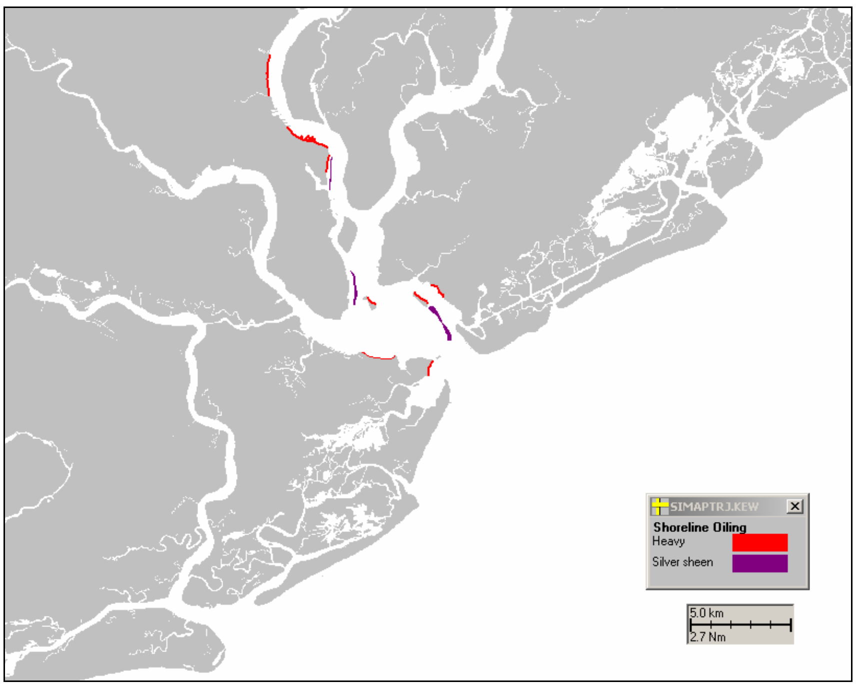

Figure B.1-3. Overflight for 4 October 2002 for 09:00 – 10:30 hours.

B.2 Shoreline Contamination

The figures in this appendix are of shoreline oiling, based on SCAT observations and data from the updated Preassessment Data Report (Polaris, 2004).

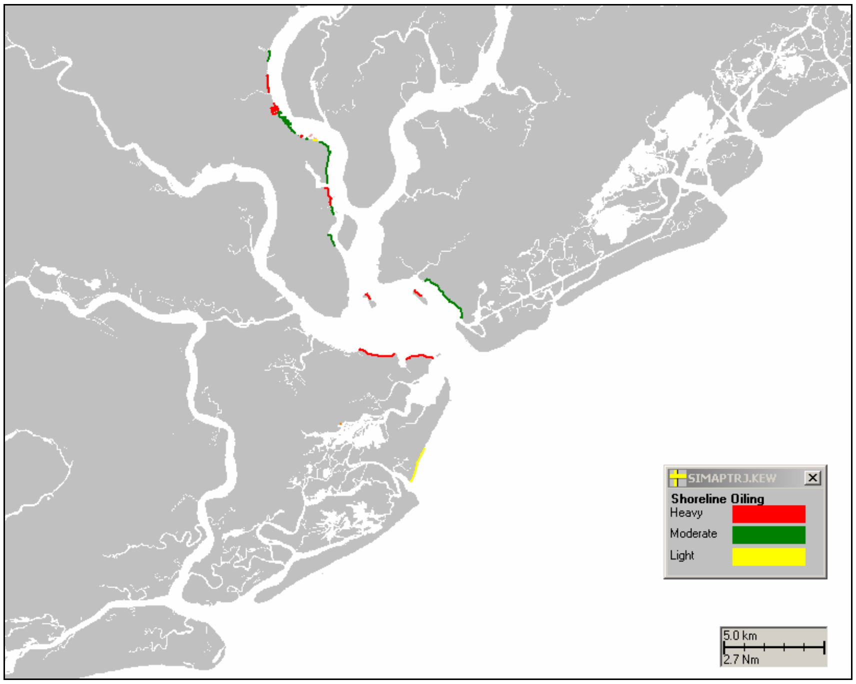

Figure B.2-1. SCAT observations for 2 October 2002.

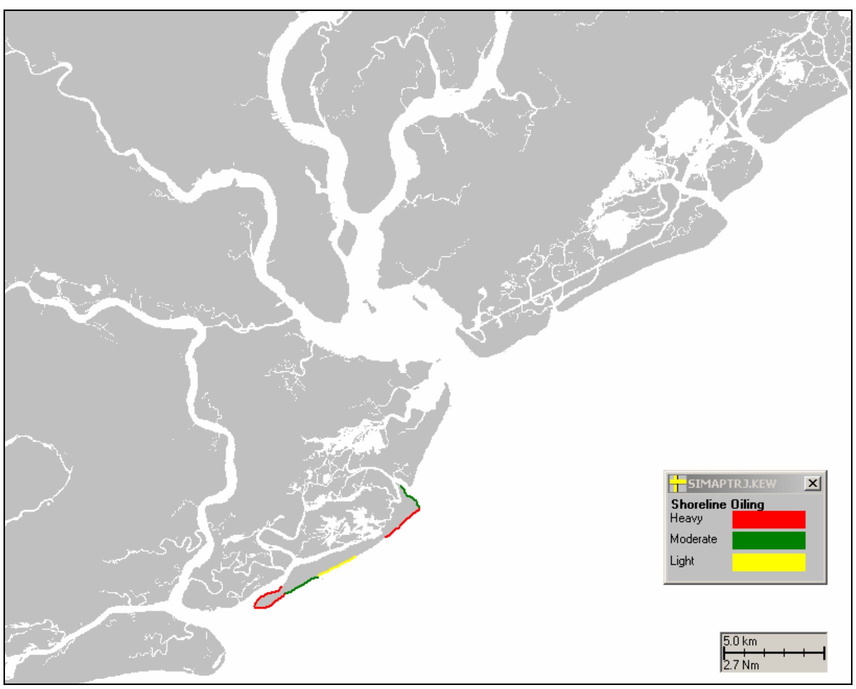

Figure B.2-2. SCAT observations for 3 October 2002.

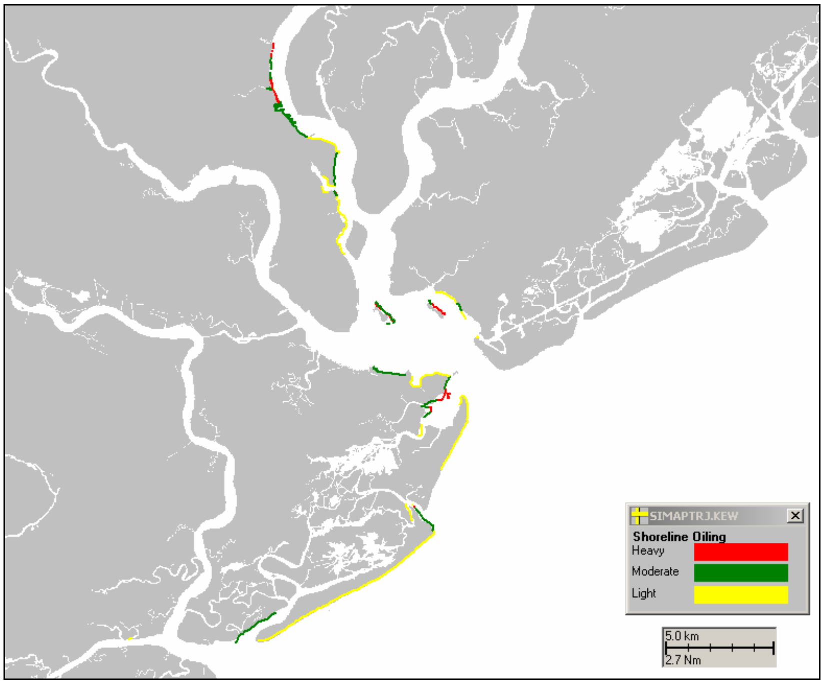

Figure B.2-3. Composite of shoreline oiling from updated data provided by Polaris 2004.

B.3 Sediment Contamination

Sediment samples were taken by South Carolina Department of Natural Resources (SCDNR) in October 2002, following the oil spill. Figure B.2-3 is a map of sampling locations and differentiates those locations for which PAH analyses were conducted.

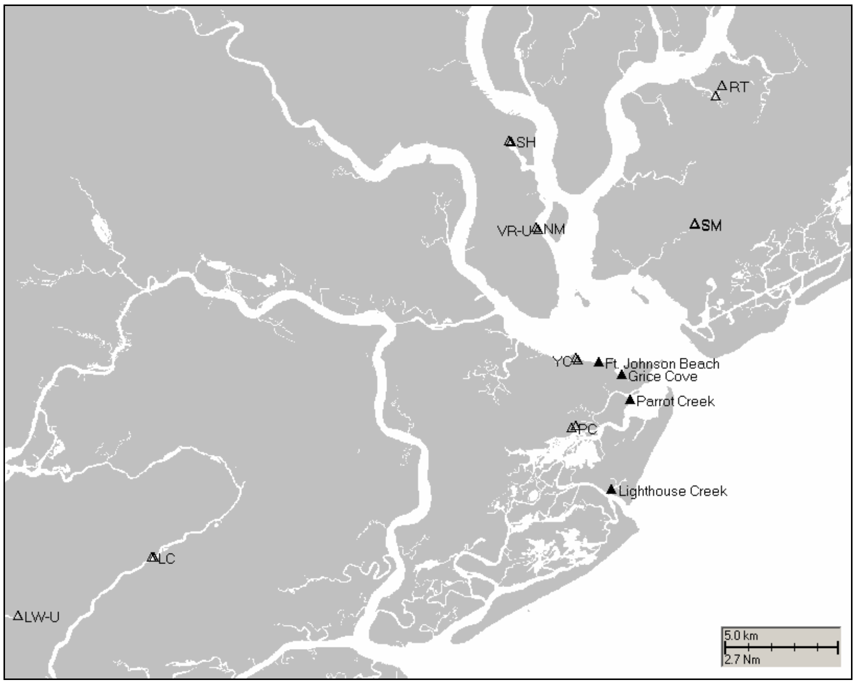

Figure B.2-3. SCDNR sediment sample locations and analyzed samples for October 2002. Open triangles indicate sites where no chemical analyses occurred, and closed triangles indicate PAH analyses.

B.4 Oiled Birds

Table B.4-1. Oiled birds observed after the spill. Of the pelicans oiled, 21 were treated by Tri-State.

Species Observed	# Oiled Birds Observed	Location Where Observed	Degree of oiling	Field Notes on Abundance
Brown pelicans	15-20	Crab Bank	moderately to heavily oiled	Total of ~200 brown pelicans noted on Crab Bank
Brown pelicans	30	Crab Bank	spots or stains of oil	
Brown pelicans	3	Hog Island	moderately oiled	Total of 10 pelicans observed on Hog Island
Great blue heron	2	Sullivan's Island to Shem's Creek	small smudges of oil	
Egrets	several	Sullivan's Island to Shem's Creek	small smudges of oil	
Wood stork				1 clean bird observed
Cormorant	1	Hog Island		
Ruddy turnstones	15	Sullivan's Island	15 with some oil: 1 heavily oiled, others with spotty or light oiling	75 birds observed on Sullivan's Island
Dowitchers				60 clean birds observed around piers
Boat-tailed grackle	1	Pier P	Oiled (treated and released)	

APPENDIX C: HOURLY WIND SPEED AND DIRECTION AT AND AFTER THE TIME OF THE SPILL

Hourly wind speed and direction data were compiled from 2 stations in the vicinity of the spill-affected area. The data are listed in the following tables.

Table C-1. Wind data from National Data Buoy Center for buoy off of Folly Beach.

Source:
(http://www.ndbc.noaa.gov/station_page.phtml?station=fbis1)
NOAA NDBC Station, Station FBIS1 - Folly Beach, SC
C-MAN station
32.68°N 79.89°W

Year	Month	Day	Hour	Direction	Speed (m/s)
2002	9	30	0	87	16
2002	9	30	1	85	16
2002	9	30	2	41	10
2002	9	30	3	32	11
2002	9	30	4	30	12
2002	9	30	5	16	11
2002	9	30	6	31	15
2002	9	30	7	32	14
2002	9	30	8	31	14
2002	9	30	9	31	13
2002	9	30	10	47	14
2002	9	30	11	55	16
2002	9	30	12	64	17
2002	9	30	13	63	18
2002	9	30	14	67	19
2002	9	30	15	97	17
2002	9	30	16	95	15
2002	9	30	17	104	16
2002	9	30	18	115	14
2002	9	30	19	103	12
2002	9	30	20	111	12
2002	9	30	21	91	10
2002	9	30	22	87	8
2002	9	30	23	98	12
2002	10	1	0	86	10
2002	10	1	1	106	13
2002	10	1	2	83	11
2002	10	1	3	93	11
2002	10	1	4	101	14
2002	10	1	5	102	13
2002	10	1	6	103	11
2002	10	1	7	23	10

2002	10	1	8	33	10
2002	10	1	9	40	9
2002	10	1	10	55	10
2002	10	1	11	71	10
2002	10	1	12	89	15
2002	10	1	13	99	12
2002	10	1	14	97	10
2002	10	1	15	98	11
2002	10	1	16	93	9
2002	10	1	17	91	9
2002	10	1	18	98	10
2002	10	1	19	94	10
2002	10	1	20	101	10
2002	10	1	21	106	10
2002	10	1	22	101	9
2002	10	1	23	105	8
2002	10	2	0	95	8
2002	10	2	1	98	9
2002	10	2	2	100	9
2002	10	2	3	93	7
2002	10	2	5	22	6
2002	10	2	6	2	5
2002	10	2	7	40	9
2002	10	2	8	39	9
2002	10	2	9	52	9
2002	10	2	10	73	9
2002	10	2	11	87	7
2002	10	2	12	82	7
2002	10	2	13	99	6
2002	10	2	14	117	7
2002	10	2	15	130	7
2002	10	2	16	132	9
2002	10	2	17	130	8
2002	10	2	18	124	8
2002	10	2	19	117	8
2002	10	2	20	138	7
2002	10	2	21	144	6
2002	10	2	22	168	5
2002	10	2	23	174	4
2002	10	3	0	186	3
2002	10	3	1	301	2
2002	10	3	2	323	2
2002	10	3	3	352	3
2002	10	3	4	3	3
2002	10	3	5	349	4
2002	10	3	6	351	4
2002	10	3	7	342	3
2002	10	3	8	346	4
2002	10	3	9	353	4
2002	10	3	10	43	4

2002	10	3	11	85	3
2002	10	3	12	148	4
2002	10	3	13	178	4
2002	10	3	14	202	5
2002	10	3	15	210	6
2002	10	3	16	212	7
2002	10	3	17	214	4
2002	10	3	18	190	4
2002	10	3	19	174	4
2002	10	3	20	253	2
2002	10	3	21	194	4
2002	10	3	22	200	3
2002	10	3	23	283	2
2002	10	4	0	229	2
2002	10	4	1	219	2
2002	10	4	2	297	3
2002	10	4	3	331	3
2002	10	4	4	305	3
2002	10	4	5	331	2
2002	10	4	6	344	4
2002	10	4	7	346	3
2002	10	4	8	2	7
2002	10	4	9	3	3
2002	10	4	10	53	4
2002	10	4	11	96	3
2002	10	4	12	131	6
2002	10	4	13	138	6
2002	10	4	14	147	5
2002	10	4	15	155	6
2002	10	4	16	189	5
2002	10	4	17	178	7
2002	10	4	18	194	8
2002	10	4	19	198	7
2002	10	4	20	204	8
2002	10	4	21	210	10
2002	10	4	22	229	9
2002	10	4	23	210	10
2002	10	5	0	219	9
2002	10	5	1	237	10
2002	10	5	2	240	8
2002	10	5	3	243	7
2002	10	5	4	258	5
2002	10	5	5	282	3
2002	10	5	6	277	5
2002	10	5	7	270	5
2002	10	5	8	272	6
2002	10	5	9	266	8
2002	10	5	10	296	6
2002	10	5	11	331	7
2002	10	5	12	348	3

2002	10	5	13	143	4
2002	10	5	14	210	10
2002	10	5	15	224	12
2002	10	5	16	221	11
2002	10	5	17	224	11
2002	10	5	18	240	9
2002	10	5	19	220	10
2002	10	5	20	249	6
2002	10	5	21	215	7
2002	10	5	22	235	10
2002	10	5	23	242	9
2002	10	6	0	248	6
2002	10	6	1	246	8
2002	10	6	2	257	4
2002	10	6	3	262	4
2002	10	6	4	287	3
2002	10	6	5	322	4
2002	10	6	6	318	4
2002	10	6	7	317	4
2002	10	6	8	336	4
2002	10	6	10	25	6
2002	10	6	11	92	3
2002	10	6	12	111	7
2002	10	6	13	98	12
2002	10	6	14	87	13
2002	10	6	15	95	13
2002	10	6	16	88	10
2002	10	6	17	89	10
2002	10	6	18	106	11
2002	10	6	20	70	9
2002	10	6	21	66	8
2002	10	6	22	95	6
2002	10	6	23	97	6
2002	10	7	0	76	3
2002	10	7	1	358	2
2002	10	7	2	353	3
2002	10	7	3	357	4
2002	10	7	4	340	4
2002	10	7	5	322	2
2002	10	7	6	344	3
2002	10	7	7	11	3
2002	10	7	8	339	5
2002	10	7	9	310	4
2002	10	7	10	284	1
2002	10	7	11	99	3
2002	10	7	12	119	4
2002	10	7	13	128	6
2002	10	7	14	138	7
2002	10	7	15	144	7
2002	10	7	16	156	5

2002	10	7	17	142	8
2002	10	7	18	136	9
2002	10	7	19	144	10
2002	10	7	20	169	9
2002	10	7	21	164	9
2002	10	7	22	175	8
2002	10	7	23	157	7
2002	10	8	0	168	4
2002	10	8	1	7	14
2002	10	8	2	355	6
2002	10	8	3	80	3
2002	10	8	4	34	8
2002	10	8	5	31	8
2002	10	8	6	6	8
2002	10	8	7	38	6
2002	10	8	8	54	3
2002	10	8	9	89	7
2002	10	8	10	64	8
2002	10	8	11	65	10
2002	10	8	12	45	7
2002	10	8	13	50	15
2002	10	8	14	45	17
2002	10	8	15	67	19
2002	10	8	16	81	18
2002	10	8	17	70	14
2002	10	8	18	56	19
2002	10	8	19	53	17
2002	10	8	20	43	14
2002	10	8	21	26	14
2002	10	8	22	16	11
2002	10	8	23	15	11
2002	10	9	0	13	13
2002	10	9	1	4	11
2002	10	9	2	3	9
2002	10	9	3	2	8
2002	10	9	4	3	8
2002	10	9	5	360	8
2002	10	9	6	359	10
2002	10	9	7	9	11
2002	10	9	8	24	12
2002	10	9	9	32	14
2002	10	9	10	51	19
2002	10	9	11	36	13
2002	10	9	12	46	14
2002	10	9	13	33	14
2002	10	9	14	62	20
2002	10	9	15	57	20
2002	10	9	16	58	21
2002	10	9	17	55	19
2002	10	9	18	43	13

2002	10	9	19	33	15
2002	10	9	20	40	12
2002	10	9	21	29	13
2002	10	9	22	34	12
2002	10	9	23	29	15

Table C-2. Wind data from Charleston International Airport.

Source: National Climatic Data Center (NCDC)
(http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20017349)
NCDC Station, Charleston, SC
32.90^{o}N 80.03^{o}W

Year	**Month**	**Day**	**Hour**	**Direction**	**Speed (m/s)**
2002	9	30	0	40	6
2002	9	30	1	40	6
2002	9	30	2	50	7
2002	9	30	3	40	8
2002	9	30	4	30	7
2002	9	30	5	30	9
2002	9	30	6	40	8
2002	9	30	7	40	12
2002	9	30	8	40	11
2002	9	30	9	30	10
2002	9	30	10	50	10
2002	9	30	11	70	9
2002	9	30	12	70	10
2002	9	30	13	70	11
2002	9	30	14	110	12
2002	9	30	15	100	13
2002	9	30	16	120	11
2002	9	30	17	120	10
2002	9	30	18	110	5
2002	9	30	19	90	4
2002	9	30	20	30	3
2002	9	30	21	20	4
2002	9	30	22	30	6
2002	9	30	23	40	8
2002	10	1	0	40	6
2002	10	1	1	50	6
2002	10	1	2	50	4
2002	10	1	3	40	5
2002	10	1	4	40	6
2002	10	1	5	30	6
2002	10	1	6	50	7
2002	10	1	7	40	7
2002	10	1	8	70	8
2002	10	1	9	80	8
2002	10	1	10	100	8

2002	10	1	11	60	5
2002	10	1	12	120	11
2002	10	1	13	110	8
2002	10	1	14	100	9
2002	10	1	15	100	9
2002	10	1	16	140	9
2002	10	1	17	110	7
2002	10	1	18	110	6
2002	10	1	19	110	5
2002	10	1	20	0	0
2002	10	1	21	0	0
2002	10	1	22	40	3
2002	10	1	23	40	3
2002	10	2	0	0	0
2002	10	2	1	0	0
2002	10	2	2	0	0
2002	10	2	3	20	3
2002	10	2	4	40	5
2002	10	2	5	40	4
2002	10	2	6	40	4
2002	10	2	7	50	5
2002	10	2	8	80	5
2002	10	2	9	70	6
2002	10	2	10	60	9
2002	10	2	11	100	5
2002	10	2	12	50	4
2002	10	2	13	0	0
2002	10	2	14	160	7
2002	10	2	15	170	7
2002	10	2	16	160	6
2002	10	2	17	150	5
2002	10	2	18	130	5
2002	10	2	19	160	3
2002	10	2	20	190	3
2002	10	2	21	0	0
2002	10	2	22	0	0
2002	10	2	23	360	3
2002	10	3	0	0	0
2002	10	3	1	0	0
2002	10	3	2	0	0
2002	10	3	3	340	3
2002	10	3	4	360	3
2002	10	3	5	0	0
2002	10	3	6	340	4
2002	10	3	7	340	6
2002	10	3	8	330	4
2002	10	3	9	10	3
2002	10	3	10	0	0
2002	10	3	11	0	0
2002	10	3	12	0	0

2002	10	3	13	130	3
2002	10	3	14	0	0
2002	10	3	15	200	6
2002	10	3	16	190	5
2002	10	3	17	200	6
2002	10	3	18	200	4
2002	10	3	19	190	3
2002	10	3	20	0	0
2002	10	3	21	0	0
2002	10	3	22	0	0
2002	10	3	23	0	0
2002	10	4	0	0	0
2002	10	4	1	0	0
2002	10	4	2	280	4
2002	10	4	3	320	3
2002	10	4	4	0	0
2002	10	4	5	0	0
2002	10	4	6	0	0
2002	10	4	7	360	4
2002	10	4	8	185	3
2002	10	4	9	10	3
2002	10	4	10	80	4
2002	10	4	11	160	4
2002	10	4	12	140	7
2002	10	4	13	145	5
2002	10	4	14	150	10
2002	10	4	15	160	6
2002	10	4	16	170	7
2002	10	4	17	210	7
2002	10	4	18	180	4
2002	10	4	19	170	3
2002	10	4	20	210	5
2002	10	4	21	200	4
2002	10	4	22	160	3
2002	10	4	23	200	4
2002	10	5	0	220	3
2002	10	5	1	0	0
2002	10	5	2	0	0
2002	10	5	3	0	0
2002	10	5	4	240	5
2002	10	5	5	260	4
2002	10	5	6	240	4
2002	10	5	7	250	8
2002	10	5	8	270	8
2002	10	5	9	295	5
2002	10	5	10	320	7
2002	10	5	11	340	8
2002	10	5	12	285	5
2002	10	5	13	270	8
2002	10	5	14	0	0

2002	10	5	15	320	5
2002	10	5	16	20	5
2002	10	5	17	250	10
2002	10	5	18	160	5
2002	10	5	19	220	5
2002	10	5	20	0	0
2002	10	5	21	200	3
2002	10	5	22	210	4
2002	10	5	23	0	0
2002	10	6	0	240	3
2002	10	6	1	0	0
2002	10	6	2	280	4
2002	10	6	3	270	4
2002	10	6	4	300	4
2002	10	6	5	260	3
2002	10	6	6	300	3
2002	10	6	7	340	4
2002	10	6	8	10	3
2002	10	6	9	10	6
2002	10	6	10	25	4
2002	10	6	11	40	6
2002	10	6	12	50	3
2002	10	6	13	80	3
2002	10	6	14	110	9
2002	10	6	15	90	10
2002	10	6	16	100	10
2002	10	6	17	100	8
2002	10	6	18	120	5
2002	10	6	19	70	4
2002	10	6	20	80	5
2002	10	6	21	80	4
2002	10	6	22	360	3
2002	10	6	23	0	0
2002	10	7	0	360	3
2002	10	7	1	30	3
2002	10	7	2	350	3
2002	10	7	3	0	0
2002	10	7	4	0	0
2002	10	7	5	0	0
2002	10	7	6	320	3
2002	10	7	7	360	4
2002	10	7	8	0	0
2002	10	7	9	340	3
2002	10	7	10	227	3
2002	10	7	11	113	5
2002	10	7	12	0	0
2002	10	7	13	180	4
2002	10	7	14	360	5
2002	10	7	15	150	7
2002	10	7	16	160	6

2002	10	7	17	180	8
2002	10	7	18	150	3
2002	10	7	19	0	0
2002	10	7	20	160	5
2002	10	7	21	180	3
2002	10	7	22	180	3
2002	10	7	23	360	13
2002	10	8	0	350	10
2002	10	8	1	140	3
2002	10	8	2	10	5
2002	10	8	3	30	5
2002	10	8	4	30	5
2002	10	8	5	10	4
2002	10	8	6	50	4
2002	10	8	7	60	4
2002	10	8	8	60	8
2002	10	8	9	60	6
2002	10	8	10	30	6
2002	10	8	11	10	5
2002	10	8	12	20	3
2002	10	8	13	70	6
2002	10	8	14	20	7
2002	10	8	15	20	9
2002	10	8	16	50	11
2002	10	8	17	50	10
2002	10	8	18	40	8
2002	10	8	19	20	7
2002	10	8	20	10	10
2002	10	8	21	20	8
2002	10	8	22	20	6
2002	10	8	23	20	7
2002	10	9	0	10	9
2002	10	9	1	10	7
2002	10	9	2	10	8
2002	10	9	3	10	7
2002	10	9	4	10	5
2002	10	9	5	20	7
2002	10	9	6	30	9
2002	10	9	7	20	6
2002	10	9	8	360	6
2002	10	9	9	30	7
2002	10	9	10	30	5
2002	10	9	11	50	8
2002	10	9	12	20	7
2002	10	9	13	20	7
2002	10	9	14	80	7
2002	10	9	15	70	8
2002	10	9	16	70	7
2002	10	9	17	50	8
2002	10	9	18	50	6

2002	10	9	19	20	8
2002	10	9	20	10	7
2002	10	9	21	30	9
2002	10	9	22	30	9
2002	10	9	23	30	8

APPENDIX D: CURRENT DATA

D.1 Development of Current Data

A current file was prepared using the hydrodynamic model BFHYDRO. Section 3.3.1 contains a description of the model and application to the area of the spill. Figure D.1-1 shows the hydrodynamic model grid.

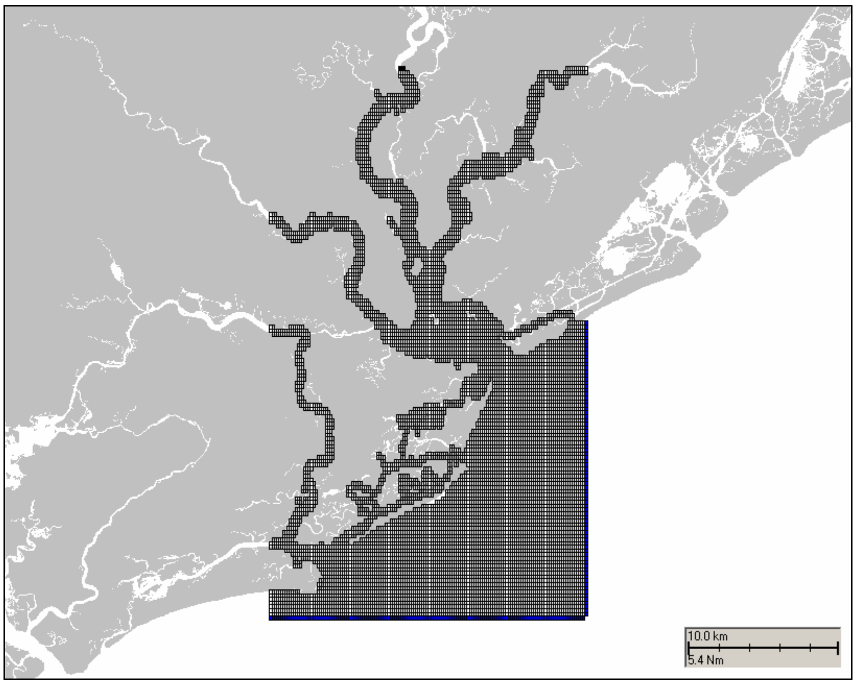

Figure D.1-1. Hydrodynamic model grid used for estimation of currents.

D.2 Current Vector Plots for Current Data Used in the Oil Spill Simulations

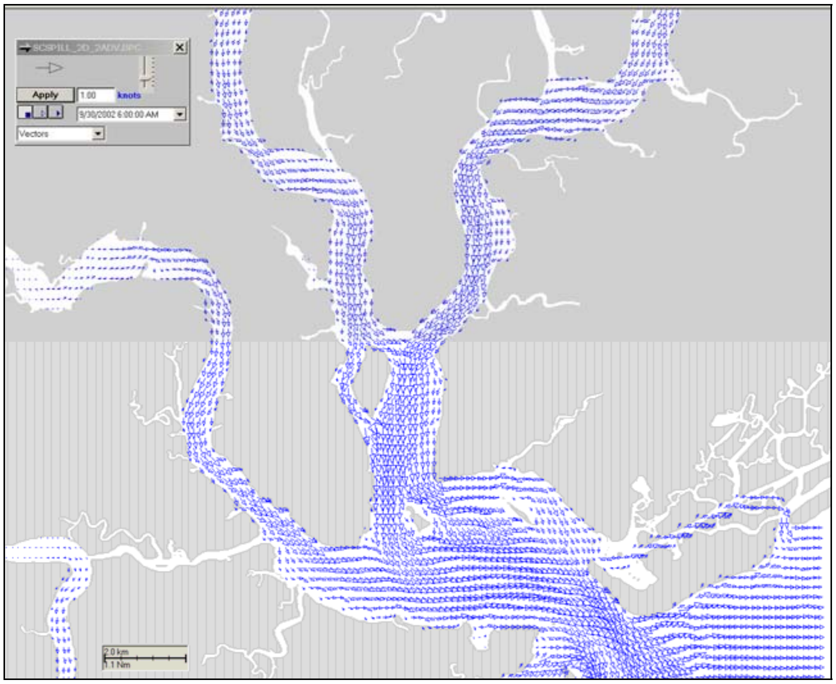

Figure D.2-1. Current data used in modeling in area of oil trajectory: 30 September at 06:00 hours. Vector length indicates speed in the indicated direction.

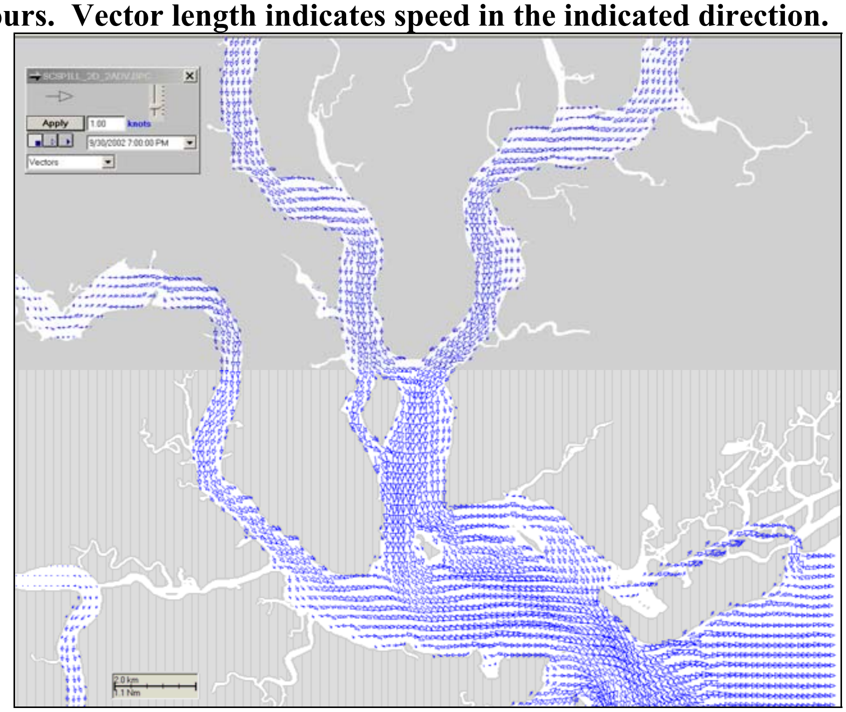

Figure D.2-2. Current data used in modeling in area of oil trajectory: 30 September at 19:00 hours. Vector length indicates speed in the indicated direction.

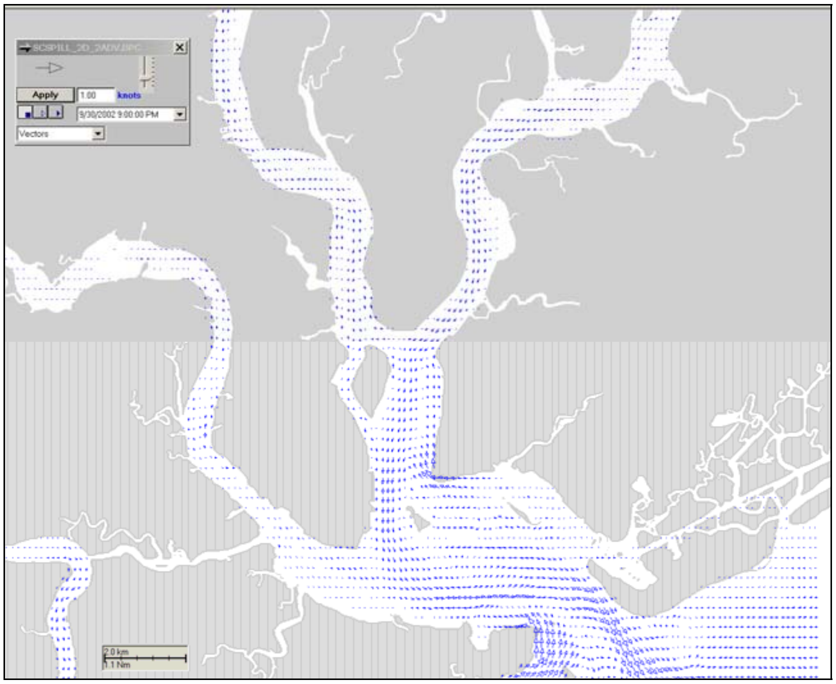

Figure D.2-3. Current data used in modeling in area of oil trajectory: 30 September at 21:00 hours. Vector length indicates speed in the indicated direction.

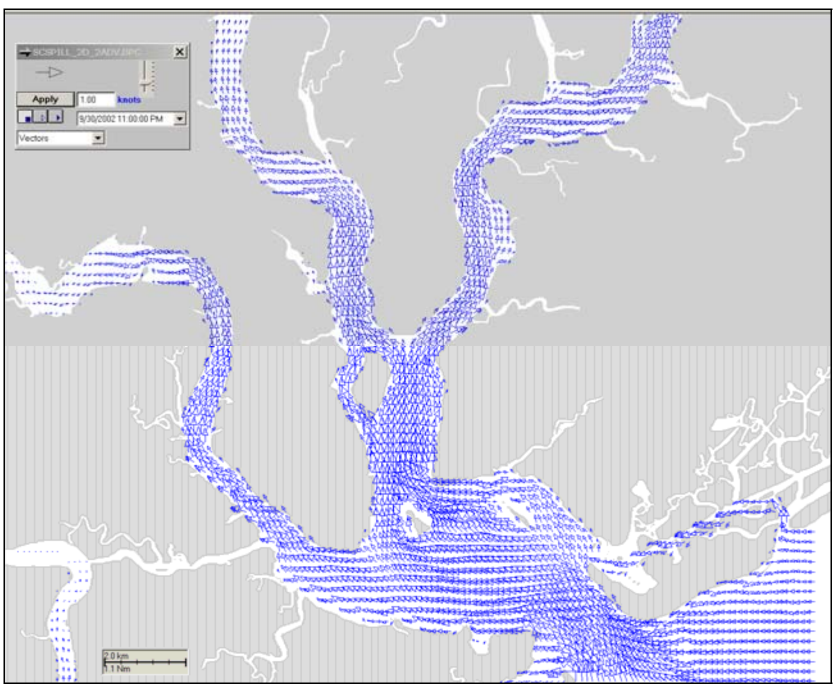

Figure D.2-4. Current data used in modeling in area of oil trajectory: 30 September at 23:00 hours. Vector length indicates speed in the indicated direction.

APPENDIX E. INPUTS TO THE SIMAP PHYSICAL FATES MODEL

Table E-1. Inputs describing the scenario.

Name	Description	Units	Source(s) of Information	Value(s)
Spill Site	Location of the spill site	-	Reports and the Ship's Log from the Responsible Party	See below and Table E-2
Spill Latitude	Latitude of the spill site	Degrees	chart	See Table E-2
Spill Longitude	Longitude of the spill site	Degrees	chart	See Table E-2
Depth of release	Depth below the water surface of the release	m	Assumed, oil would float immediately	0 m (surface)
Start time and date	Date and time the release began	Date, hr,min	USCG and Responsible Party	30 Sept 2002 05:35 EST
Duration	Duration of the release	(hrs)	Assumed until last waypoint outbound	16.74 hours
Total spill volume or mass	Total volume (or weight) released	bbl, gal., MT, kg, m^3	USCG	12,500 gal. (46.4 MT)
Salinity	Surface water salinity	ppt	French et al. (1996b)	27 ppt
Water Temperature	Surface water temperature	Degrees C	NOAA CO-OPS, http://co-ops.nos.noaa.gov	23^{o}C
Air Temper-ature	Air water temperature at water surface	Degrees C	(assume = water temperature)	23^{o}C
Fetch	Fetch = distance to land to N, S, E, W (if landfall not in model domain)	km	>0 km; 1000 km if open ocean	Charts
Wind drift speed	Speed oil moves down wind relative to wind	% of wind speed	ASCE, 1996: see section 3.3.2	3.5%
Wind drift angle	Angle to right of wind (in northern hemisphere) oil drifts	Deg. to right of downwind	ASCE, 1996: see section 3.3.2	0^o
Horizontal turbulent diffusion coefficient	Randomized turbulent mixing parameter in x & y	m^2/sec	French et al. (1996a, 1999) based on Okubo and Ozmidov (1970); Okubo (1971)	1 m^2/sec (estuaries and low energy coastal areas)
Vertical turbulent diffusion coefficient	Randomized turbulent mixing parameter in z	m^2/sec	French et al. (1996a, 1999) based on Okubo and Ozmidov (1970); Okubo (1971)	0.0001 m^2/sec
Suspended sediment concentration	Average suspended sediment concentration during spill period	mg/l	SCDHEC (David Graves, pers. comm., January 2004)	11.7 mg/l
Suspended sediment settling rate	Net settling rate for suspended sediments	m/day	French et al. (1996b)	1 m/day

Table E-2. Assumed ship locations and times during the oil release.

GIS Point #	Model Point #	Longitude (deg.)	Latitude (deg.)	Location	Time	Hours After Spill
0	1	-79.936424	32.85283	At dredge pipe	05:35	0.00
1	2	-79.956429	32.86052			0.19
2	3	-79.964562	32.87533			0.38
3	4	-79.962868	32.89042	HWY 526 Bridge	06:09	0.57
4	5	-79.95948	32.89754			0.95
5	6	-79.961174	32.89953	First line ashore	06:54	1.32
6	7	-79.962189	32.89981	Fast at Berth 1	07:18	1.72
7	8	-79.962189	32.89981	Left Berth 1	19:00	13.42
8	9	-79.965241	32.87533			13.65
9	10	-79.95948	32.86337			13.78
10	11	-79.95134	32.85796			13.87
11	12	-79.947609	32.85682			13.90
12	13	-79.936424	32.85254			13.99
13	14	-79.93235	32.8514			14.02
14	15	-79.929642	32.84314			14.10
15	16	-79.928619	32.82149			14.29
16	17	-79.915741	32.8138			14.33
17	18	-79.91404	32.80439	Cooper R. Bridge	20:04	14.49
18	19	-79.913704	32.78957			14.61
19	20	-79.909638	32.78302	by Shutes Folly	20:15	14.67
20	21	-79.901161	32.78017			14.71
21	22	-79.895393	32.77817			14.74
22	23	-79.888954	32.77446	by Crab Bank	20:21	14.77
23	24	-79.878777	32.76933			14.86
24	25	-79.865898	32.75964			14.92
25	26	-79.856064	32.74852			14.98
26	27	-79.846565	32.73996			15.03
27	28	-79.793678	32.714			15.26
28	29	-79.756714	32.69318			15.43
29	30	-79.67704	32.64151	GPS noted	21:24	15.82
30	31	-79.624481	32.59496			16.10
31	32	-79.552261	32.53181			16.48
32	33	-79.499703	32.48835	GPS noted	22:19	16.74

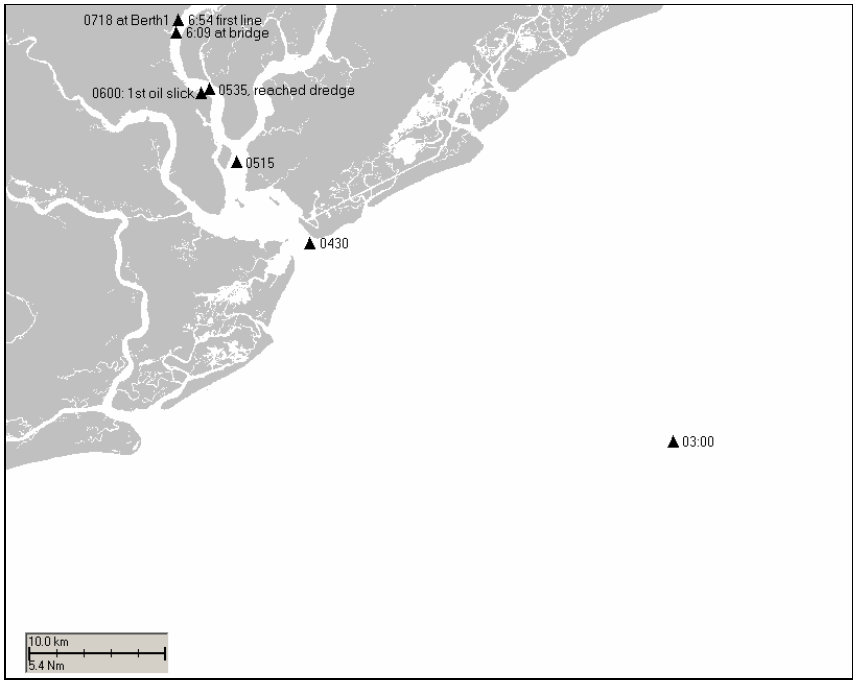

Figure E-1. Waypoints for vessel entering the harbor.

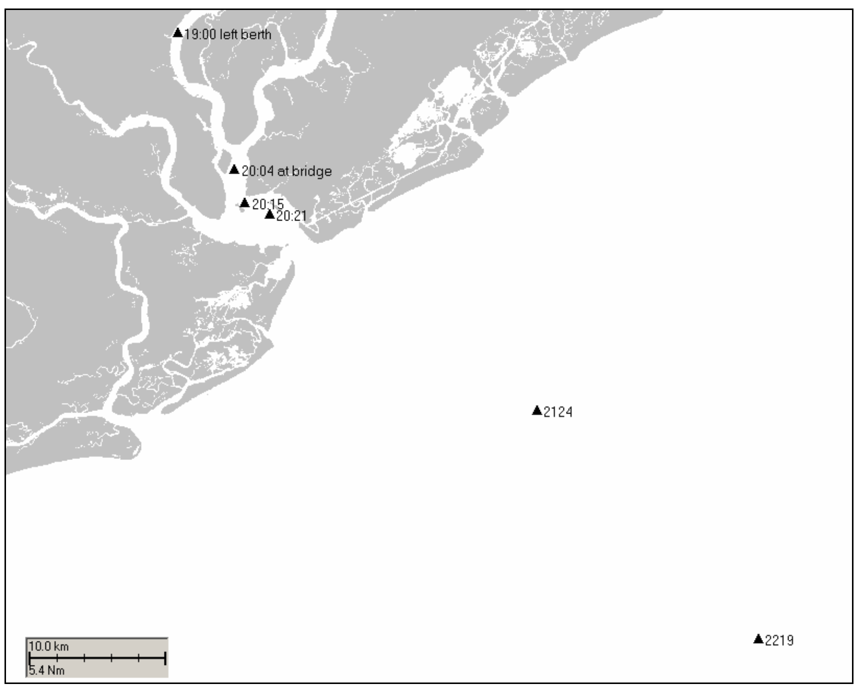

Figure E-2. Waypoints for vessel exiting the harbor.

Table E-3. Oil name and properties.

Name	Description	Units	Source(s) of Information	Value(s)
Oil: name	Oil type or chemical released	(name)	USCG	IFO 380 (heavy fuel oil)
Oil: density	Density of the oil	g/cm^3 or API	Typical heavy fuel oil (Jokuty et al., 1996)	0.98 g/cm^3 (API = 12.888)
Oil: viscosity	Viscosity of the oil	Centi-poise (cp)	Typical heavy fuel oil (Jokuty et al., 1996)	14,470 cp
Oil: surface tension	Surface tension of the oil	Dyne/cm	Typical heavy fuel oil (Jokuty et al., 1996)	32.6 dyne/cm
Oil: BTEX fraction	Fraction of oil which is monoaromatics (BTEX)	fraction	Typical heavy fuel oil (Wang et al., 1995)	0.000640
Oil: 2-ring PAH fraction	Fraction of oil which is 2-ring aromatics (PAHs)	fraction	analysis of source oil (Battelle)	0.004756
Oil: 3-ring PAH fraction	Fraction of oil which is 3-ring aromatics (PAHs)	fraction	analysis of source oil (Battelle)	0.009086
Oil: non-aromatic volatile fraction	Fraction of oil which is not aromatic and with boiling point <180^{o}C (volatilizes)	fraction	Typical heavy fuel oil (Jokuty et al., 1996)	0.004355
Oil: non-aromatic volatile fraction	Fraction of oil which is not aromatic and with boiling point 180-265^{o}C (semi-volatilizes)	fraction	Typical heavy fuel oil (Jokuty et al., 1996)	0.046530
Oil: non-aromatic volatile fraction	Fraction of oil which is not aromatic and with boiling point 265-380^{o}C (low volatility)	fraction	Typical heavy fuel oil (Jokuty et al., 1996)	0.083310
Oil: initial water fraction	Fraction of initial spill volume which is water	fraction	(assumed)	0
Oil: water fraction in mousse	Fraction of oil mousse which is water (maximum)	fraction	analysis of mousse (Jokuty et al., 1996)	0%

APPENDIX F. FATES MODEL RESULTS

The figures in this appendix show the fates model results for the best simulation of the spill, scenario name "P7V2-2PHA-3W2DA-35-0-H1". Other model runs may be examined using the SIMAP Viewer. Below is a list of the cases run and the assumptions that varied.

Table F-1 Model scenarios run and parameters varied between runs.

Scenario Name	Horizontal turbulent diffusion coefficient (m^2/sec)	Wind Drift (% of wind speed, angle)
P7V2-2PHA-3W2DA-35-0-Hp1	0.1	3.5%, 0^o
P7V2-2PHA-3W2DA-35-0-H1	1.0	3.5%, 0^o
P7V2-2PHA-3W2DA-35-0-H5	5.0	3.5%, 0^o
P7V2-2PHA-3W2DA-35-0-H10	10.0	3.5%, 0^o
P7V2-2PHA-3W2DA- MDRFT -H1	1.0	Model calculated
P7V2-2PHA-3W2DA- MDRFT -H10	10.0	Model calculated
AtDredge-3W2DA-35-0-H1	1.0	3.5%, 0^o

F.1 Description of Fate and Mass Balance

The over-all mass balance of oil hydrocarbons as a function of time is in Figure F.1-1.

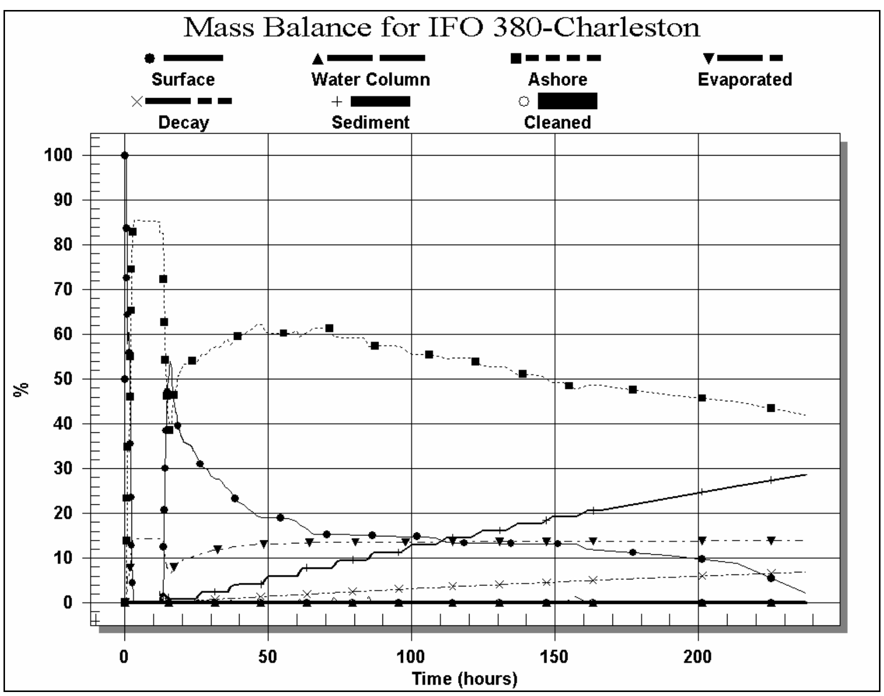

Figure F.1-1. Over all mass balance of oil versus time after the spill.

Table F-2 Mass balance of oil over time (hours since the spill started) in the best simulation.

Time (hr)	% on Water Surface	% in Atmos-phere	% in Water Column	% in Sediment	% Ashore	% Decayed	% Spilled	% of Soluble Aromatics in Surface Oil	% of Soluble Aromatics in Subsurface Droplets	% of Soluble Aromatics Dissolved in Water
0.08	99.8918	0.1048	0.0000	0.0000	0.0000	0.0035	1.5	99.1741	0.0000	0.0002
0.17	99.8876	0.1071	0.0000	0.0000	0.0000	0.0053	2.9	99.1563	0.0000	0.0003
0.25	99.8810	0.1120	0.0000	0.0000	0.0000	0.0069	4.4	99.1185	0.0000	0.0003
0.33	99.8695	0.1218	0.0000	0.0000	0.0000	0.0087	5.8	99.0415	0.0000	0.0003
0.42	99.8586	0.1310	0.0000	0.0000	0.0000	0.0104	7.3	98.9695	0.0000	0.0004
0.5	99.8449	0.1429	0.0000	0.0000	0.0000	0.0122	8.7	98.8765	0.0000	0.0004
0.58	99.8187	0.1674	0.0000	0.0000	0.0000	0.0139	10.2	98.6864	0.0000	0.0004
0.67	90.3522	1.5168	0.0001	0.0000	8.1153	0.0156	11.6	89.3267	0.0001	0.0005
0.75	76.9711	3.4137	0.0001	0.0000	19.5979	0.0172	13.1	76.1801	0.0001	0.0005
0.83	68.1716	4.6615	0.0002	0.0000	27.1478	0.0188	14.5	67.5316	0.0001	0.0005
0.92	60.5384	5.7466	0.0003	0.0000	33.6944	0.0204	16.0	60.0087	0.0002	0.0005
1	57.9644	6.1130	0.0003	0.0000	35.9002	0.0220	17.4	57.4662	0.0002	0.0006
2	38.5389	8.9448	0.0004	0.0000	52.4694	0.0465	30	37.7574	0.0003	0.0009
3	0.9890	14.2609	0.0005	0.0000	84.6668	0.0828	30	0.9218	0.0004	0.0011
4	0.0000	14.3945	0.0005	0.0000	85.4865	0.1185	30	0.0000	0.0004	0.0011
5	0.0000	14.3945	0.0005	0.0000	85.4509	0.1541	30	0.0000	0.0004	0.0011
6	0.0000	14.3945	0.0005	0.0000	85.4153	0.1897	30	0.0000	0.0004	0.0011
7	0.0000	14.3945	0.0005	0.0000	85.3798	0.2253	30	0.0000	0.0004	0.0011
8	0.0000	14.3945	0.0005	0.0000	85.3442	0.2608	30	0.0000	0.0004	0.0011
9	0.0000	14.3945	0.0005	0.0000	85.3086	0.2964	30	0.0000	0.0004	0.0011
10	0.0000	14.3945	0.0005	0.0000	85.2731	0.3319	30	0.0000	0.0004	0.0011
11	0.0000	14.3945	0.0005	0.0000	85.2376	0.3674	30	0.0000	0.0004	0.0011
12	0.0000	14.3945	0.0005	0.0000	85.2021	0.4029	30	0.0000	0.0004	0.0011

13	0.0000	14.3945	0.7467	1.7938	82.6237	0.4412	30	0.0000	0.0004	0.0011
14	28.6490	10.2873	0.1445	1.6592	58.9156	0.3445	42	28.5119	0.0003	0.0009
15	49.0505	7.3864	0.0349	1.1659	42.0991	0.2631	63	48.6170	0.0002	0.0010
16	53.1556	6.8083	0.0102	0.8901	38.9029	0.2329	84	52.6082	0.0001	0.0013
17	45.4705	7.9316	0.0045	0.7528	45.6064	0.2342	100	44.7741	0.0001	0.0016
18	42.2380	8.4957	0.0019	0.7534	48.2370	0.2740	100	40.7584	0.0002	0.0022
19	38.6020	9.1235	0.0009	0.7524	51.2076	0.3136	100	36.3296	0.0002	0.0028
20	36.5602	9.5264	0.0006	0.7506	52.8092	0.3531	100	33.4951	0.0002	0.0036
21	35.8166	9.7425	0.0005	0.7485	53.2995	0.3925	100	31.9792	0.0003	0.0042
22	35.4541	9.9184	0.0013	0.7463	53.4480	0.4318	100	30.7562	0.0010	0.0047
23	35.0821	10.1037	0.0027	0.7441	53.5964	0.4710	100	29.4783	0.0021	0.0050
24	33.8484	10.3839	0.0035	0.7419	54.5122	0.5101	100	27.5486	0.0028	0.0052
25	33.0398	10.5816	1.3724	1.0099	53.4472	0.5491	100	26.1865	0.0027	0.0053
26	31.4456	10.8837	0.4519	1.9279	54.7031	0.5877	100	24.1067	0.0029	0.0054
27	30.3433	11.1213	0.0538	2.3236	55.5321	0.6259	100	22.4735	0.0028	0.0055
28	30.1278	11.2390	0.0094	2.3657	55.5941	0.6639	100	21.6655	0.0027	0.0056
29	29.7224	11.3765	0.0045	2.3683	55.8263	0.7019	100	20.7211	0.0027	0.0056
30	28.4513	11.6141	0.0042	2.3666	56.8240	0.7398	100	19.0866	0.0028	0.0057
31	27.9531	11.7602	0.0042	2.3643	57.1405	0.7777	100	18.0836	0.0028	0.0058
32	27.7625	11.8543	0.0041	2.3619	57.2017	0.8155	100	17.4379	0.0027	0.0059
33	27.6745	11.9308	0.0041	2.3596	57.1779	0.8532	100	16.9128	0.0026	0.0060
34	27.0322	12.0520	0.0040	2.3572	57.6637	0.8909	100	16.0766	0.0025	0.0061
35	25.8431	12.2111	0.0040	2.3547	58.6585	0.9286	100	14.9750	0.0024	0.0062
36	25.4989	12.2899	0.0040	2.3523	58.8887	0.9662	100	14.4308	0.0024	0.0063
37	24.8785	12.3907	0.5547	3.5605	57.6121	1.0035	100	13.7339	0.0023	0.0064
38	23.6190	12.5375	0.1446	3.9680	58.6905	1.0403	100	12.7156	0.0023	0.0065
39	22.7343	12.6494	0.0661	4.0441	59.4290	1.0771	100	11.9400	0.0023	0.0066
40	22.3166	12.7187	0.0250	4.0827	59.7432	1.1138	100	11.4596	0.0023	0.0067
41	22.0896	12.7671	0.0094	4.0958	59.8877	1.1504	100	11.1245	0.0022	0.0067
42	21.5002	12.8393	0.0049	4.0977	60.3708	1.1870	100	10.6222	0.0022	0.0068
43	20.9136	12.9093	0.0041	4.0960	60.8534	1.2236	100	10.1356	0.0021	0.0069

44	20.6938	12.9512	0.0040	4.0936	60.9973	1.2602	100	9.8448	0.0021	0.0070
45	20.0246	13.0199	0.0039	4.0911	61.5638	1.2967	100	9.3654	0.0020	0.0070
46	19.2703	13.0897	0.0039	4.0885	62.2144	1.3332	100	8.8776	0.0020	0.0071
47	19.1542	13.1133	0.0039	4.0859	62.2730	1.3697	100	8.7125	0.0020	0.0072
48	19.1320	13.1275	0.0039	4.0833	62.2471	1.4062	100	8.6131	0.0019	0.0072
49	19.1080	13.1436	0.5745	5.3657	60.3659	1.4424	100	8.5006	0.0019	0.0073
50	19.0809	13.1626	0.0602	5.8774	60.3408	1.4781	100	8.3679	0.0019	0.0074
51	19.0548	13.1808	0.0094	5.9257	60.3157	1.5136	100	8.2411	0.0018	0.0074
52	19.0307	13.1970	0.0044	5.9282	60.2906	1.5492	100	8.1283	0.0018	0.0075
53	19.0089	13.2109	0.0039	5.9261	60.2655	1.5847	100	8.0309	0.0018	0.0075
54	18.9883	13.2236	0.0039	5.9237	60.2404	1.6202	100	7.9416	0.0017	0.0076
55	18.9687	13.2353	0.0039	5.9212	60.2154	1.6556	100	7.8591	0.0017	0.0077
56	18.9498	13.2463	0.0039	5.9187	60.1903	1.6911	100	7.7815	0.0017	0.0077
57	18.8418	13.2622	0.0039	5.9162	60.2494	1.7265	100	7.6690	0.0017	0.0078
58	18.7334	13.2786	0.0038	5.9137	60.3085	1.7619	100	7.5532	0.0016	0.0078
59	18.3578	13.3102	0.0038	5.9112	60.6197	1.7973	100	7.3306	0.0016	0.0079
60	17.8949	13.3453	0.0038	5.9086	61.0146	1.8327	100	7.0828	0.0016	0.0079
61	17.3442	13.3847	0.6573	7.0780	59.6680	1.8679	100	6.8046	0.0016	0.0080
62	17.1506	13.4031	0.0877	7.6450	59.8111	1.9025	100	6.6744	0.0016	0.0080
63	16.3362	13.4550	0.0164	7.7138	60.5416	1.9370	100	6.3072	0.0015	0.0081
64	15.9681	13.4807	0.0061	7.7216	60.8520	1.9715	100	6.1249	0.0015	0.0081
65	15.6904	13.5001	0.0043	7.7208	61.0783	2.0060	100	5.9867	0.0015	0.0082
66	15.5028	13.5136	0.0039	7.7187	61.2206	2.0404	100	5.8900	0.0015	0.0082
67	15.4936	13.5163	0.0038	7.7162	61.1951	2.0749	100	5.8696	0.0015	0.0083
68	15.4850	13.5184	0.0038	7.7137	61.1697	2.1093	100	5.8525	0.0014	0.0083
69	15.4762	13.5208	0.0038	7.7112	61.1443	2.1438	100	5.8342	0.0014	0.0084
70	15.4675	13.5230	0.0038	7.7086	61.1189	2.1782	100	5.8164	0.0014	0.0084
71	15.4583	13.5258	0.0038	7.7061	61.0935	2.2126	100	5.7951	0.0014	0.0084
72	15.4487	13.5289	0.0038	7.7036	61.0681	2.2469	100	5.7715	0.0014	0.0085
73	15.4399	13.5313	1.1725	8.3507	59.2243	2.2812	100	5.7533	0.0014	0.0085
74	15.4314	13.5334	0.3007	9.2198	59.1997	2.3149	100	5.7363	0.0013	0.0086

75	15.4223	13.5361	0.0704	9.4477	59.1751	2.3485	100	5.7160	0.0013	0.0086
76	15.4129	13.5391	0.0191	9.4965	59.1505	2.3820	100	5.6935	0.0013	0.0086
77	15.4037	13.5418	0.0077	9.5054	59.1260	2.4154	100	5.6723	0.0013	0.0087
78	15.3947	13.5444	0.0048	9.5058	59.1014	2.4489	100	5.6525	0.0013	0.0087
79	15.3856	13.5471	0.0040	9.5042	59.0768	2.4823	100	5.6319	0.0013	0.0088
80	15.3763	13.5499	0.0038	9.5019	59.0523	2.5157	100	5.6105	0.0013	0.0088
81	15.3670	13.5529	0.0038	9.4995	59.0278	2.5491	100	5.5882	0.0012	0.0088
82	15.3575	13.5560	0.0038	9.4970	59.0032	2.5825	100	5.5649	0.0012	0.0089
83	15.3485	13.5586	0.0038	9.4946	58.9787	2.6158	100	5.5449	0.0012	0.0089
84	15.3402	13.5605	0.0038	9.4921	58.9542	2.6492	100	5.5300	0.0012	0.0090
85	15.3319	13.5624	1.1868	10.0611	57.1754	2.6824	100	5.5146	0.0012	0.0090
86	15.1486	13.5731	0.3576	10.8877	57.3179	2.7152	100	5.4373	0.0012	0.0090
87	15.1408	13.5746	0.1108	11.1320	57.2941	2.7478	100	5.4247	0.0012	0.0091
88	14.9577	13.5852	0.0314	11.2090	57.4364	2.7803	100	5.3476	0.0012	0.0091
89	14.8626	13.5910	0.0128	11.2252	57.4956	2.8128	100	5.3049	0.0011	0.0091
90	14.8554	13.5921	0.0071	11.2285	57.4717	2.8452	100	5.2954	0.0011	0.0092
91	14.8481	13.5932	0.0050	11.2283	57.4479	2.8777	100	5.2856	0.0011	0.0092
92	14.7534	13.5987	0.0041	11.2267	57.5069	2.9101	100	5.2443	0.0011	0.0093
93	14.7460	13.5999	0.0038	11.2246	57.4831	2.9425	100	5.2341	0.0011	0.0093
94	14.7385	13.6013	0.0038	11.2223	57.4592	2.9749	100	5.2226	0.0011	0.0093
95	14.7312	13.6025	0.0037	11.2199	57.4353	3.0073	100	5.2124	0.0011	0.0094
96	14.7238	13.6037	0.0037	11.2176	57.4115	3.0397	100	5.2018	0.0011	0.0094
97	14.7163	13.6051	1.3550	11.5715	55.6802	3.0720	100	5.1905	0.0011	0.0094
98	14.7084	13.6069	0.3010	12.6228	55.6571	3.1038	100	5.1765	0.0011	0.0095
99	14.7007	13.6085	0.0624	12.8591	55.6340	3.1354	100	5.1633	0.0010	0.0095
100	14.6935	13.6095	0.0185	12.9006	55.6109	3.1669	100	5.1540	0.0010	0.0095
101	14.6862	13.6107	0.0074	12.9094	55.5878	3.1985	100	5.1441	0.0010	0.0096
102	14.6789	13.6119	0.0045	12.9100	55.5647	3.2299	100	5.1335	0.0010	0.0096
103	14.6713	13.6134	0.0038	12.9084	55.5417	3.2614	100	5.1213	0.0010	0.0096
104	14.6638	13.6147	0.0037	12.9062	55.5186	3.2929	100	5.1103	0.0010	0.0097
105	14.6565	13.6160	0.0037	12.9039	55.4956	3.3243	100	5.1000	0.0010	0.0097

106	14.6492	13.6171	0.0037	12.9016	55.4726	3.3558	100	5.0899	0.0010	0.0097
107	14.6419	13.6184	0.0037	12.8993	55.4496	3.3872	100	5.0793	0.0010	0.0098
108	14.5476	13.6242	0.0037	12.8970	55.5089	3.4186	100	5.0368	0.0010	0.0098
109	14.4535	13.6299	1.2137	13.3371	53.9159	3.4500	100	4.9945	0.0009	0.0098
110	14.0998	13.6483	0.1673	14.3810	54.2228	3.4808	100	4.8623	0.0009	0.0099
111	13.6600	13.6709	0.0208	14.5252	54.6117	3.5114	100	4.7003	0.0009	0.0099
112	13.5664	13.6765	0.0055	14.5383	54.6713	3.5421	100	4.6589	0.0009	0.0099
113	13.4729	13.6821	0.0039	14.5376	54.7308	3.5726	100	4.6180	0.0009	0.0100
114	13.4661	13.6833	0.0038	14.5355	54.7081	3.6032	100	4.6078	0.0009	0.0100
115	13.3730	13.6887	0.0038	14.5332	54.7676	3.6338	100	4.5682	0.0009	0.0100
116	13.3663	13.6897	0.0038	14.5309	54.7449	3.6644	100	4.5591	0.0009	0.0100
117	13.3599	13.6906	0.0038	14.5287	54.7221	3.6949	100	4.5512	0.0009	0.0101
118	13.3537	13.6913	0.0037	14.5264	54.6995	3.7254	100	4.5447	0.0009	0.0101
119	13.3477	13.6917	0.0037	14.5241	54.6768	3.7560	100	4.5400	0.0009	0.0101
120	13.3417	13.6922	0.0037	14.5219	54.6541	3.7865	100	4.5352	0.0009	0.0101
121	13.3356	13.6927	1.4084	14.7385	53.0079	3.8169	100	4.5298	0.0008	0.0102
122	13.3296	13.6932	0.2584	15.8859	52.9859	3.8469	100	4.5244	0.0008	0.0102
123	13.3234	13.6938	0.0375	16.1046	52.9640	3.8767	100	4.5183	0.0008	0.0102
124	13.3173	13.6944	0.0082	16.1317	52.9420	3.9064	100	4.5125	0.0008	0.0102
125	13.3112	13.6949	0.0043	16.1334	52.9201	3.9361	100	4.5073	0.0008	0.0102
126	13.3053	13.6953	0.0038	16.1317	52.8981	3.9658	100	4.5026	0.0008	0.0103
127	13.2994	13.6957	0.0037	16.1296	52.8762	3.9954	100	4.4983	0.0008	0.0103
128	13.2931	13.6963	0.0038	16.1275	52.8543	4.0251	100	4.4926	0.0008	0.0103
129	13.2868	13.6970	0.0039	16.1253	52.8324	4.0547	100	4.4858	0.0009	0.0103
130	13.2805	13.6977	0.0040	16.1231	52.8105	4.0843	100	4.4793	0.0009	0.0103
131	13.2743	13.6983	0.0040	16.1209	52.7886	4.1139	100	4.4734	0.0009	0.0104
132	13.2683	13.6988	0.0039	16.1187	52.7667	4.1435	100	4.4682	0.0009	0.0104
133	13.2624	13.6992	1.4140	16.2728	51.1785	4.1731	100	4.4633	0.0008	0.0104
134	13.1709	13.7037	0.1967	17.4878	51.2387	4.2022	100	4.4300	0.0008	0.0104
135	13.1652	13.7040	0.0340	17.6483	51.2175	4.2310	100	4.4260	0.0008	0.0104
136	13.1593	13.7044	0.0073	17.6729	51.1963	4.2599	100	4.4217	0.0008	0.0104

137	13.1534	13.7047	0.0042	17.6739	51.1751	4.2887	100	4.4173	0.0008	0.0105
138	13.1477	13.7050	0.0039	17.6720	51.1539	4.3175	100	4.4135	0.0008	0.0105
139	13.1419	13.7053	0.0038	17.6699	51.1327	4.3463	100	4.4099	0.0008	0.0105
140	13.1363	13.7055	0.0038	17.6678	51.1115	4.3750	100	4.4066	0.0008	0.0105
141	13.1307	13.7057	0.0038	17.6657	51.0904	4.4038	100	4.4038	0.0008	0.0105
142	13.1251	13.7058	0.0038	17.6636	51.0692	4.4325	100	4.4012	0.0007	0.0105
143	13.1195	13.7059	0.0038	17.6615	51.0481	4.4613	100	4.3985	0.0007	0.0105
144	13.1139	13.7061	0.0038	17.6594	51.0269	4.4900	100	4.3957	0.0007	0.0105
145	13.1083	13.7062	1.5175	17.6573	49.4921	4.5187	100	4.3930	0.0007	0.0105
146	13.1027	13.7063	0.4569	18.7154	49.4716	4.5471	100	4.3903	0.0007	0.0105
147	13.0971	13.7064	0.0948	19.0754	49.4511	4.5752	100	4.3876	0.0007	0.0105
148	13.0915	13.7066	0.0188	19.1493	49.4306	4.6031	100	4.3849	0.0007	0.0105
149	13.0859	13.7067	0.0069	19.1592	49.4102	4.6311	100	4.3822	0.0007	0.0105
150	13.0803	13.7069	0.0044	19.1597	49.3897	4.6591	100	4.3795	0.0007	0.0105
151	13.0745	13.7071	0.0040	19.1582	49.3693	4.6870	100	4.3761	0.0007	0.0106
152	13.0687	13.7073	0.0040	19.1562	49.3488	4.7149	100	4.3726	0.0008	0.0106
153	13.0630	13.7076	0.0040	19.1541	49.3284	4.7428	100	4.3693	0.0008	0.0106
154	13.0575	13.7077	0.0040	19.1521	49.3080	4.7707	100	4.3662	0.0007	0.0106
155	12.8824	13.7159	0.0039	19.1501	49.4492	4.7986	100	4.3066	0.0007	0.0106
156	12.8768	13.7160	0.0039	19.1480	49.4287	4.8265	100	4.3038	0.0007	0.0106
157	12.8713	13.7162	0.0039	19.1460	49.4082	4.8544	100	4.3010	0.0007	0.0106
158	12.4426	13.7362	0.2198	20.3930	48.3265	4.8818	100	4.1568	0.0007	0.0106
159	12.0142	13.7562	0.0278	20.5829	48.7098	4.9091	100	4.0130	0.0007	0.0106
160	11.7554	13.7682	0.0073	20.6015	48.9315	4.9362	100	3.9260	0.0007	0.0106
161	11.6659	13.7722	0.0044	20.6023	48.9918	4.9634	100	3.8956	0.0006	0.0106
162	11.5765	13.7762	0.0038	20.6008	49.0521	4.9906	100	3.8654	0.0006	0.0106
163	11.4872	13.7802	0.0037	20.5988	49.1123	5.0177	100	3.8354	0.0006	0.0106
164	11.3135	13.7882	0.0037	20.5968	49.2530	5.0448	100	3.7772	0.0006	0.0106
165	11.3087	13.7882	0.0037	20.5948	49.2326	5.0720	100	3.7754	0.0006	0.0106
166	11.2196	13.7922	0.0037	20.5928	49.2927	5.0991	100	3.7453	0.0006	0.0106
167	11.2149	13.7922	0.0037	20.5907	49.2723	5.1262	100	3.7435	0.0006	0.0106

168	11.2102	13.7923	0.0037	20.5887	49.2519	5.1533	100	3.7418	0.0006	0.0106
174	11.0976	13.7964	0.0068	22.0321	47.7521	5.3150	100	3.7031	0.0006	0.0106
180	11.0697	13.7966	0.0036	22.0234	47.6338	5.4729	100	3.6923	0.0005	0.0106
186	10.0379	13.8439	0.0038	23.4239	47.0630	5.6275	100	3.3469	0.0005	0.0106
192	10.0125	13.8440	0.0038	23.4125	46.9465	5.7808	100	3.3377	0.0006	0.0106
198	9.5712	13.8636	0.0039	24.7942	45.8361	5.9310	100	3.1901	0.0005	0.0106
204	9.2964	13.8754	0.0055	24.7830	45.9601	6.0797	100	3.0979	0.0011	0.0106
210	8.9411	13.8909	0.0062	26.1329	44.8036	6.2253	100	2.9792	0.0013	0.0107
216	8.8363	13.8948	0.0060	26.1219	44.7716	6.3694	100	2.9442	0.0012	0.0107
222	8.8134	13.8948	0.0067	27.4334	43.3409	6.5107	100	2.9364	0.0015	0.0107
228	8.7883	13.8948	0.0088	27.4227	43.2338	6.6505	100	2.9279	0.0023	0.0107
234	6.3899	13.8948	0.0033	28.6880	41.8534	6.7848	100	2.1288	0.0009	0.0108
240	0.3268	13.8948	0.0005	28.6777	41.7501	6.9061	100	0.1089	0.0002	0.0108

F.2 Model Trajectory

The following figures show the model trajectory for the best simulation of the spill indicating where there is exposure to surface oil. The points in the trajectory plots below represent the center of mass for “spillets” used to simulate the spill. The map locations are cumulative, the previous oil locations are displayed along with the present ones at the time of the snapshot. Each spillet is a sublot of the total mass spilled. The spillet is transported by currents and surface wind drift. The mass distribution around the spillet center spreads (for surface slicks) and disperses over time according to the horizontal dispersion coefficient. Note that the shoreline shown in these model outputs are for visual reference only, whereas the habitat (and corresponding depth) grid (Appendix A.2) defines the actual shoreline to the model.

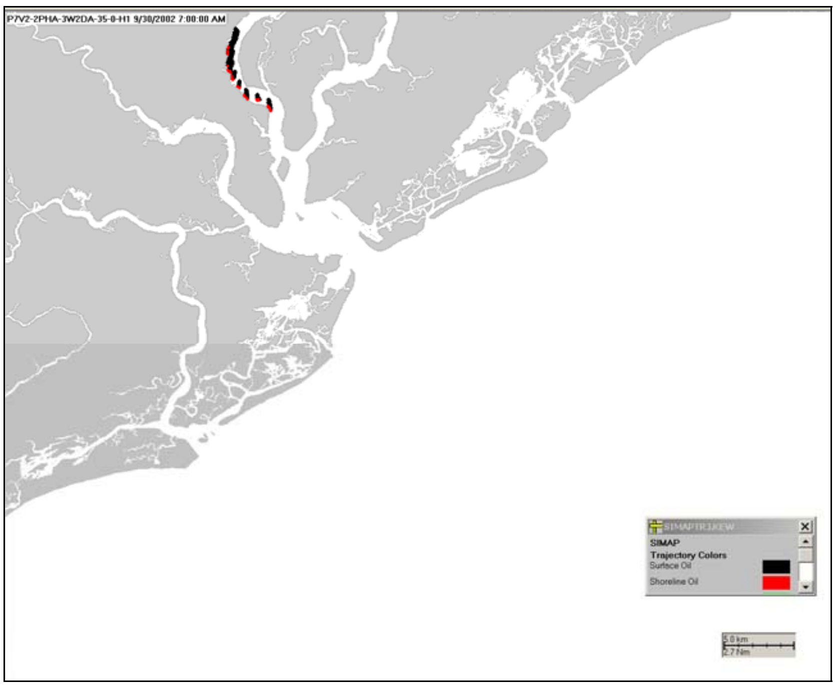

Figure F.2-1. Trajectory of surface oil at 07:00 on 30 September 2002.

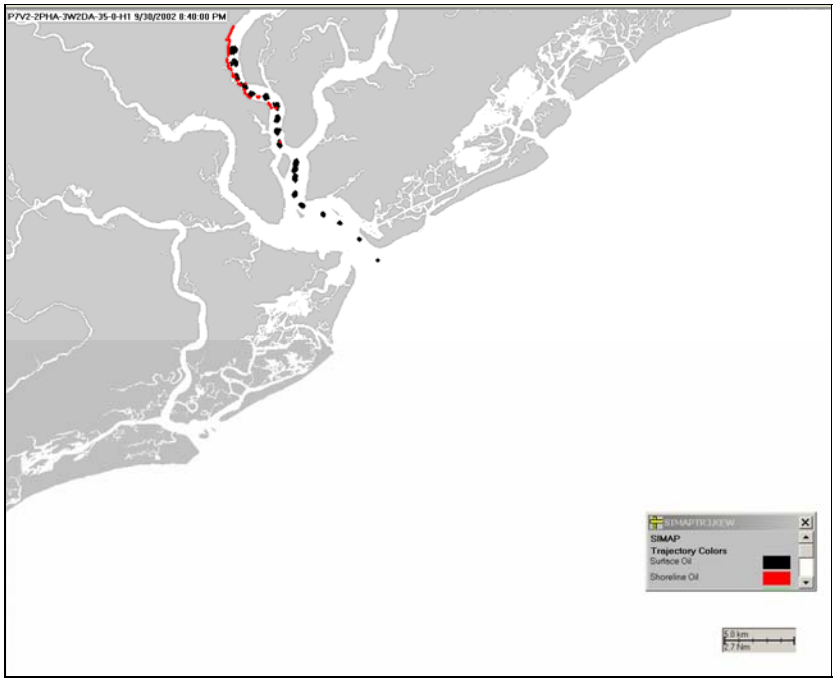

Figure F.2-2. Trajectory of surface oil at 20:40 on 30 September 2002.

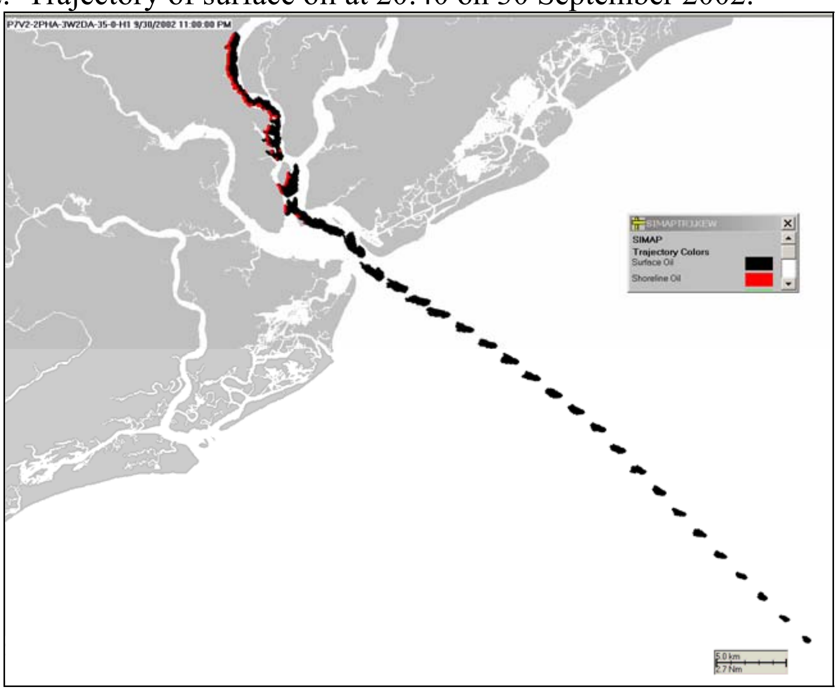

Figure F.2-3. Trajectory of surface oil at 23:00 on 30 September 2002.

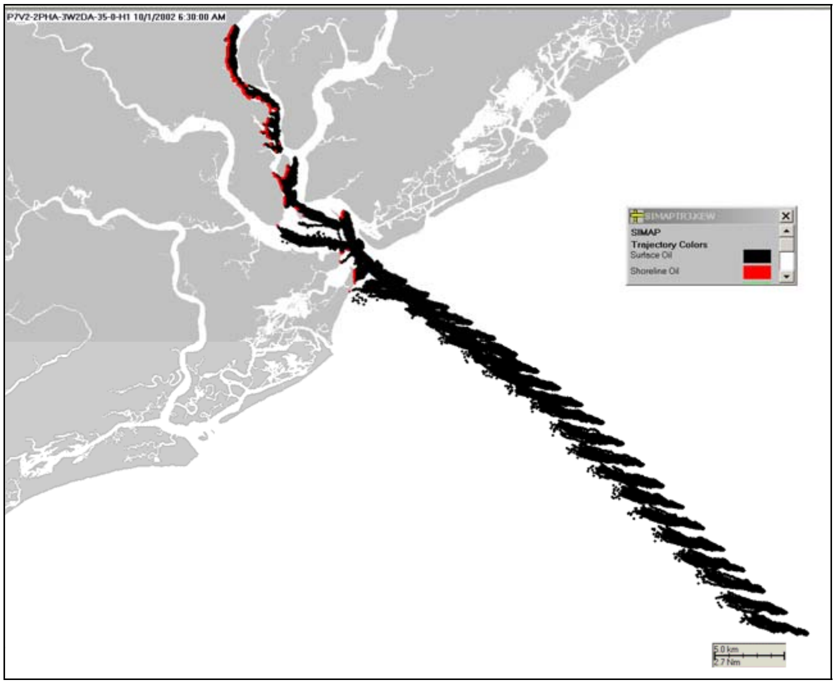

Figure F.2-4. Trajectory of surface oil at 06:30 on 01 October 2002.

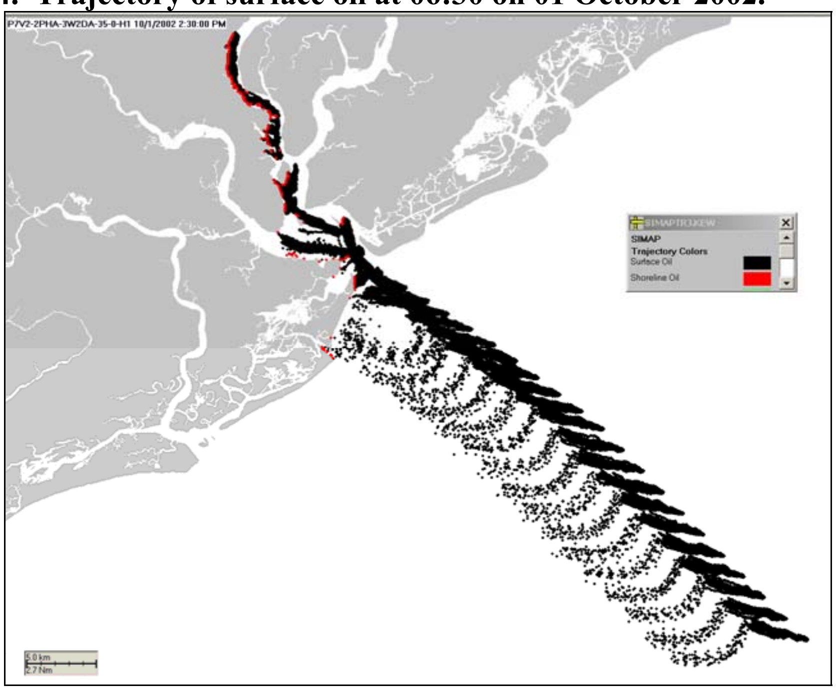

Figure F.2-5. Trajectory of surface oil at 14:30 on 01 October 2002.

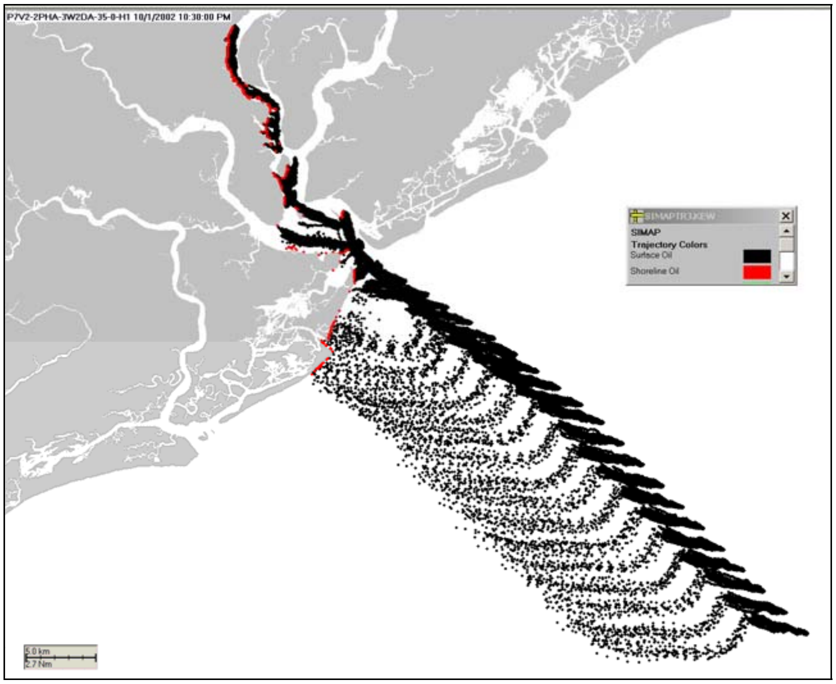

Figure F.2-6. Trajectory of surface oil at 22:30 on 01 October 2002.

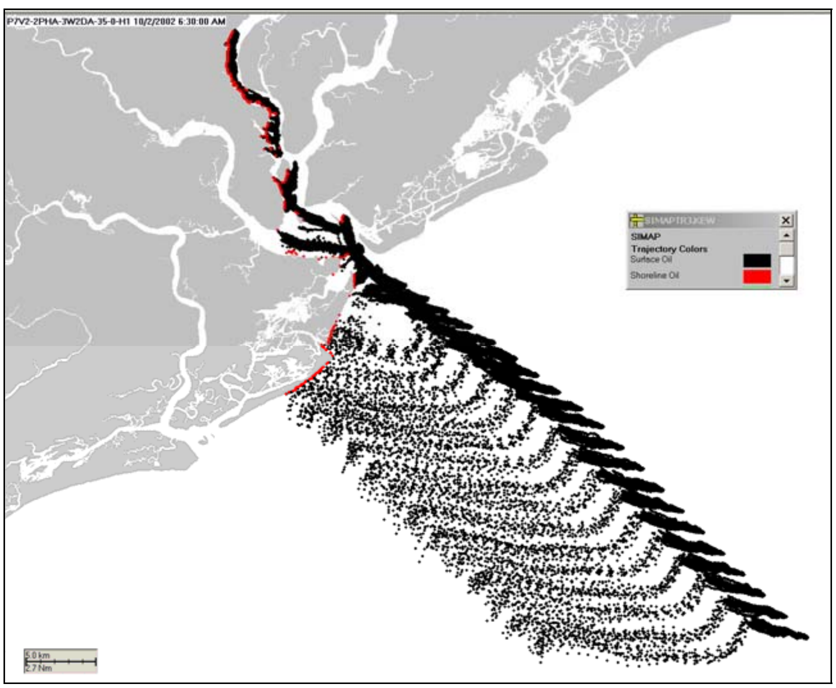

Figure F.2-7. Trajectory of surface oil at 06:30 on 02 October 2002.

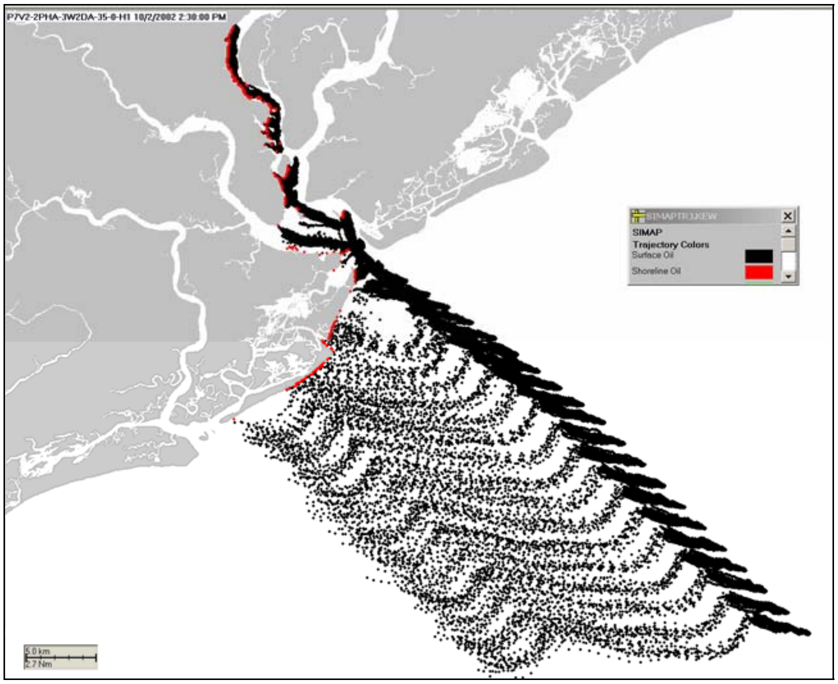

Figure F.2-8. Trajectory of surface oil at 14:30 on 02 October 2002.

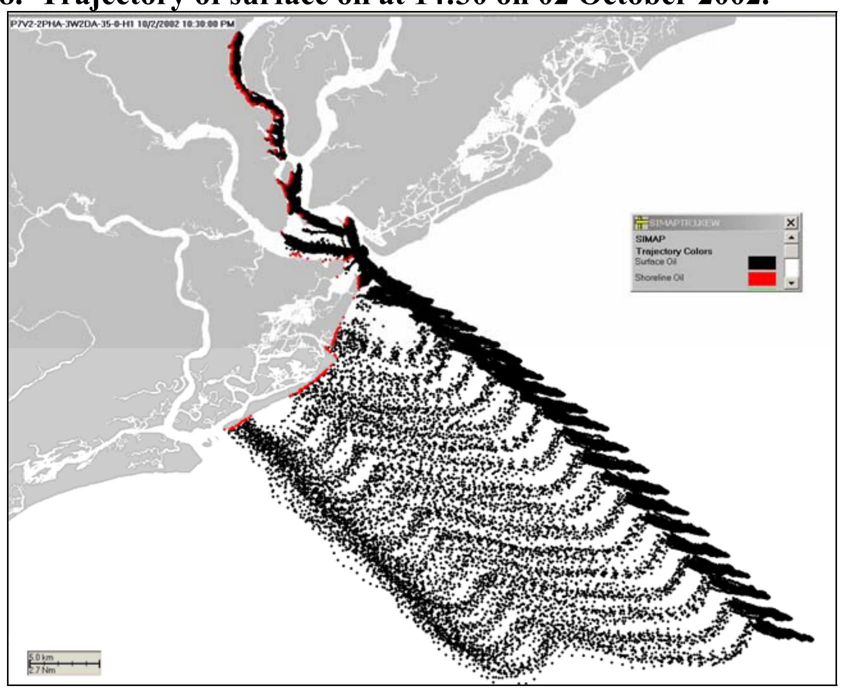

Figure F.2-9. Trajectory of surface oil at 22:30 on 02 October 2002.

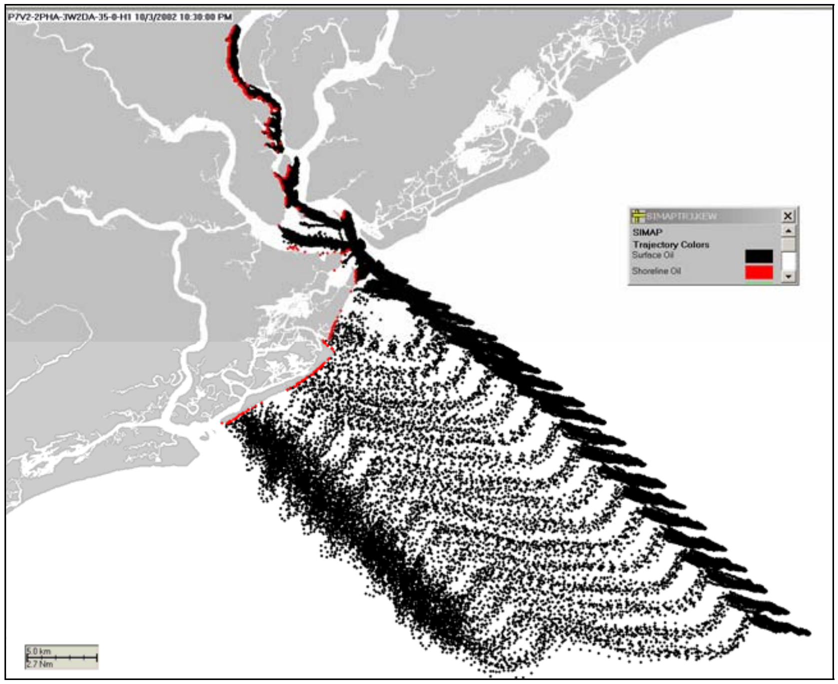

Figure F.2-10. Trajectory of surface oil at 22:30 on 03 October 2002.

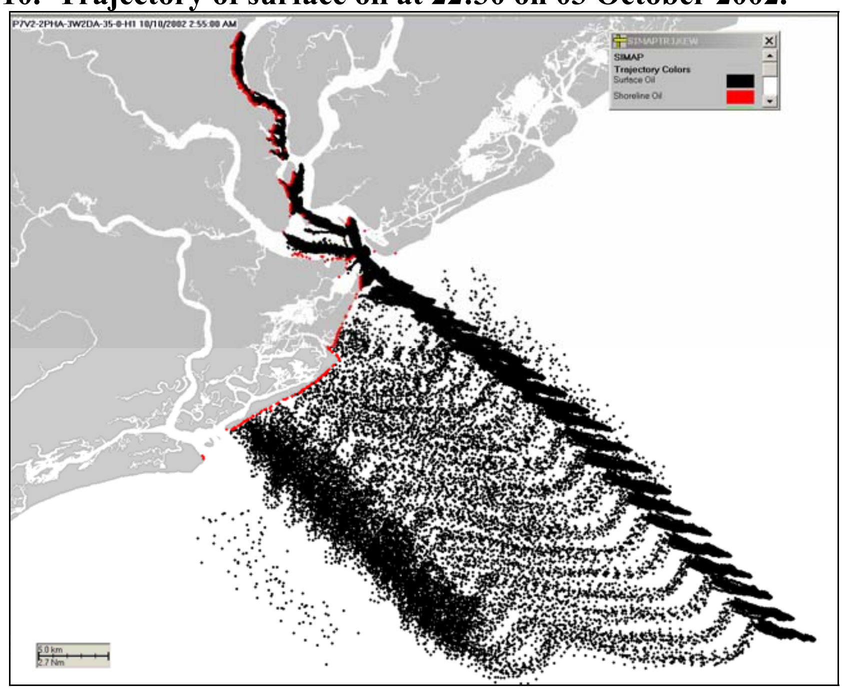

Figure F.2-11. Trajectory of surface oil at end of simulations (02:55 on 10 October 2002).

F.3 Contamination on Shorelines and in Sediments

The following figures show mass of total hydrocarbons remaining on shorelines at the end of the simulations. Sediment contamination was negligible in all the simulations. No shoreline cleanup was simulated in the model. Thus, oil simply accumulates and remains on the shore.

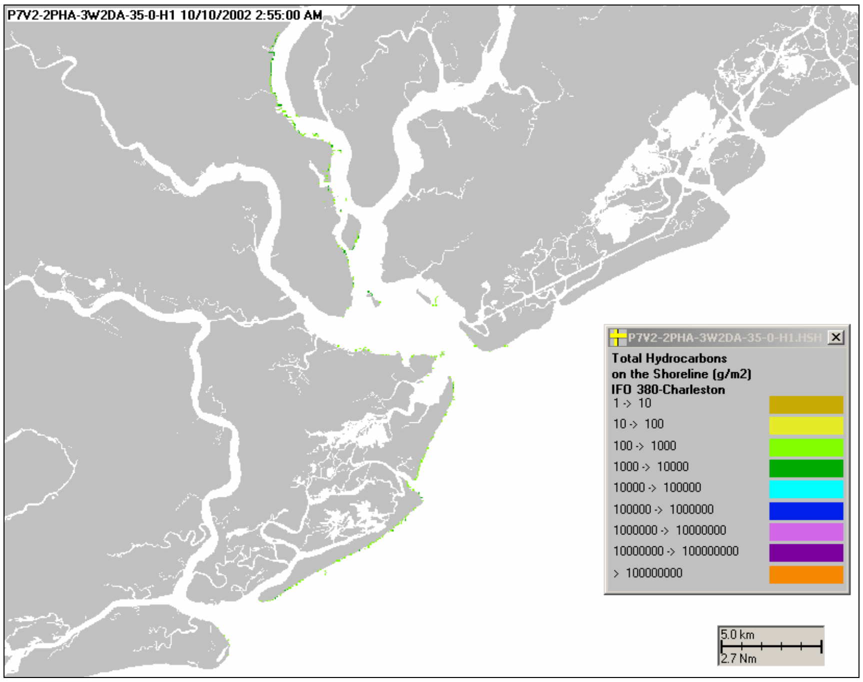

Figure F.3-1. Total hydrocarbons on shorelines for the base case (P7V2-2PHA-3W2DA-35-0-H1).

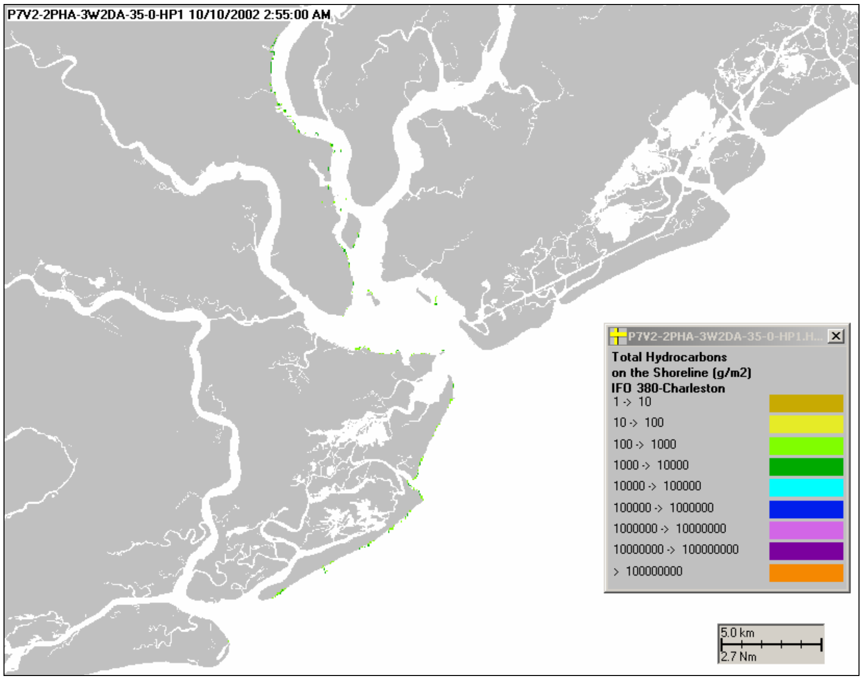

Figure F.3-2. Total hydrocarbons on shorelines for the case with the horizontal diffusion coefficient changed to 0.1 m^2/sec (P7V2-2PHA-3W2DA-35-0-Hp1).

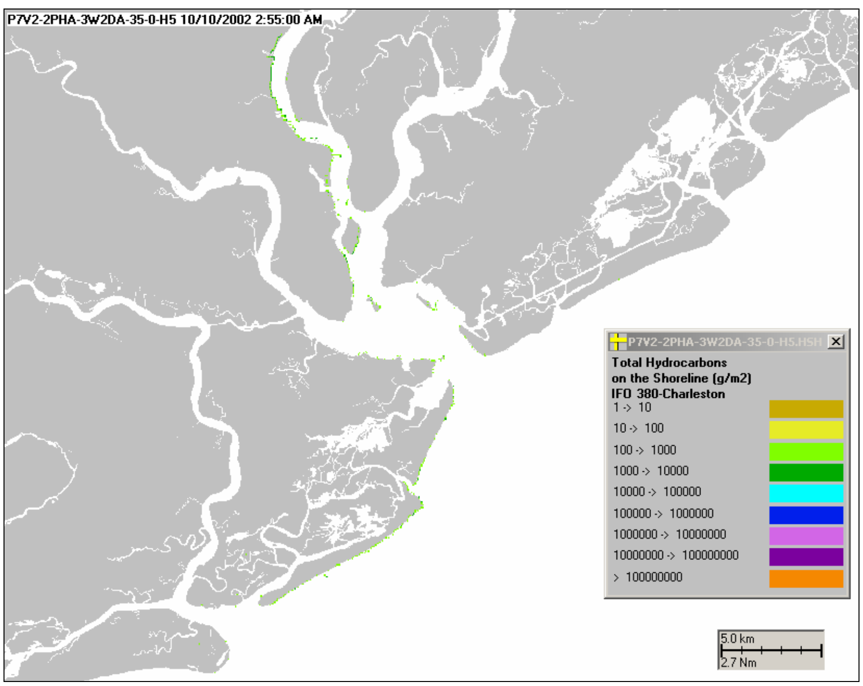

Figure F.3-3. Total hydrocarbons on shorelines for the case with the horizontal diffusion coefficient changed to 5.0 m^2/sec (P7V2-2PHA-3W2DA-35-0-H5).

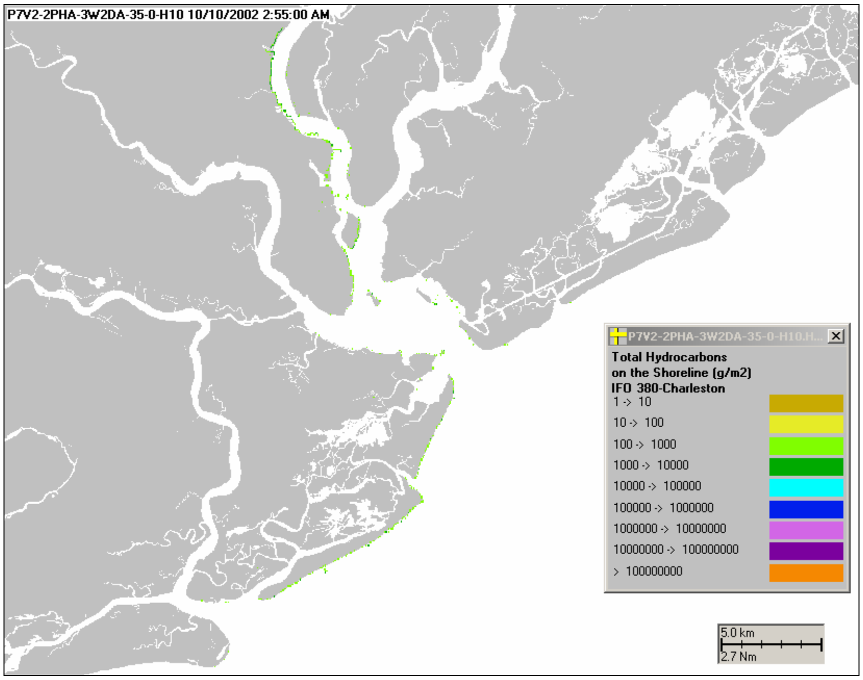

Figure F.3-4. Total hydrocarbons on shorelines for the case with the horizontal diffusion coefficient changed to 10.0 m^2/sec (P7V2-2PHA-3W2DA-35-0-H10).

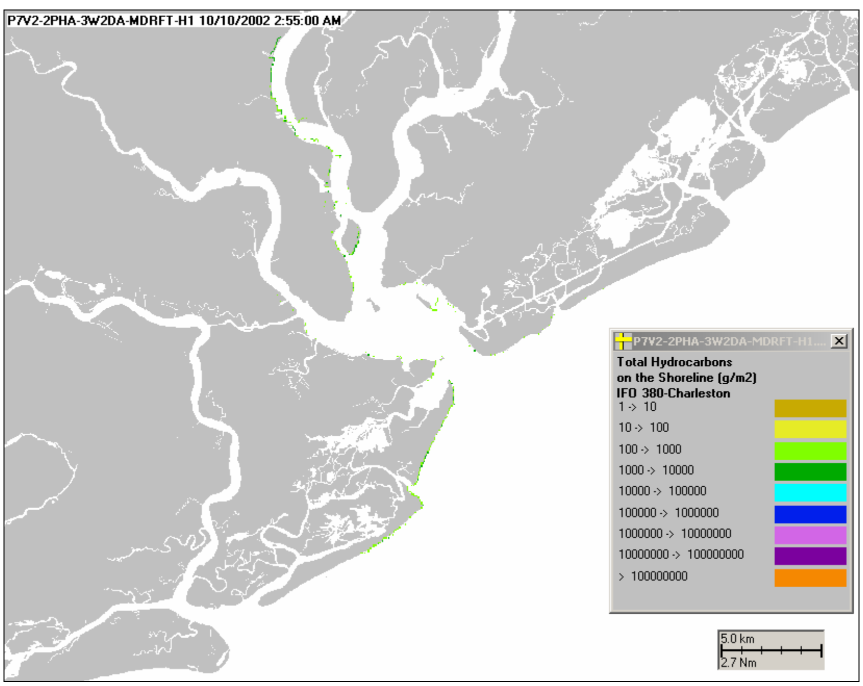

Figure F.3-5. Total hydrocarbons on shorelines for the case with model drift calculated by the model and the horizontal diffusion coefficient 1.0 m^2/sec (P7V2-2PHA-3W2DA-MDRFT-H1).

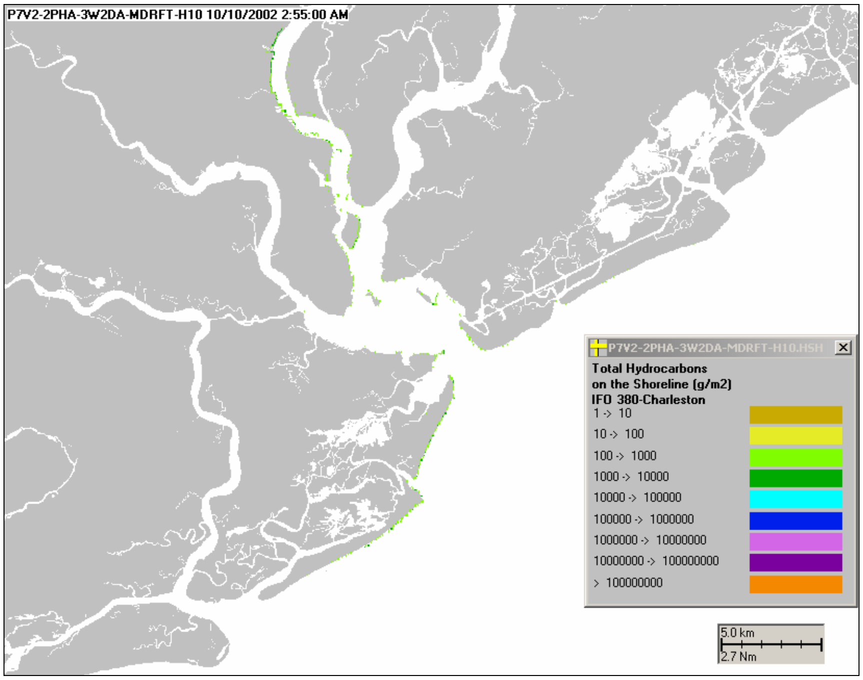

Figure F.3-6. Total hydrocarbons on shorelines for the case with model drift calculated by the model and the horizontal diffusion coefficient 10.0 m^2/sec (P7V2-2PHA-3W2DA- MDRFT-H10).

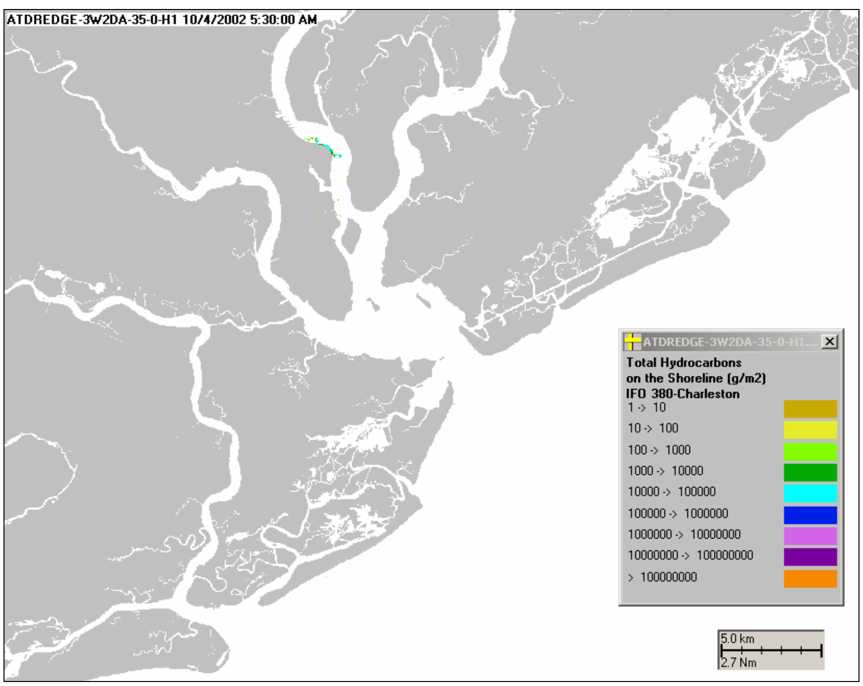

Figure F.3-7. Total hydrocarbons on shorelines for the case where the spill is assumed instantaneous at the submerged dredge site (AtDredge-3W2DA-35-0-H1).

F.4 Floating Oil Distribution

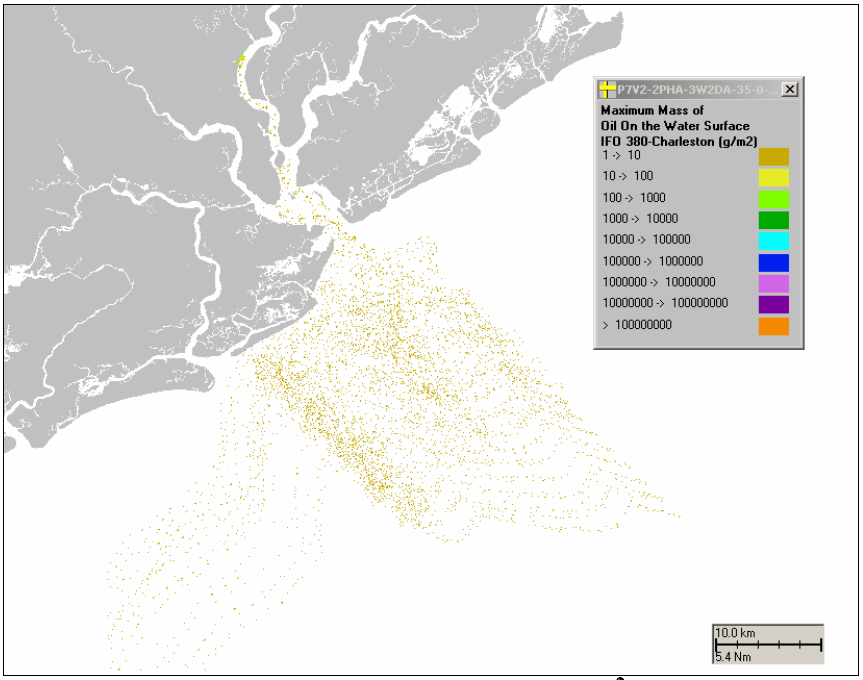

Figure F.4-1. The maximum amount of surface oil (g/m^2) passing through each model grid cell.

APPENDIX G. BIOLOGICAL DATA FOR FISH AND INVERTEBRATES

Biological data used as model inputs are listed in this appendix. Data for fish and invertebrates are in Tables G-1 to G-3. All of the data were obtained from French et al. (1996c) using province 21, for South Carolina coastal waters

Table G-1. Fish and invertebrate densities (kg/km^2) by habitat.

Species group	Habitat	Winter	Spring	Summer	Fall
Atlantic anchovies	Seaward Open Water	29	68	11	27
	Landward Open Water	0.7	24	7	6
	Swd Wetland/Seagrass	0.7	24	7	6
	Seaward Reef	0.7	24	7	6
	Lwd Wetland/Seagrass	0.7	24	7	6
	Landward Reef	0.7	24	7	6
Atlantic mackerel	Seaward Open Water	7	5	2	31
Atlantic menhaden	Landward Open Water	1198	221	9	13
	Swd Wetland/Seagrass	1198	221	9	13
	Seaward Reef	1198	221	9	13
	Lwd Wetland/Seagrass	1198	221	9	13
	Landward Reef	1198	221	9	13
Bay anchovy	Landward Open Water	27	39	4	20
	Swd Wetland/Seagrass	27	39	4	20
	Seaward Reef	27	39	4	20
	Lwd Wetland/Seagrass	27	39	4	20
	Landward Reef	27	39	4	20
Butterfish	Seaward Open Water	186	177	5	20
	Landward Open Water	59	24	12	16
	Swd Wetland/Seagrass	59	24	12	16
	Seaward Reef	59	24	12	16
	Lwd Wetland/Seagrass	59	24	12	16
	Landward Reef	59	24	12	16
Sardines	Seaward Open Water	132	150	10	222
Spanish sardine	Seaward Open Water	3	19	110	219
Striped anchovy	Seaward Open Water	44	1	0	30
	Landward Open Water	9	22	40	107
	Swd Wetland/Seagrass	9	22	40	107
	Seaward Reef	9	22	40	107
	Lwd Wetland/Seagrass	9	22	40	107
	Landward Reef	9	22	40	107
Thread herrings	Landward Open Water	9	26	21	40
	Swd Wetland/Seagrass	9	26	21	40
	Seaward Reef	9	26	21	40
	Lwd Wetland/Seagrass	9	26	21	40
	Landward Reef	9	26	21	40

Atlantic bumper	Seaward Open Water	0	18	392	1
	Landward Open Water	0	315	104	16
	Swd Wetland/Seagrass	0	315	104	16
	Seaward Reef	0	315	104	16
	Lwd Wetland/Seagrass	0	315	104	16
	Landward Reef	0	315	104	16
Atlantic moonfish	Landward Open Water	0	6	13	22
	Swd Wetland/Seagrass	0	6	13	22
	Seaward Reef	0	6	13	22
	Lwd Wetland/Seagrass	0	6	13	22
	Landward Reef	0	6	13	22
Blue runner	Seaward Open Water	0	0	2	0
Bluefish	Seaward Open Water	0	0	0	30
	Landward Open Water	27	77	25	84
	Swd Wetland/Seagrass	27	77	25	84
	Seaward Reef	27	77	25	84
	Lwd Wetland/Seagrass	27	77	25	84
	Landward Reef	27	77	25	84
Scads	Seaward Open Water	29	170	176	484
Cobia	Seaward Open Water	68	37	25	245
Dogfish, general	Seaward Open Water	295	51	0	0
Hakes (similar)	Seaward Open Water	66	56	21	129
King mackerel	Seaward Open Water	98	98	98	98
	Landward Open Water	98	98	98	98
	Swd Wetland/Seagrass	98	98	98	98
	Seaward Reef	98	98	98	98
	Lwd Wetland/Seagrass	98	98	98	98
	Landward Reef	98	98	98	98
Kingfish	Seaward Open Water	26	6	0	9
	Landward Open Water	108	159	402	543
	Swd Wetland/Seagrass	108	159	402	543
	Seaward Reef	108	159	402	543
	Lwd Wetland/Seagrass	108	159	402	543
	Landward Reef	108	159	402	543
Northern searobin	Landward Open Water	0.1	161	102	1
	Swd Wetland/Seagrass	0.1	161	102	1
	Seaward Reef	0.1	161	102	1
	Lwd Wetland/Seagrass	0.1	161	102	1
	Landward Reef	0.1	161	102	1
Silver sea trout	Seaward Open Water	0	0	5	1
	Landward Open Water	11	89	86	406
	Swd Wetland/Seagrass	11	89	86	406
	Seaward Reef	11	89	86	406
	Lwd Wetland/Seagrass	11	89	86	406
	Landward Reef	11	89	86	406

Snappers, general	Seaward Open Water	12	45	28	52
Spanish mackerel	Seaward Open Water	50	50	50	50
	Landward Open Water	25	25	25	25
	Swd Wetland/Seagrass	25	25	25	25
	Seaward Reef	25	25	25	25
	Lwd Wetland/Seagrass	25	25	25	25
	Landward Reef	25	25	25	25
Weakfish	Seaward Open Water	0	0	1	0
	Landward Open Water	84	158	34	98
	Swd Wetland/Seagrass	84	158	34	98
	Seaward Reef	84	158	34	98
	Lwd Wetland/Seagrass	84	158	34	98
	Landward Reef	84	158	34	98
Atlantic croaker	Seaward Open Water	24	8	9	58
	Landward Open Water	3483	348	408	256
	Swd Wetland/Seagrass	3483	348	408	256
	Seaward Reef	3483	348	408	256
	Lwd Wetland/Seagrass	3483	348	408	256
	Landward Reef	3483	348	408	256
Black drum	Seaward Open Water	54	0	0	0
Black sea bass	Seaward Open Water	6	14	3	55
Catfishes, general	Seaward Open Water	0	43	51	23
	Landward Open Water	0	74	406	6
	Swd Wetland/Seagrass	0	74	406	6
	Seaward Reef	0	74	406	6
	Lwd Wetland/Seagrass	0	74	406	6
	Landward Reef	0	74	406	6
Cutlassfishes	Landward Open Water	44	44	101	68
	Swd Wetland/Seagrass	44	44	101	68
	Seaward Reef	44	44	101	68
	Lwd Wetland/Seagrass	44	44	101	68
	Landward Reef	44	44	101	68
Drums, general	Landward Open Water	5	139	373	48
	Swd Wetland/Seagrass	5	139	373	48
	Seaward Reef	5	139	373	48
	Lwd Wetland/Seagrass	5	139	373	48
	Landward Reef	5	139	373	48
Flatfish	Landward Open Water	42	125	40	359
	Swd Wetland/Seagrass	42	125	40	359
	Seaward Reef	42	125	40	359
	Lwd Wetland/Seagrass	42	125	40	359
	Landward Reef	42	125	40	359

Flounders	Seaward Open Water	53	68	56	40
	Landward Open Water	4	8	38	11
	Swd Wetland/Seagrass	4	8	38	11
	Seaward Reef	4	8	38	11
	Lwd Wetland/Seagrass	4	8	38	11
	Landward Reef	4	8	38	11
Fringed flounder	Landward Open Water	15	11	46	43
	Swd Wetland/Seagrass	15	11	46	43
	Seaward Reef	15	11	46	43
	Lwd Wetland/Seagrass	15	11	46	43
	Landward Reef	15	11	46	43
Groupers, general	Seaward Open Water	0	0	23	0
Grunts, general	Seaward Open Water	24	24	6	124
Hogchoker	Landward Open Water	0.9	95	38	48
	Swd Wetland/Seagrass	0.9	95	38	48
	Seaward Reef	0.9	95	38	48
	Lwd Wetland/Seagrass	0.9	95	38	48
	Landward Reef	0.9	95	38	48
Lizardfish	Seaward Open Water	56	152	103	114
Porgies=sparids,gen	Seaward Open Water	189	951	340	1174
Rays, general	Seaward Open Water	2406	4584	1708	1134
Rock sea bass	Landward Open Water	4	10	69	59
	Swd Wetland/Seagrass	4	10	69	59
	Seaward Reef	4	10	69	59
	Lwd Wetland/Seagrass	4	10	69	59
	Landward Reef	4	10	69	59
Sand perch	Seaward Open Water	48	112	105	57
Spot	Seaward Open Water	88	52	15	48
	Landward Open Water	3864	6127	1257	1090
	Swd Wetland/Seagrass	3864	6127	1257	1090
	Seaward Reef	3864	6127	1257	1090
	Lwd Wetland/Seagrass	3864	6127	1257	1090
	Landward Reef	3864	6127	1257	1090
Triggerfish	Seaward Open Water	280	488	135	237
Windowpane flounder	Landward Open Water	6	82	62	47
	Swd Wetland/Seagrass	6	82	62	47
	Seaward Reef	6	82	62	47
	Lwd Wetland/Seagrass	6	82	62	47
	Landward Reef	6	82	62	47
Blue crab	Seaward Open Water	55.5	95	0	204
	Landward Open Water	0	95	7965	204
	Swd Wetland/Seagrass	0	95	7965	204
	Seaward Reef	0	95	7965	204
	Lwd Wetland/Seagrass	0	95	7965	204
	Landward Reef	0	95	7965	204

Brown shrimp	Seaward Open Water	1.7	0.6	13.1	12.2
	Landward Open Water	1.7	0.6	13.1	12.2
	Swd Wetland/Seagrass	1.7	0.6	13.1	12.2
	Seaward Reef	1.7	0.6	13.1	12.2
	Lwd Wetland/Seagrass	1.7	0.6	13.1	12.2
	Landward Reef	1.7	0.6	13.1	12.2
Pink shrimp	Seaward Open Water	0.3	0.3	0.4	0.4
Stone crab	Seaward Open Water	0.4	0.4	0.4	0.4
	Landward Open Water	0.4	0.4	0.4	0.4
	Swd Wetland/Seagrass	0.4	0.4	0.4	0.4
	Seaward Reef	0.4	0.4	0.4	0.4
	Lwd Wetland/Seagrass	0.4	0.4	0.4	0.4
	Landward Reef	0.4	0.4	0.4	0.4
White shrimp	Seaward Open Water	1.1	7.2	10.8	1.6
	Landward Open Water	1.1	7.2	10.8	1.6
	Swd Wetland/Seagrass	1.1	7.2	10.8	1.6
	Seaward Reef	1.1	7.2	10.8	1.6
	Lwd Wetland/Seagrass	1.1	7.2	10.8	1.6
	Landward Reef	1.1	7.2	10.8	1.6
Squid, general	Seaward Open Water	0.2	0.2	0.2	0.2
	Landward Open Water	0.2	0.2	0.2	0.2
	Swd Wetland/Seagrass	0.2	0.2	0.2	0.2
	Seaward Reef	0.2	0.2	0.2	0.2
	Lwd Wetland/Seagrass	0.2	0.2	0.2	0.2
	Landward Reef	0.2	0.2	0.2	0.2
Bay scallop	Landward Open Water	12.1	12.1	12.1	12.1
	Swd Wetland/Seagrass	12.1	12.1	12.1	12.1
	Seaward Reef	12.1	12.1	12.1	12.1
	Lwd Wetland/Seagrass	12.1	12.1	12.1	12.1
	Landward Reef	12.1	12.1	12.1	12.1
Conchs, whelks, gen.	Seaward Open Water	5.7	5.7	5.7	5.7
	Landward Open Water	5.7	5.7	5.7	5.7
	Swd Wetland/Seagrass	5.7	5.7	5.7	5.7
	Seaward Reef	5.7	5.7	5.7	5.7
	Lwd Wetland/Seagrass	5.7	5.7	5.7	5.7
	Landward Reef	5.7	5.7	5.7	5.7
Hard clams, general	Landward Open Water	1000	1000	1000	1000
	Swd Wetland/Seagrass	1000	1000	1000	1000
	Seaward Reef	1000	1000	1000	1000
	Lwd Wetland/Seagrass	1000	1000	1000	1000
	Landward Reef	1000	1000	1000	1000

Octopus, general	Seaward Open Water	0.4	0.4	0.4	0.4
	Landward Open Water	0.4	0.4	0.4	0.4
	Swd Wetland/Seagrass	0.4	0.4	0.4	0.4
	Seaward Reef	0.4	0.4	0.4	0.4
	Lwd Wetland/Seagrass	0.4	0.4	0.4	0.4
	Landward Reef	0.4	0.4	0.4	0.4
Total all species	Seaward Open Water	4338.3	7556.8	3521	4936.9
	Landward Open Water	10145.3	9628.601	12827.7	4766.6
	Swd Wetland/Seagrass	10145.3	9628.601	12827.7	4766.6
	Seaward Reef	10145.3	9628.601	12827.7	4766.6
	Lwd Wetland/Seagrass	10145.3	9628.601	12827.7	4766.6
	Landward Reef	10145.3	9628.601	12827.7	4766.6

Table G-2. Fish and invertebrate young-of-the-year densities (# age-1 equivalents/km^2) by habitat, as seasonal means.

Species group	Habitat	Winter	Spring	Summer	Fall
Bay anchovy	Seaward Open Water	530.43	440.9	165.4	255.83
	Landward Open Water	310.7	786.03	2249.33	1769
Cobia	Seaward Open Water	4.52	3.93	5.53	4.61
	Landward Open Water	4.52	3.32	2.9	4.38
Spanish mackerel	Landward Open Water	2.12	2.12	2.12	2.12
Weakfish	Landward Open Water	704.8	704.73	704.77	704.8
Black sea bass	Seaward Open Water	6.01	42.2	2.86	0
	Landward Open Water	296.5	140.25	324.9	324.9
	Swd Wetland/Seagrass	296.5	140.25	324.9	324.9
	Seaward Reef	296.5	140.25	324.9	324.9
	Lwd Wetland/Seagrass	296.5	140.25	324.9	324.9
	Landward Reef	296.5	140.25	324.9	324.9
Grunts, general	Seaward Open Water	173.76	173.76	173.76	173.76
Spot	Seaward Open Water	4.85	1.52	0	3.3
	Landward Open Water	311.7	417.63	466.2	361.07
Blue crab	Seaward Open Water	43.72	305.6	308	165.91
	Landward Open Water	52873.34	45362.04	45294	49371.53
Stone crab	Seaward Open Water	0	97.57	114.8	54.19
	Landward Open Water	4637	4118.67	4027	4349
White shrimp	Seaward Open Water	174.07	125	177.33	192.8
	Landward Open Water	16.17	58.49	13.35	0
	Swd Wetland/Seagrass	16.17	58.49	13.35	0
	Seaward Reef	16.17	58.49	13.35	0
	Lwd Wetland/Seagrass	16.17	58.49	13.35	0
	Landward Reef	16.17	58.49	13.35	0
Bay scallop	Landward Open Water	320	320	319.95	319.93
Total all species	Seaward Open Water	937.36	1190.48	947.67	850.41
	Landward Open Water	59476.84	51913.28	53404.52	57206.74
	Swd Wetland/Seagrass	312.67	198.74	338.25	324.9
	Seaward Reef	312.67	198.74	338.25	324.9
	Lwd Wetland/Seagrass	312.67	198.74	338.25	324.9
	Landward Reef	312.67	198.74	338.25	324.9

Table G-3. Fish and invertebrate life history parameters.
(M = annual instantaneous natural mortality rate, F = annual instantaneous fishing mortality rate; YrRecr = age of recruitment (yr), Life = maximum age (yrs); Lmax, K, to = von Bertallanfy parameters; a,b =wt(kg)-L(cm) parameters; kg-max = maximum weight in kg)

Species group	M	F	YrRecr	Life	Lmax(cm)	K	to	a	b	kg-max
Atlantic anchovies	1.5	1	1	3	12	0.28	-1.1	0	2.81	0.012
Atlantic mackerel	0.15	0.02	2	20	42.9	0.36	-1.14	0	3.21	0.695
Atlantic menhaden	1.1	0.43	2	4	23.8	0.493	-0.385	0	3.25	0.286
Bay anchovy	1.5	1	1	3	12	0.28	-1.1	0	2.81	0.012
Butterfish	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Sardines	1	0.13	1	13	29	0.45	0	0	3	0.146
Spanish sardine	1	0.13	1	13	29	0.45	0	0	3	0.146
Striped anchovy	1.5	1	1	3	12	0.28	-1.1	0	2.81	0.012
Thread herrings	1	0.13	1	13	29	0.45	0	0	3	0.146
Atlantic bumper	0.2	0.4	2	10	165	0.173	-0.653	0	2.84	57.749
Atlantic moonfish	0.2	0.4	2	10	165	0.173	-0.653	0	2.84	57.749
Blue runner	0.2	0.4	2	10	165	0.173	-0.653	0	2.84	57.749
Bluefish	0.35	0.35	1	9	94.4	0.18	-1.033	0	2.99	11.575
Scads	0.2	0.4	2	10	165	0.173	-0.653	0	2.84	57.749
Cobia	0.4	0.3	2	10	143	0.253	0.07	0	3.09	36.566
Dogfish, general	0.05	0.08	1	28	96	0.093	0	0	3.15	3.334
Hakes (similar)	0.4	0.56	2	15	50.7	0.246	0	0	3.1	7.681
King mackerel	0.51	0.29	2	7	67.2	0.328	-1.085	0	3.06	3.633
Kingfish	0.45	0.24	3	5	77.4	0.09	-2.54	0	3.11	4.489
Northern searobin	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Silver sea trout	0.45	0.24	3	5	77.4	0.09	-2.54	0	3.11	4.489
Snappers, general	0.2	0.53	2	13	58.2	0.076	-1.268	0	2.93	2.314
Spanish mackerel	0.51	0.29	2	7	67.2	0.328	-1.085	0	3.06	3.633
Weakfish	0.45	0.24	3	5	77.4	0.09	-2.54	0	3.11	4.489
Atlantic croaker	0.15	0.86	2	27	105.3	0.29	-0.636	0	3.05	15.768

Black drum	0.15	0.86	2	27	105.3	0.29	-0.636	0	3.05	15.768
Black sea bass	0.3	0.3	1	10	35	0.222	0.186	0	3.02	1.289
Catfishes, general	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Cutlassfishes	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Drums, general	0.15	0.86	2	27	105.3	0.29	-0.636	0	3.05	15.768
Flatfish	0.1	0.3	2	9	146.1	0.031	0.137	0	2.95	67.085
Flounders	0.1	0.3	2	9	146.1	0.031	0.137	0	2.95	67.085
Fringed flounder	0.1	0.3	2	9	146.1	0.031	0.137	0	2.95	67.085
Groupers, general	0.3	0.3	1	10	35	0.222	0.186	0	3.02	1.289
Grunts, general	0.6	0.4	1	11	47.5	0.164	-1.144	0	3.06	1.729
Hogchoker	0.1	0.3	2	9	146.1	0.031	0.137	0	2.95	67.085
Lizardfish	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Porgies=sparids,gen	0.2	0.3	5	20	76.3	0.096	-1.88	0	2.89	5.46
Rays, general	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Rock sea bass	0.3	0.3	1	10	35	0.222	0.186	0	3.02	1.289
Sand perch	0.3	0.3	1	10	35	0.222	0.186	0	3.02	1.289
Spot	0.15	0.86	2	27	105.3	0.29	-0.636	0	3.05	15.768
Triggerfish	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Windowpane flounder	0.1	0.3	2	9	146.1	0.031	0.137	0	2.95	67.085
Blue crab	0.1	2.3	1	3	24	0.75	0	0	2.71	0.644
Brown shrimp	3.3	3.2	1	1	19.6	2.4	0	0	3.21	0.094
Pink shrimp	3.3	3.2	1	1	19.6	2.4	0	0	3.21	0.094
Stone crab	0.7	0.3	3	7	14	0.173	-0.397	0	3.3	0.012
White shrimp	3.3	3.2	1	1	19.6	2.4	0	0	3.21	0.094
Squid, general	0.3	0.1	1	1	28.5	0.7	0	0	2.29	0.73
Bay scallop	0.1	1	1	2	6.4	1.95	0.058	0	2.93	0.041
Conchs, whelks, gen.	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125
Hard clams, general	0.1	0.3	3	20	8.5	0.333	0.594	0	2.83	0.066
Octopus, general	0.1	0.2	3	20	50	0.1	0.1	0	3	0.125