Appendix 3: ROUGE RIVER 2002 MYSTERY OIL SPILL REVISED SIMAP INJURY REPORT

Attachment A: State-of-the-Art and Research Needs for Oil Spill Impact Assessment Modeling

Attachment B: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Sensitivity Analysis for Trajectory

Attachment C: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Fates Model Results

Attachment D: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Biological Data

Attachment E: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Biological Model Results

Note: The attachments noted above are identified in the body of Appendix 3 as appendices to the report. In order to distinguish the appendices of the DARP / EA from supplementary materials to individual reports, they are referred to here as attachments. Where, in the body of this Appendix, there is a reference to an appendix (A-E), the reader should refer to the attachments (A-E) noted above.

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ROUGE RIVER 2002 MYSTERY OIL SPILL
REVISED SIMAP INJURY REPORT
Draft for Trustee Review

Submitted To:
Stephanie Millsap, Contaminants Specialist
U.S. Fish and Wildlife Service
USEPA LLRS
9311 Groh Rd.
Grosse Ile, MI 48138

Submitted By:
Jonathan R. Grant and Timothy J. Reilly
Lighthouse Technical Consultants, Inc.
Deborah French McCay, Jill Rowe, and Eileen Graham
Applied Science Associates, Inc. (ASA)

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EXECUTIVE SUMMARY

Oil spill modeling was performed for the 9 April 2002 oil spill into the Rouge River, MI. According to U.S. Environmental Protection Agency (EPA) reports, an estimated 255,544 gallons of mixed diesel and waste lubricating oil were visible on the waters of the Detroit River at or about mid-day on 10 April 2002 (Allen, 2002). The 255,544 gallons were identified as a portion of the 9 April oil spill that released oil into the Rouge River from an unknown source. Over the next few days, the spilled oil washed into the Detroit River, oiling 17 miles of the U.S. Detroit River coastline and 16 kilometers of the Canadian coastline. A second release of oil occurred from a similar release location on the night of 12 April 2002. Over the next two weeks, U.S. Coast Guard (USCG) pollution reports indicate that cleanup efforts removed 66,359 gallons of emulsion, which contained some lesser volume of oil, and much of the oiled coastal flora from the U.S. shorelines. A portion of the spill was contained within the Rouge River system with booms and most of the recovered oil was collected in this region. Oil was found in the nearby sewer system; thus, the source of the oil to the river was found to be the sewer system outfalls during and/or after a period of increased sewer flow during rain events in the area.

The objectives were to provide (1) an assessment of the pathways and fate of the oil; (2) an estimate exposure to the water surface, shoreline and other habitats, water column, and sediments; and (3) an estimate of injuries to wildlife, aquatic organisms, and habitats 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 Modeling Analysis Package). The physical fate 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. The biological exposure model in SIMAP estimates the area, volume, or portion of a stock or population affected by surface oil, concentrations of oil components in the water, and sediment contamination. Losses are estimated by species or species group for wildlife, fish and invertebrates by multiplying percent loss by species density.

The model uses incident-specific wind and current data, and transport algorithms, to calculate mass balance in various environmental compartments (water column, atmosphere, sediments, etc.) and concentrations of the oil components in water and sediments. Geographical data (habitat mapping and shoreline location) were obtained from existing Geographical Information System (GIS) databases. Depth data for the Rouge River were obtained from the National Oceanic and Atmospheric Administration (NOAA) hydrodynamic CATS model, while data for the Detroit River and Lake Erie were obtained from both the CATS model and from NOAA's National Geophysical Data Center (NGDC). Hourly wind speed and direction data during and after the spill were

obtained from nearby meteorological stations. Currents were modeled with CATS using wind forcing for the time period of the spill.

Specifications for the scenario (date, timing, amount, duration of release, etc.) were based on information obtained and distributed during the response through the U.S. EPA pollution reports (EPA), U.S. Fish and Wildlife Service reports (USFWS), U.S. Coast Guard press releases and pollution reports (USCG-Press and USCG-PolReps), NOAA SCAT maps, NOAA overflight maps, and material compiled by the Detroit Free Press (DFP).

To manage (and bound) uncertainty associated with oil spill release conditions, and in order to derive a best base case scenario, several uncertain model inputs were varied as a sensitivity analysis. Some of the parameters that were varied included duration and timing of the release; width of oiling on the shore; horizontal dispersion rate (i.e., the coefficient); droplet size distribution; current flow speed, and percentage of the total oil spill volume withheld after the initial first release in order to match observations of 1,000 gal of oil remaining within the Rouge River by noon on 10 April.

Table 1 lists the total injury of wildlife, including birds, mammals, reptiles, and amphibians, for the best base case scenario for the three areas (Rouge River, Detroit River and Lake Erie) impacted by the spill. Species affected with a total injury of greater than 100 individuals per species or species group include muskrat, waterfowl, such as common merganser, greater scaup, and lesser scaup, and seabirds, such as Bonapartes gull, herring gull, and double-crested cormorant.

Table 1. Summary of estimated injuries to wildlife resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie.

Wildlife Group	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Waterfowl (other than scaup)	410	25	436
Scaup*	4,106		4,106
Seabirds	737	1	738
Wading birds	10	-	10
Shorebirds	58	-	58
Mammals (Muskrats)	308	0	308
Reptiles	114	0	114
Amphibians	78	0	78
Total	**5,821**	**26**	**5,848**

* Scaups are assumed to be found in Lake Erie only in waters 1-3 meters deep.

It should be noted that it is uncertain what the pre-spill densities of birds and other wildlife were before the spill. The density data used for the modeling, which was best

available information, was from other locations and times (see Appendix D). However, the model results are directly proportional to the density data assumed. Therefore, if the densities assumed were a factor 2 lower, the injury results would also be a factor 2 lower. The counts of oiled animals observed oiled or dead in the field totaled 110 birds and 3 turtles. Thus, these model results suggest that one in 49 birds oiled were actually observed; whereas the rule of thumb for past spills has been about 1 in 10 might be observed. Yet, these ratios are highly uncertain, and dependant on the degree of search effort, losses to scavengers, and other factors. Estimates for the likelihood of observing oiled turtles are not available, but 1 in 100 is not unreasonable in this situation.

The injuries in fledgling or hatchling equivalents, as well as individual-years of loss, which are potential measures of injury useful in scaling restoration, are provided. Tables 2 and 3 list the equivalent losses for fledglings, hatchlings and age-one individuals, and the injury reported in equivalents losses for individual bird-, herptile- or mammal-years for the best base case scenario for the three areas (Rouge River, Detroit River and Lake Erie) impacted by the spill.

Table 2. Summary of estimated equivalent losses of bird fledglings, mammal age-zero (newly weaned) mammals, and herpetofauna hatchlings resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie.

	Equivalent Losses		
Wildlife Group	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Waterfowl (other than scaup) fledglings	1,401	84	1,485
Scaup fledglings*	14,332	-	14,332
Seabird fledglings	2,753	4	2,757
Wading bird fledglings	34	-	34
Shorebird fledglings	200	-	200
Muskrats (newly weaned)	940	-	940
Reptile hatchlings	1,700	-	1,700
Amphibian hatchlings	143,600	-	143,600
Total	**164,960**	**88**	**165,048**

* Scaups are assumed to be found in Lake Erie only in waters 1-3 meters deep.

Table 3. Summary of estimated injuries (interim loss) as individual bird-years, mammals-years and herptile years (all age classes combined for each group) resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie.

	Individual-years Lost (all ages)		
Wildlife Group	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Waterfowl (other than scaup)	1,057	78	1,135
Scaups*	8,855	-	8,855
Seabirds	11,977	16	11,992
Wading birds	31	-	31
Shorebirds	351	-	351
Muskrats	398	-	398
Reptiles	1,238	-	1,238
Amphibians	9,448	-	9,448
Total	**33,355**	**94**	**33,448**

* Scaups are assumed to be found in Lake Erie only in waters 1-3 meters deep.

Table 4 lists the total injury (interim loss) of fish as production forgone, i.e., the sum of the direct kill plus net growth normally to be expected of the killed organisms over the remainder of their life spans (lifetime production), for the best base case scenario using an $LC50_{\infty}$ (i.e., LC50 for infinite exposure time, which in the model is corrected for duration of exposure) value of 44ppb for species of average sensitivity to the diesel and lubricating oil mixture that was released during the spill.

Table 4. Summary of estimated injuries to fish resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie using a $LC50_{\infty}$ value of 44ppb for species of average sensitivity.

Fishery Species	Biomass Killed (kg)	Production Forgone (kg)	Total Injury (kg)
Total small pelagic fish	2.2	0.0	2.2
Total large pelagic fish	8.4	7.2	15.6
Total demersal fish	108	102	211
Total	**119**	**110**	**228**

1. INTRODUCTION

Oil spill modeling was performed for the 9 April 2002 oil spill into the Rouge River, MI. According to U.S. Environmental Protection Agency (EPA) reports, an estimated 255,544 gallons of mixed diesel and waste lubricating oil were visible on the waters of the Detroit River at or about mid-day on 10 April 2002 (Allen, 2002). The 255,544 gallons were identified as a portion of the 9 April oil spill that released oil into the Rouge River from an unknown source. Over the next few days, the spilled oil washed into the Detroit River, oiling 17 miles of the U.S. Detroit River coastline and 16 kilometers of the Canadian coastline. A second release of oil occurred from a similar release location on the night of 12 April 2002. Over the next two weeks, U.S. Coast Guard (USCG) pollution reports indicate that cleanup efforts removed 66,359 gallons of emulsion, which contained some lesser volume of oil, and much of the oiled coastal flora from the U.S. shorelines. A portion of the spill was contained within the Rouge River system with booms and most of the recovered oil was collected in this region. Oil was found in the nearby sewer system; thus, the source of the oil to the river was found to be the sewer system outfalls during and/or after a period of increased sewer flow during rain events in the area.

Surface oil was first observed by the Fort Street Bridge operator at 1000 (local time) on 9 April, and by the end of the day oil had been observed throughout the Rouge River and as far south as the Detroit River Light on Lake Erie. On 10 April, booms were deployed around sensitive areas throughout the Detroit River, including Elizabeth Park and Humbug Marsh, and at several locations within the Rouge River. NOAA SCAT reports indicated black oil windrows in the Detroit River south of the Rouge River; and shore oiling was observed along much of the western bank of the Detroit River (Figure 1-1). Overflights on 11 and 12 April found additional shore oiling and sheening on the banks and islands within the Detroit River (Figures 1-2 and 1-3). A second spill from a sewer outfall in the same location was reported on the morning of 13 April, involving a release of a significant amount of additional oil into the Rouge River. NOAA SCAT maps from 14 and 15 April indicated extensive staining on the western banks of the Detroit (Figures 1-4 and 1-5) and the final overflight on 16 April found sheening as far south as northwestern Lake Erie (Figure 1-6). Clean-up efforts continued for the next week and a reported 66,359 gallons of emulsion, which contains some lesser volume of oil, was removed from the Detroit and Rouge Rivers.

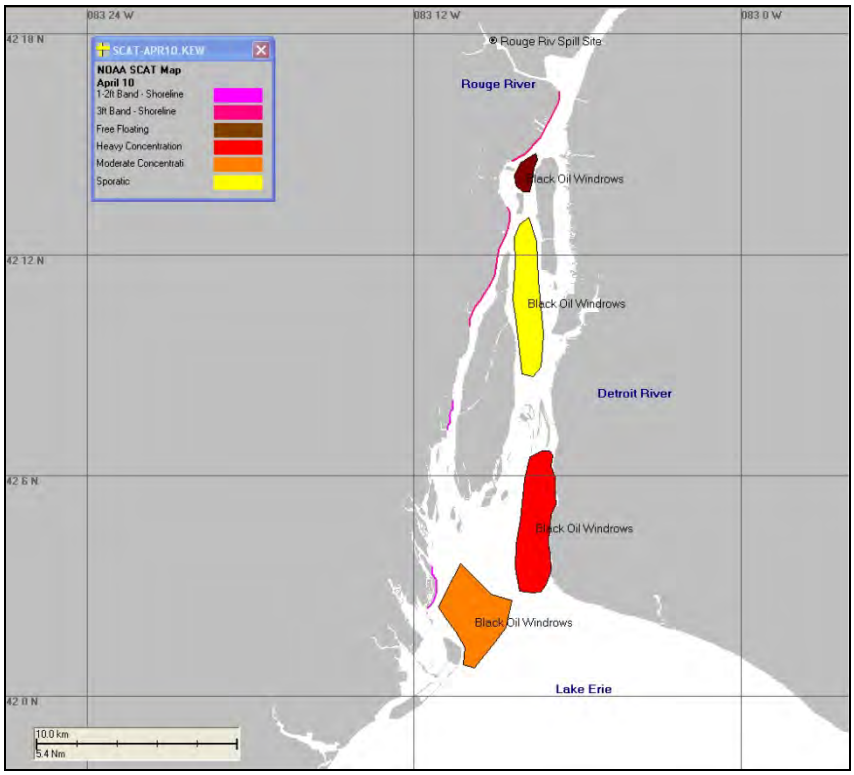

Figure 1-1. NOAA SCAT observations from 10 April 2002.

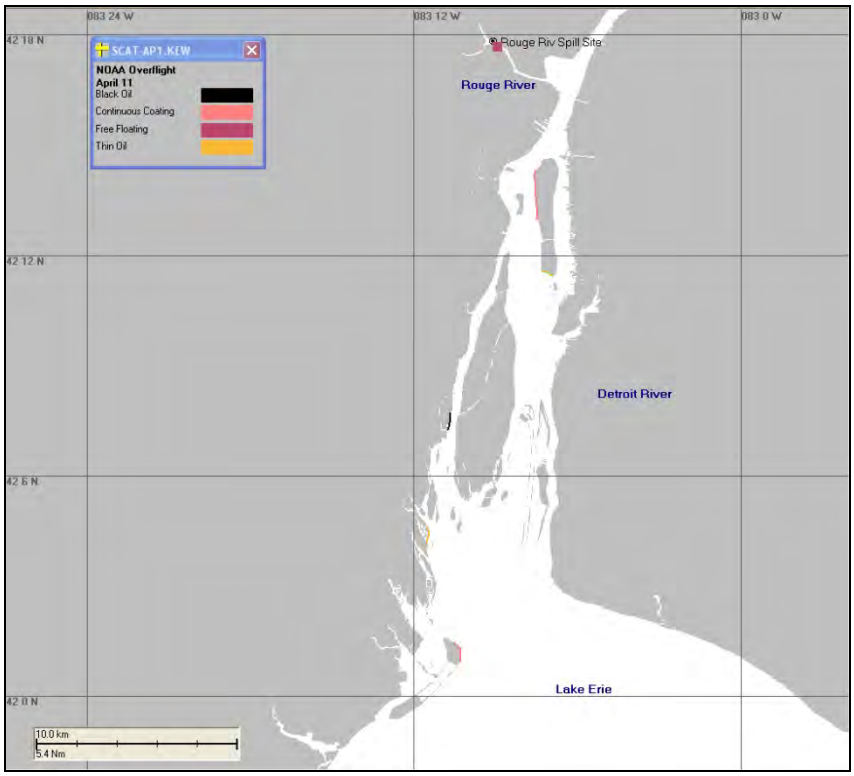

Figure 1-2. NOAA overflight observations from 11 April 2002.

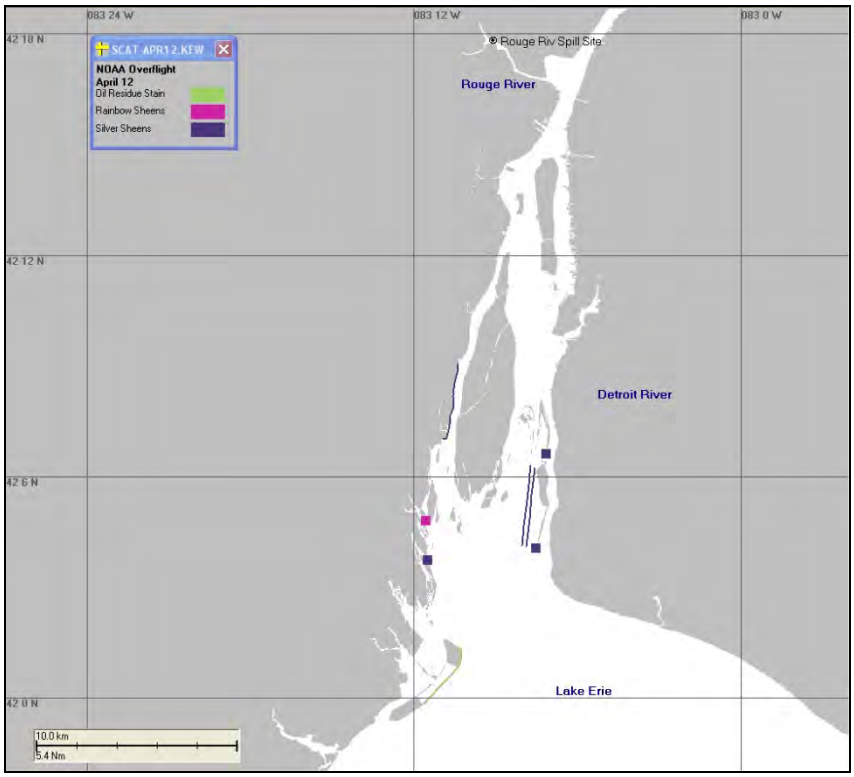

Figure 1-3. NOAA overflight observations from 12 April 2002.

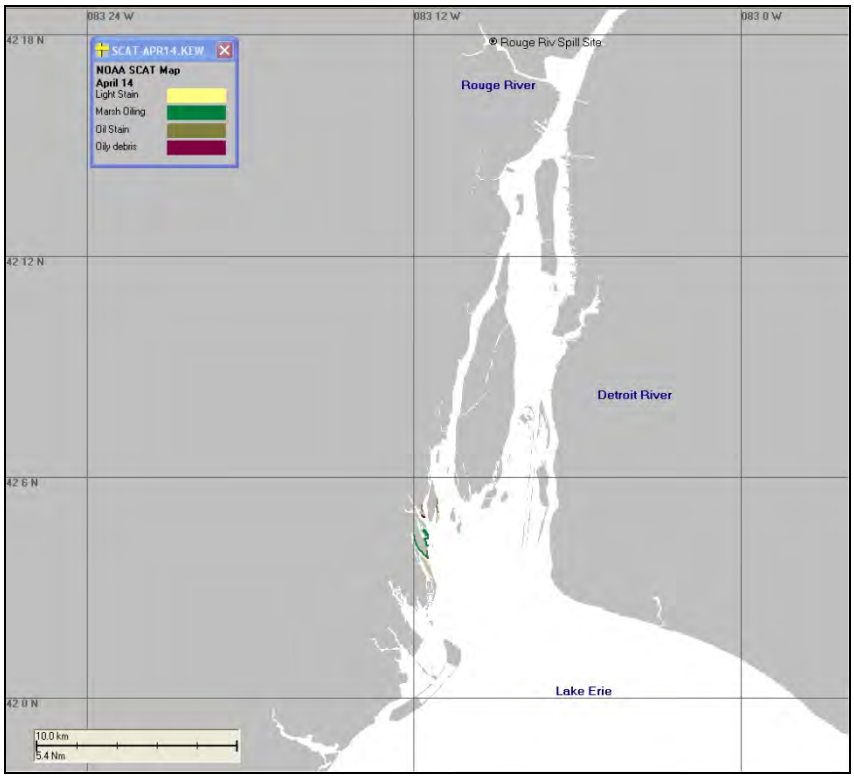

Figure 1-4. NOAA SCAT observations from 14 April 2002.

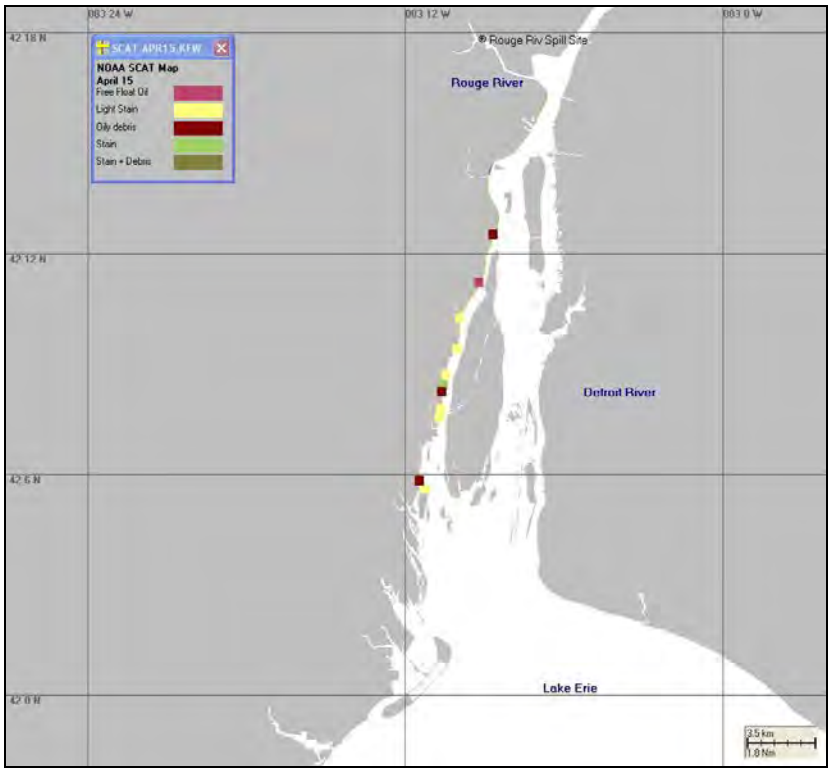

Figure 1-5. NOAA SCAT observations from 15 April 2002.

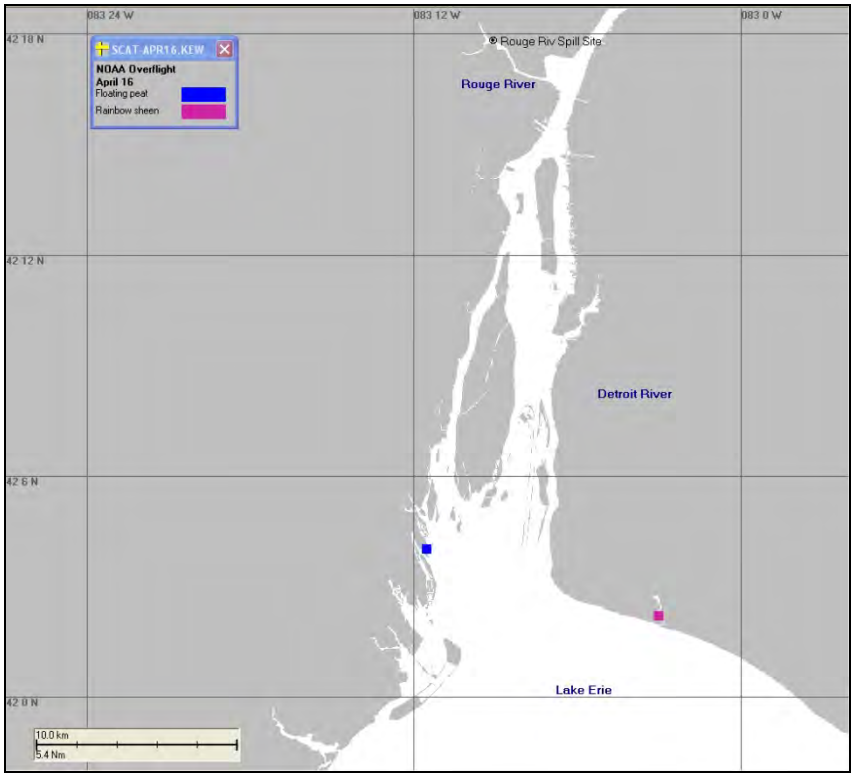

Figure 1-6. NOAA overflight observations from 16 April 2002.

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, aquatic organisms, and habitats 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 were used to make the assessment as site-specific as possible.

This report describes the data inputs for and results of the modeling. Inputs include habitat and depth mapping, winds, currents, other environmental conditions, oil properties, specifications of the release (amount, timing, etc.), and biological abundance.

2. MODEL DESCRIPTION

The oil spill modeling was performed using SIMAP (French McCay, 2003, 2004), which uses wind data, current data, and transport and weathering algorithms to calculate the mass of oil components in various environmental compartments (water surface, shoreline, water column, atmosphere, sediments, etc.), oil pathway over time (trajectory), surface oil distribution, and concentrations of the oil components in water and sediments. SIMAP was derived from the physical fates and biological effects submodels in the Natural Resource Damage Assessment Models for Coastal and Marine and Great Lakes Environments (NRDAM/CME and NRDAM/GLE), which were developed for the U.S. Department of the Interior (USDOI) as the basis of Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) Natural Resource Damage Assessment (NRDA) regulations for Type A assessments (French et al., 1996; Reed et al., 1996).

SIMAP contains physical fate and biological effects models, which estimate exposure and impact on each habitat and species (or species group) in the area of the spill. Environmental, geographical, physical-chemical, and biological databases supply required information to the model for computation of fates and effects. The technical documentation for the model is described in detail in Appendix A, as well as in French McCay (2003, 2004).

2.1 Physical Fates Model

The physical fate model estimates the distribution of oil (as mass and concentrations) on the water surface, on shorelines, in the water column, and in the sediments. Processes simulated include slick spreading, evaporation of volatiles from surface oil, transport on the water surface and in the water column, randomized dispersion, emulsification, entrainment of oil as droplets into the water column, resurfacing of larger droplets, dissolution of soluble components, volatilization from the water column, partitioning, sedimentation, stranding on shorelines, and degradation. Oil mass is tracked separately for lower-molecular-weight aromatics (1 to 3-ring aromatics), which are soluble and cause toxicity to aquatic organisms (French McCay, 2002), other volatiles, and non-volatiles. The lower molecular weight aromatics dissolve both from the surface oil slick and whole oil droplets in the water column, and they are partitioned in the water column and sediments according to equilibrium partitioning theory (French et al., 1996; French McCay, 2003, 2004).

“Whole” oil (containing non-volatiles and volatile components not yet volatilized or dissolved from the oil) is simulated as floating slicks, emulsions and/or tar balls, or as dispersed oil droplets of varying diameter (some of which may resurface). Sublots of the spilled oil are represented by Lagrangian elements (“spillets”), each characterized by mass of hydrocarbon components and water content, location, thickness, diameter, density, and viscosity. Spreading (gravitational and by transport processes), emulsification, weathering (volatilization and dissolution loss), entrainment, resurfacing, and transport processes determine the thickness, dimensions, and locations of floating oil

over time. The output of the fate model includes the location, dimensions, and physical-chemical characteristics over time of each spillet representing the oil (French McCay, 2003, 2004).

Concentrations in the water column were calculated by summing mass (in the Lagrangian particles) within each grid cell of a 50 (east-west) by 50 (north-south) by 5 vertical layer grid scaled in size each time step to just cover the dimensions of the plume. Thus, this grid expands over time. This includes all potential contamination in the water column, while maximizing the resolution of the contour map at each time step to reduce 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 and $2D_zt$ 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. Concentrations of particulate (oil droplet) and dissolved aromatic concentrations are calculated in each cell and time step and saved to files for later viewing and calculations. These data are used by the biological effects model to evaluate exposure, toxicity, and effects. In addition, calculations of dissolved concentrations were made for smaller grids localized around the spill site to resolve details of potential plumes derived from fresh oil.

The SIMAP fates 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).

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

2.2 Biological Effects Model – Exposure and Direct Losses of Fauna

The biological exposure model in SIMAP (Appendix A) estimates the area, volume, or portion of a stock or population affected by surface oil, concentrations of oil components in the water, and sediment contamination (French McCay, 2003, 2004). For wildlife (birds, mammals, and sea turtles), the number or fraction of a population suffering oil-induced effects is proportional to the water-surface area swept by oil of sufficient quantity to provide a lethal dose to an exposed animal. Dose is modeled as the product of concentration and exposure time (or duration). Based on calculations of the approximate area of a bird swimming through the water, an exposure index was developed for seabirds and other offshore wildlife, which is the water area swept by more than 10-μm thick (> 10 g/m^2) oil (which is sufficient to provide a lethal dose (French et al., 1996; French McCay and Rowe, 2004; Appendix A). The probability of exposure is related to behavior: i.e., the habitats used and percentage of the time spent in those habitats on the surface of the water. For shorebirds and other wildlife on or along the shore, an exposure index is length of shoreline oiled by > 10 g/m^2. Areas of exposure above these thresholds are a normal model output from SIMAP.

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 floating oil and 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.

Habitats include open water, mud flat, wetland and shoreline habitats (e.g., rocky shore, gravel beach, sand beach, and artificial habitat). Habitat types are defined by depth, proximity to shoreline(s), bottom/shore type, and dominant vegetation type. With respect to proximity to shoreline(s), habitats are designated as landward or seaward (i.e., landward within the Rouge River or seaward in the Detroit River and Lake Erie,

respectively). 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).

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

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, reptiles). 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 2-1. Estimates for the probabilities are derived from information on behavior and field observations of mortality after spills (reviewed in French et al., 1996). The threshold is 10 micron (~10g/m^2) thick oil, based on data and calculations in French et al. (1996). 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 2-1. 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 2-1.

Table 2-1. 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%	Nearshore and shoreline habitats
Nearshore aerial divers	35%	Nearshore and shoreline habitats
Surface seabirds	99%	All water and shorelines
Aerial seabirds	5%	All water and shorelines
Wetland wildlife (waders and shorebirds)	35%	Wetlands, shorelines, vegetated beds
Furbearing marine mammals	75%	All water and shorelines
Surface birds in Detroit River and Lake Erie open water only	99%	All Detroit River and Lake Erie open water
Surface diving birds in Detroit River and Lake Erie open water only	35%	All Detroit River and Lake Erie open water
Aerial divers in Detroit River and Lake Erie open water only, juvenile and adult sea turtles	5%	All Detroit River and Lake Erie open water
Surface birds in Rouge River open water only	99%	All Rouge River open water
Surface diving birds in Rouge River open water only	35%	All Rouge River open water
Aerial divers in Rouge River open water only	5%	All Rouge River open water
Surface diving birds in water only	35%	All waters
Aerial divers in water only	5%	All waters

The probabilities listed in Table 2-1 are based on the literature review and analysis in French et al. (1996).

2.2.2 Fish and Invertebrates

The most toxic components of oil to water column and benthic organisms are low molecular weight compounds, which are both volatile and soluble in water, especially the aromatic compounds (Neff et al., 1976; Rice et al., 1977; Neff and Anderson, 1981; Malins and Hodgins, 1981; National Research Council, 1985, 2002; Anderson, 1985; and French McCay, 2002). This is because organisms must be exposed to hydrocarbons in order for uptake to occur and aquatic biota are exposed primarily to hydrocarbons (primarily aromatics) dissolved in water. Thus, exposure and potential effects to water column and bottom-dwelling aquatic organisms are related to concentrations of dissolved aromatics in the water. Exposure to microscopic oil droplets could also impact aquatic biota either mechanically (especially filter feeders) or as a conduit for exposure to semi-soluble aromatics (which might be taken up via the gills or digestive tract). The effects of the dissolved hydrocarbon components are additive. Other soluble compounds in oil may also add to toxic effects on biota.

Mortality is a function of duration of exposure – the longer the duration of exposure, the lower the effects concentration (see review in French McCay, 2002). At a given concentration after a certain period of time, all individuals that will die have done so. The LC50 is the lethal concentration to 50% of exposed organisms. The incipient LC50 ($LC50_{\infty}$) is the asymptotic LC50 reached after infinite exposure time (or long enough that that level is approached, Figure 2-1). Percent mortality is a log-normal function of concentration, with the $LC50_{\infty}$ or the time-corrected $LC50_t$, the center of the distribution.

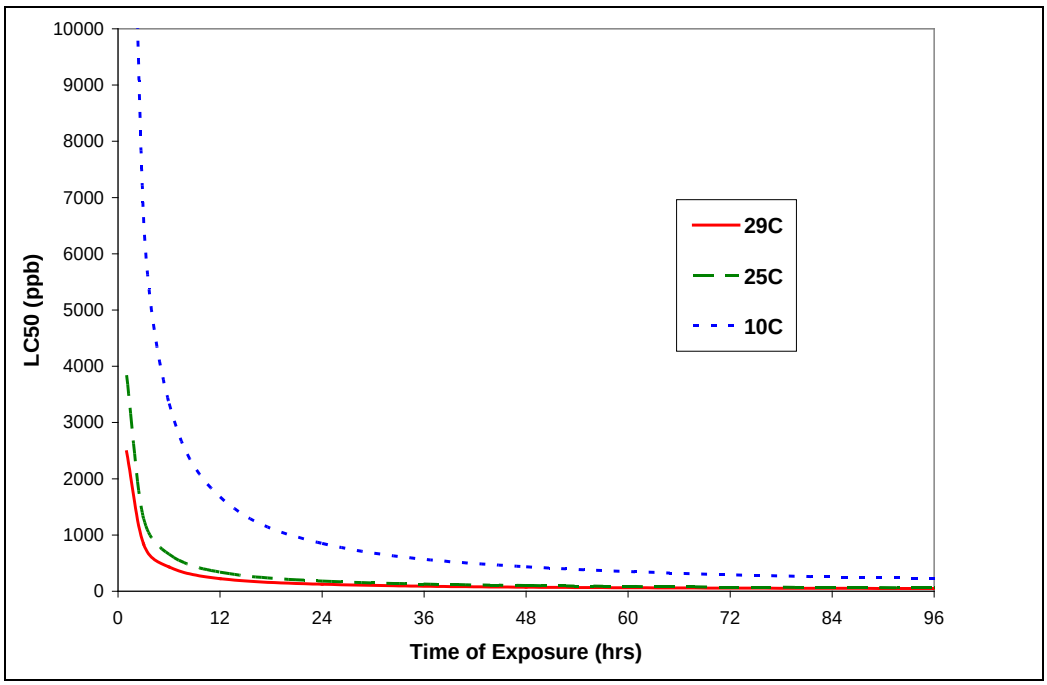

Figure 2-1. LC50 of dissolved PAH mixtures from oil, as a function of exposure duration and temperature.

The value of $LC50_\infty$ ranges from 5-400 μg/L for 95% of species exposed to dissolved PAH mixtures for over 96 hrs (French McCay, 2002; Figure 2-2). The $LC50_\infty$ for the average species is about 40-50 μg/L (ppb) of dissolved PAH (varying slightly among oils and fuels by percent composition of the PAH mixture). These $LC50_\infty$ values have been validated with oil bioassay data (French McCay, 2002), as well as in an application of SIMAP to the *North Cape* oil spill where field and model estimates of lobster impacts were within 10% of each other (French McCay, 2003). In the present spill assessment, model runs were made for the range of potential $LC50_\infty$ values based on those for species previously tested, as all species exposed have not been tested for sensitivity to oil hydrocarbons to date.

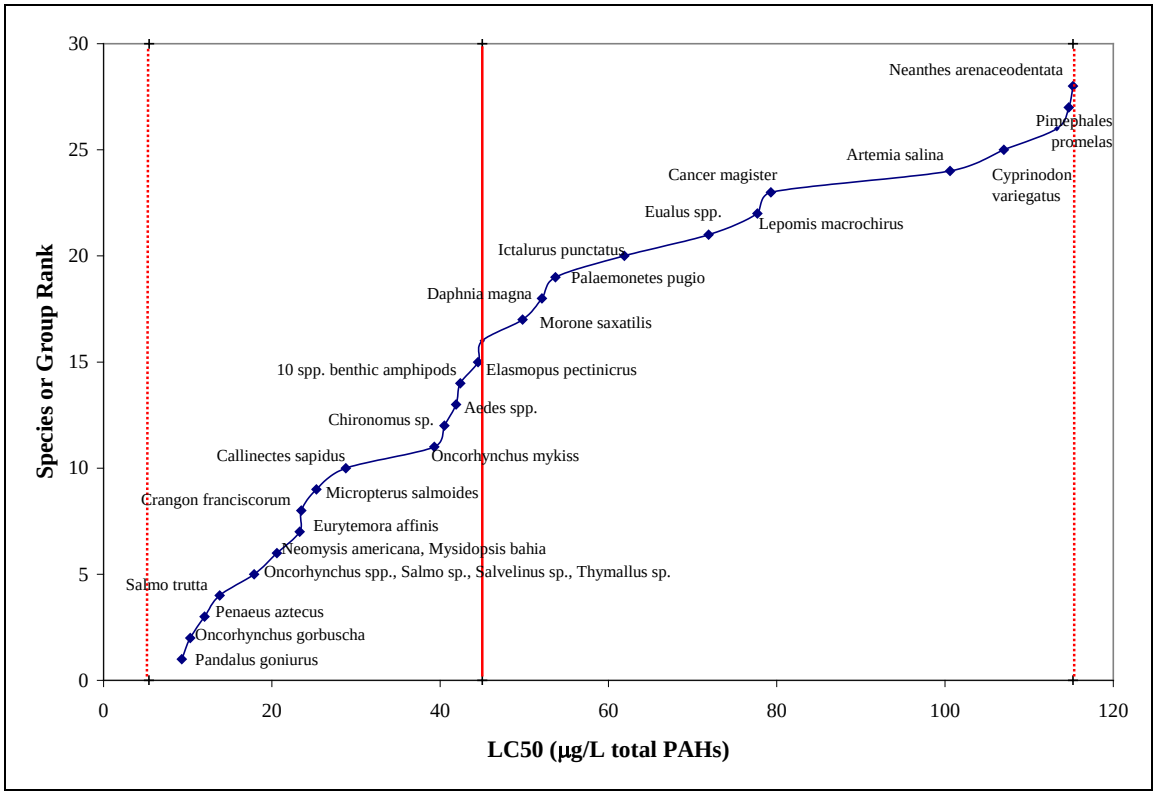

Figure 2-2. Variation in $LC50_\infty$ for dissolved PAH mixtures from a typical oil, by species in rank order of sensitivity.

Mortality of fish, invertebrates, and their eggs and larvae was computed as a function of temperature, concentration, and time of exposure. Percent mortality was estimated for each of a large number of Lagrangian particles representing organisms of a particular behavior class (i.e., planktonic, demersal, and benthic, or fish that are classed as small pelagic, large pelagic, or demersal). For each Lagrangian particle, the model evaluates exposure duration, and corrects the $LC50_\infty$ for time of exposure and temperature (Figure 2-1) to calculate mortality. (See Appendix A for details.) The percent mortalities were summed, weighed by the area represented by each Lagrangian particle to estimate a total equivalent volume for 100% mortality. In this way, mortality was estimated on a volume basis, rather than necessitating estimates of species densities to evaluate potential impacts. In addition to the mortality estimates, the volume exceeding 1 μg/L total

dissolved aromatics was used as an index for exposure for fish, invertebrates, and plankton. The algorithms for these calculations and their validation are described in French McCay (2002, 2003, 2004).

2.3 Validation of the Biological Effects Exposure and Mortality 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 Injury to Habitats

Several shoreline habitats that line the Rouge and Detroit Rivers were oiled during the spill. Wetlands are particularly vulnerable to oiling. Based on observations from spills, documented in Appendix A, Section 3.4, exposure to more than 1 mm of oil at the beginning or during the growing season adversely impacts marsh plants significantly. Thus, 1 mm is the assumed lethal threshold for wetland vegetation.

Also based on the review and analysis in Appendix A, Section 3.4, exposure to more than 0.1 mm (100 g/m^2) of oil is assumed lethal for invertebrates on all substrates. In the area of the Detroit and Rouge Rivers, significant densities of invertebrates would only occur in natural soft-sediment shorelines. Thus, injuries are quantified for wetland, sand and mud shorelines, but are assumed insignificant on man-made or rocky shorelines.

Plant and invertebrate production rates, as well as recovery rates, for each habitat type are taken into account when determining injury in these shoreline habitats. Natural recovery time for freshwater wetlands is about 5 years, based on the review of Reed et al. (1996) who cite Dunn and Best (1983) and D'Avanzo et al. (1989). The estimated time for natural recovery of estuarine intertidal invertebrates is 3-5 years (Appendix A). Recovery time estimates for freshwater shorelines are not available; however, a recovery rate at the lower end of that range, 3 years, would be expected and is assumed. The total lost production in oiled wetland and shoreline habitats was calculated from daily production rate, a sigmoid function scaled to the number of years to (99%) recovery (5 years for wetlands; 3 years for invertebrates), and annual discount rate (3%) using the equations described in Section 3.4 of Appendix A.

These injuries would typically be compensated with a wetland restoration project. If wetland injury is compensated by wetland restoration with an in-kind habitat, the scaling of that restoration requirement may be calculated with traditional Habitat Equivalency Analysis (HEA) methods (NOAA 1997, 1999). If, however, the restored habitat is not in kind, or the expected production rate of the restored habitat is expected to differ from those injured, then a modified HEA model can be used to calculate the scale of the

compensatory restoration effort, where production rate of the injured and restored habitats are included in the calculations.

The required compensatory production (P_C, i.e., the injury expressed as lost production at a specific trophic level, such as primary production) is translated to area of restored habitat (H_R) by dividing by expected net gain in annual productivity per unit area in the restored habitat (P_R) times a discounting factor (D) accounting for the project life, i.e. the number of years the restored habitat will exist (λ), and the delay before realizing the benefits. Thus,

$$H_R = P_c / (P_R * D)$$

$$D = (1+d)^{\rho} \sum_{n=0}^{n=\lambda} F_n (1+d)^{-n}$$

where d is the annual discount rate (0.03), ρ is the number of years after the spill when the restoration project begins, and F_n is the functional value of the restored habitat n years after planting as a fraction of full function. The discount factors, $(1+d)^{\rho}$ and $(1+d)^{-n}$, decrease the value of the production by 3% for each year into the future that must pass before that production would be realized. This follows the economic model that losses or gains of restoration in the future are less valued than present production. Including identical discounting on both the injury and restoration sides of the equation allows time lags in both losses and benefits to be appropriately treated in order to measure values lost and gained fixed to a common year.

If the habitat is fully-functional from the start of the restoration project, i.e. in the case of preservation, $F_n = 1$ for all values of n, while the value of ρ is the years after the spill the habitat would be lost if it were not preserved. For an expected project life of greater than 50 years, the value of $\sum (1+d)^{-n}$ approaches 31.6. However, if new habitat is created, there will be a period of "recovery" while it develops to full function. The recovery curve is assumed sigmoid in shape and fit to a logistic equation (see Appendix A). The sigmoid curve is based on the notion that habitats would develop function slowly at first and then more rapidly, but the increase in function would level off as an asymptotic full-function level is approached.

2.5 Quantification of Wildlife Injury

Direct oiling mortalities of wildlife (birds, mammals, and reptiles) were calculated as described above in Section 2.2.1. These direct kills are a mix of adults and juveniles of varying ages. If the natural and hunting mortality rates of a species are stable in time, the population approaches an age distribution of declining numbers with age, with the total (i.e., natural plus hunting) age-specific mortality rates defining the percentage remaining alive in each subsequent age class. Restoration and restocking programs would normally be scaled to provide replacements at a particular age class. For example, a project that

increases fledging rates would result in a net gain of fledglings, and the compensatory number would be equal to the fledgling-equivalents of the killed animals of mixed age classes. The fledgling-equivalents (or hatchling equivalents) to the mixed age classes of adults and juveniles killed is calculated using stage-specific and annual survival rates to construct a life table (number by age class) and then calculating a ratio of number of fledglings (or hatchlings) per animal in the population (weighed by age distribution).

In the population model, natural and hunting (harvest) mortality rates for stage (first year) and annual (>1 year old) age classes are used to estimate numbers that would remain alive by each age class. The number remaining alive at age *t* (years), N_t, is:

$$N_t = N_0 \, e^{(-Z_a(t))}$$

$$Z_a = M_a + H_a$$

where N_0 is the number at age zero, Z_a is stage-specific or annual instantaneous total mortality, M_a is stage-specific or annual instantaneous natural mortality, and H_a is stage-specific or annual instantaneous hunting mortality, for age class *a*. In performing these calculations, M_a and H_a are typically higher for age class 0 to 1 than for older age classes (which are assumed to have the same annual mortality rates). Data used in these calculations are in Appendix D.

Another measure of injury is the sum of the product of number of animals killed in a given age class times the numbers of years an individual in that age class would have lived had there not been a spill (i.e., life expectancy). This injury measure is expressed as bird-years, or more generically as individual-years. The life expectancy of an age *a* individual is the sum of survival rate to each age, $\Sigma \, e^{(-Z_a(t-a))}$, summing *t* from age *a* to the maximum age (λ):

$$\sum_{t=a}^{\lambda} e^{(-Z_a(t-a))}$$

Discounting at 3% per year is included to translate losses in future years (interim loss) to present-day values (i.e., for the year of the spill). The discounting multiplier for translating value *n* years after the spill to present value (i.e., for the year of the spill) is calculated as $(1+d)^{-n} = 1/(1+d)^n$, where d=0.03. Thus, the losses in future years have a discounted value at the time of the spill. In this analysis, all discounting was calculated based on the number of years from the year of the spill. Thus, additional discounting is needed to translate all the injuries to compensatory equivalents for the year the restoration is performed. The multiplier for this calculation is $(1+d)^m$, where *m* is the number of years after the spill when restoration is accomplished.

2.6 Quantification of Fish and Invertebrate Injury as Lost Production

2.6.1 Approach

The injury quantification approach is provided in detail in Appendix A. The biomass (kg) of fish and invertebrates killed by the oil ("direct kill") 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 and reproduce until they died naturally or were lost to fishing. This lost future (somatic) production ("production foregone") is estimated and added to the direct kill injury. The total injury is the total of the direct injury and production foregone. This total injury is expressed in "present day" (i.e., year of the spill) 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 injury inflated to the year restoration occurs or the restoration discounted back to the year of the spill.

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 (production foregone), 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 potentially 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 metric with which to evaluate ecological services than is standing stock alone (as number or kg).

This injury estimation approach was developed and used previously in the injury quantification for the *North Cape* spill of January 1996 (French McCay et al., 2003a, French McCay and Rowe, 2003) and many other spill cases (e.g., French McCay et al., 2003b). The method makes use of the population model in SIMAP. Injuries are calculated in three steps:

1. The direct kill is quantified by life stage and 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 production foregone).
3. Future interim losses are calculated in "present day" (year of the spill) 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. Production forgone is then estimated using the model of Jensen et al. (1988), which is commonly used in fisheries science (see below).

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, as both losses result from the spill. This may be accomplished by providing additional prey production to compensate for the direct predator loss.

2.6.2 Equations

The production foregone population model as described by the U.S. Environmental Protection Agency in its 316(b) rule (Final Rule, Clean Water Act §316(b), National Pollutant Discharge Elimination System, Final Regulations to Establish Requirements for Cooling Water Intake Structures at Phase II Existing Facilities, USEPA, 2004) was used. This approach is recommended by fisheries scientists and the models are those typically used for entrainment and impingement fisheries impact evaluations (EPRI, 2004). The equations are based on fisheries model development described in Ricker (1975).

The production foregone population model makes use of survival rates from one stage to the next. For eggs, survival to age one (S_{e1}) is calculated as:

$$S_{e1} = 2\ S_e\ e^{-\ln(1+Se)}\ S_L\ S_j$$

where S_e, S_L, and S_j are the survival rates for each stage: egg, larvae, and juvenile. For larvae, survival to age one (S_{L1}) is calculated as:

$$S_{L1} = 2\ S_L\ e^{-\ln(1+S_L)}\ S_j$$

Natural and fishing mortality rates for annual age classes are used to estimate numbers that would remain alive by each age class. The number remaining alive at age *t* (years), N_t, is:

$$N_t = N_1\ e^{(-Z_a\ (t-1))}$$

$$Z_a = M_a + F_a$$

where N_1 is the number at age one, Z_a is annual instantaneous total mortality, M_a is annual instantaneous natural mortality, and F_a is annual instantaneous fishing mortality, for age class *a*. The annual survival rate for age *t* (S_t) is thus:

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

The fraction dying in a year is $1\text{-}S_t$.

Yield foregone (Y_k) (i.e., equivalent yield, or lost catch) may be calculated using the Thompson-Bell equilibrium yield model (Ricker, 1975) where the harvest at each age class is calculated from number starting the class multiplied by fishing mortality rate, $(F_a/Z_a)(1\text{-}e^{-Za})$:

$$Y_k = \sum_j \sum_a L_{jk} S_{ja}\ W_a\ (F_a/Z_a)(1\text{-}e^{-Za})$$

Y_k = foregone yield (kg) in year *k*
L_{jk} = losses of individual fish of stage *j* in the year *k*
S_{ja} = cumulative survival fraction from stage *j* to age *a*
W_a = average weight (kg) of fish at age *a*
F_a = instantaneous annual fishing mortality rate for fish of age *a*
Z_a =instantaneous annual total mortality rate for fish of age *a*

Total natural mortality (TM_k) is calculated using an analogous model:

$$TM_k = \sum_j \sum_a L_{jk} S_{ja}\ W_a\ (M_a/Z_a)(1\text{-}e^{-Za})$$

M_a = instantaneous annual natural mortality rate for fish of age *a*

For this analysis, the losses are for eggs and larvae translated to 1 year of age, i.e., one stage where j=1.

Production foregone (USEPA, 2004, Chapter A-5; based on Rago 1984 and Jensen et al., 1988) which includes yield (harvest) and the production consumed in the food web, is estimated using:

$$Y_k = \sum_j \sum_a [\ G_a L_{jk} W_a (e^{Ga-Za} - 1)\ ]/[\ G_a - Z_a\ ]$$

where G_a is the instantaneous growth rate for individuals of age a

Length and weight at age are estimated using the von Bertalanffy equation and a power curve of weight versus length following methods in Ricker (1975). The equations used are as follows. For length (mm) at age *t* (years):

$$L_t = L_\infty\ [1 - e^{(-K\ (t - t_o))}]$$

where L_t is length (mm) at age *t* (years), L_∞ is the asymptotic maximum length (mm), K is the Brody growth coefficient, and t_o is a constant. Weight as a function of length (mm) is:

$$W_t = \alpha\ L_t^{\ \beta}$$

where W_t is wet weight (g) at age *t* years and α and β are constants.

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 (i.e., for the year of the spill) is calculated as $(1+d)^{-n} = 1/(1+d)^n$, where d=0.03. Thus, the losses in future years have a discounted value at the time of the spill. In this analysis, all discounting will be calculated based on the number of years from the year of the spill. Thus, additional discounting is needed to translate all the injuries to compensatory equivalents for the year the restoration is performed. The multiplier for this calculation is $(1+d)^m$, where *m* is the number of years after the spill when restoration is accomplished.

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.

Ecological habitat types (Table 3-1) are broadly categorized into two zones: fringing/shoreline and water. Fringing habitat types create boundaries between land and water and are typically much narrower than the size of a grid cell. Fringing habitats include river banks and various shore types. Thus, these fringing types have typical (for the region) widths associated with them in the model. In this case, "landward" is used for all habitats in the Rouge River, whereas seaward is used for Detroit River and Lake Erie.

The digital shoreline, shore type, and habitat mapping were obtained from the Environmental Sensitivity Index (ESI) Atlas database for the Lake Erie System compiled for the area by Research Planning, Inc. (RPI). These data are distributed by NOAA Hazmat (Seattle, WA). The shoreline/riparian habitats were assigned based on the shore types in the ESI Atlas. Open water areas were defaulted to sand bottom, as open water bottom type has no influence on the model results. The ESI data were compared with more recent images from Google Earth to ensure no major discrepancies in land use. Wetlands were added to the habitat grid using data from the National Wetland Inventory (http://www.fws.gov/wetlands/data/index.html). Emergent wetlands, or locations where surface water is present for extended periods especially at the beginning of the growing season, were queried from the Geospatial Wetland Digital Database and transferred into the habitat grid.

Table 3-1. Classification of habitats. Seaward (Sw) and landward (Lw) system codes are listed. (Fringing types indicated by (F) are only as wide as the shoreline habitat. Others (W = water) are a full grid cell wide and must have a fringing type on the land side.)

Habitat Code (Sw,lw)	Ecological Habitat	F or W
Water/Benthic		
11,41	Sand Bottom	W
Shoreline/Riparian		
1,31	Rocky Shore	F
2,32	Gravel Beach	F
3,33	Sand Beach	F
4,34	Fringing Mud Flat	F
5,35	Fringing Wetland	F
	Extensive Mud Flat	W
	Extensive Wetland	W

Habitat Code (Sw,lw)	Ecological Habitat	F or W
18,48	Man-made, Artificial	F

Depth data for the Rouge River were obtained from the CATS model (see Section 3.3), while data for the Detroit River and Lake Erie were obtained from both the CATS model and from National Oceanic and Atmospheric Administration, National Geophysical Data Center (NGDC). NGDC hydrographic survey data consist of large numbers of individual depth soundings and contours were generated at 1-meter intervals (Holcombe et al., 1997; Holcombe et al., 2005).

Two habitat grids were created to allow different bird densities to be applied by habitat type. In the first grid, all waters and marshes less than 1 m deep were assigned as littoral and all waters greater than 1m deep as limnetic (Figures 3-1 to 3-4). This allowed different species and densities of birds to be assigned in deeper waters than waters shallower than 1m because most waterfowl feed and rest in shallow waters (as opposed to the open deeper waters of Lake Erie and the deep channels of the rivers). The second grid was applied only to scaup, a waterfowl species that is unlikely to use the Detroit or Rouge Rivers, but has been counted in large numbers along the shores of Lake Erie in spring (Figure 3-5). Scaup commonly feed in water 1-9 meters deep, but are more commonly found in 1-3 meters of water depth (G. Souillere, USFWS, pers. comm., September 2009). In this grid (Figure 3-5), scaup were assigned to only waters between 1-3 meters deep within Lake Erie.

The gridded habitat and depth data are shown in Figures 3-1 through 3-5.

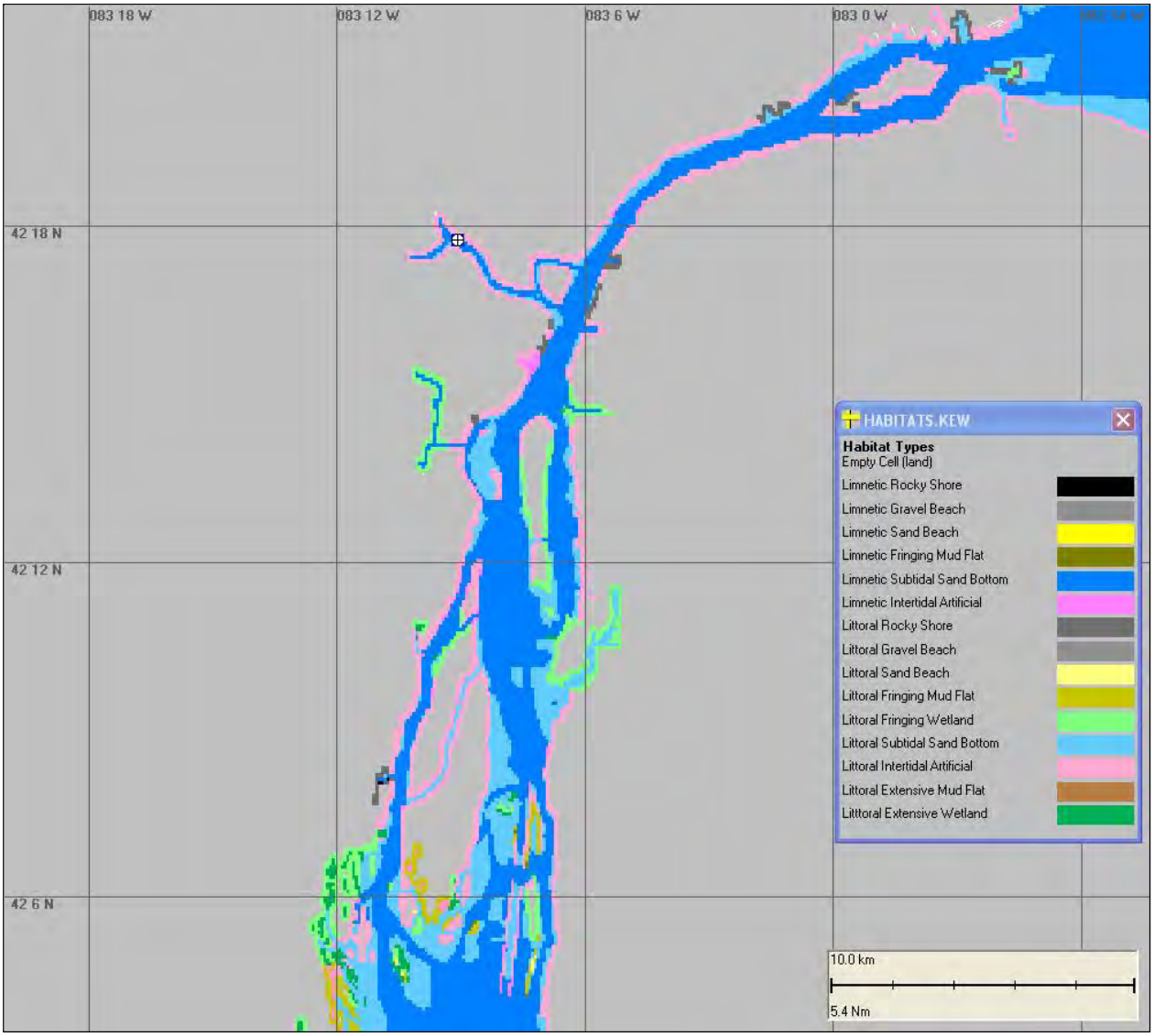

Figure 3-1. Habitat grid developed for the Rouge and Detroit Rivers. Mapped habitats based on ESI GIS data.

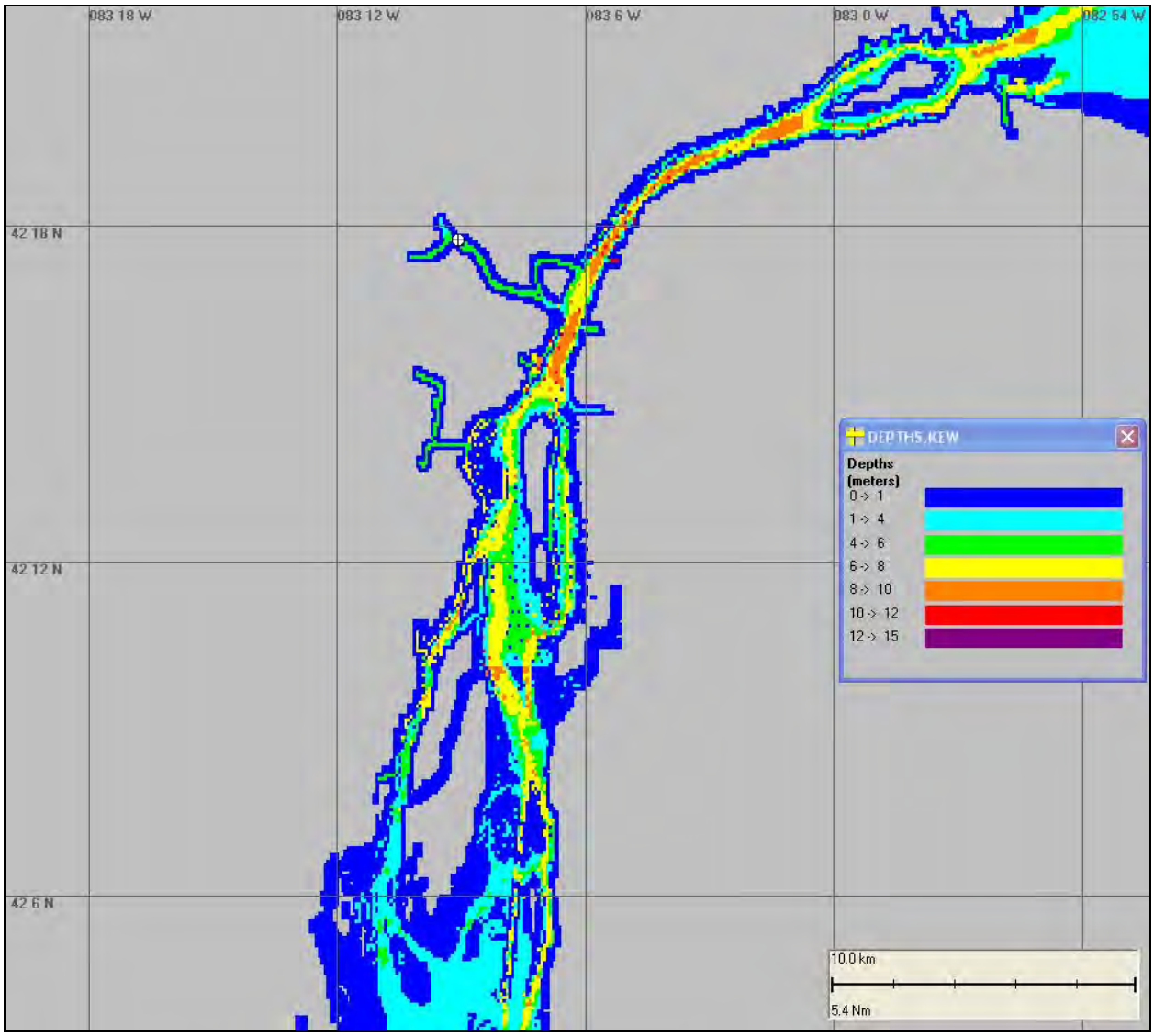

Figure 3-2. Depth grid developed for the Rouge and Detroit Rivers. Mapped depths are based on NGDC data.

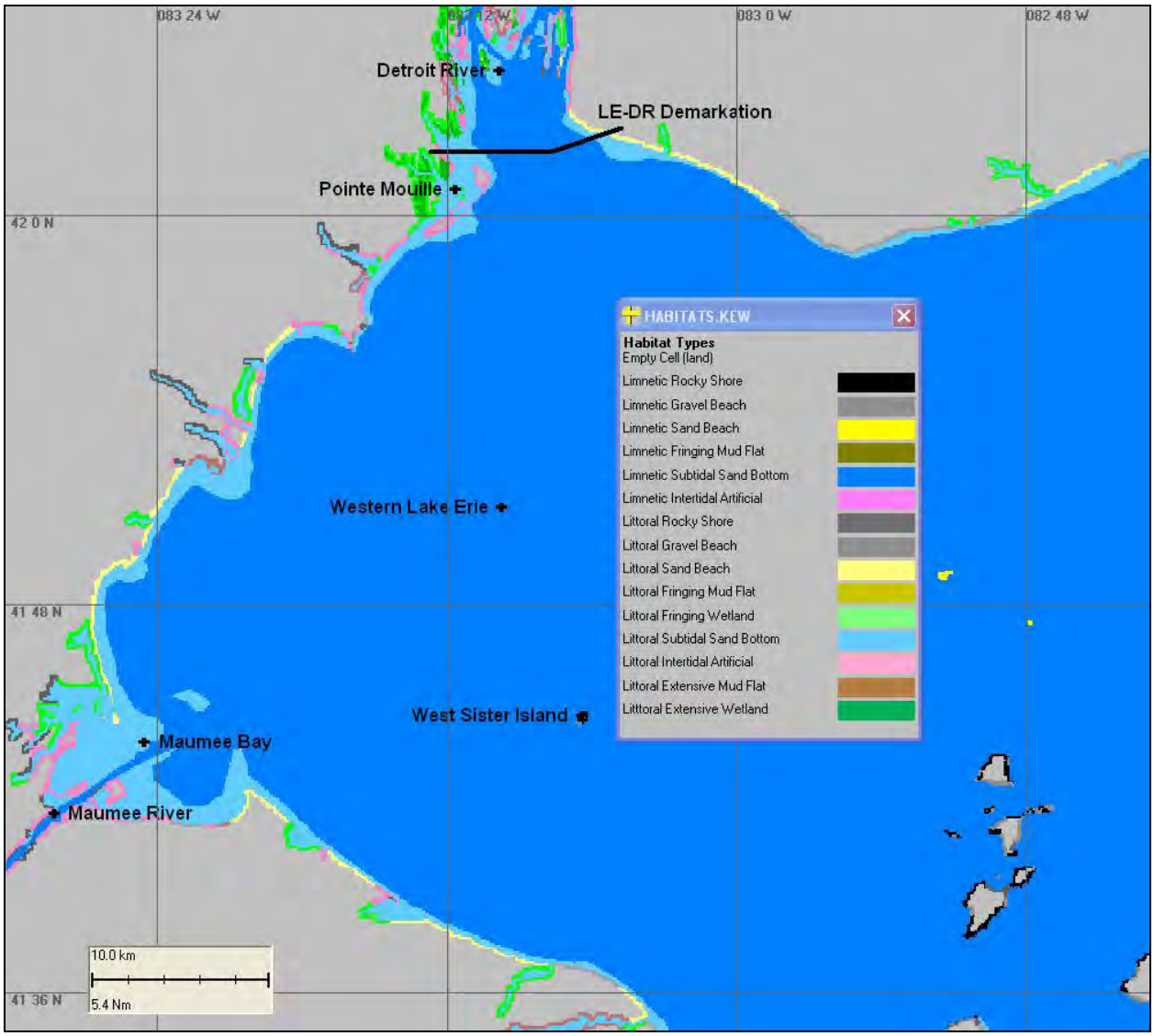

Figure 3-3. Habitat grid developed for Western Lake Erie. Mapped habitats based on ESI GIS data. The solid black line marks the delineation between the Detroit River and Lake Erie.

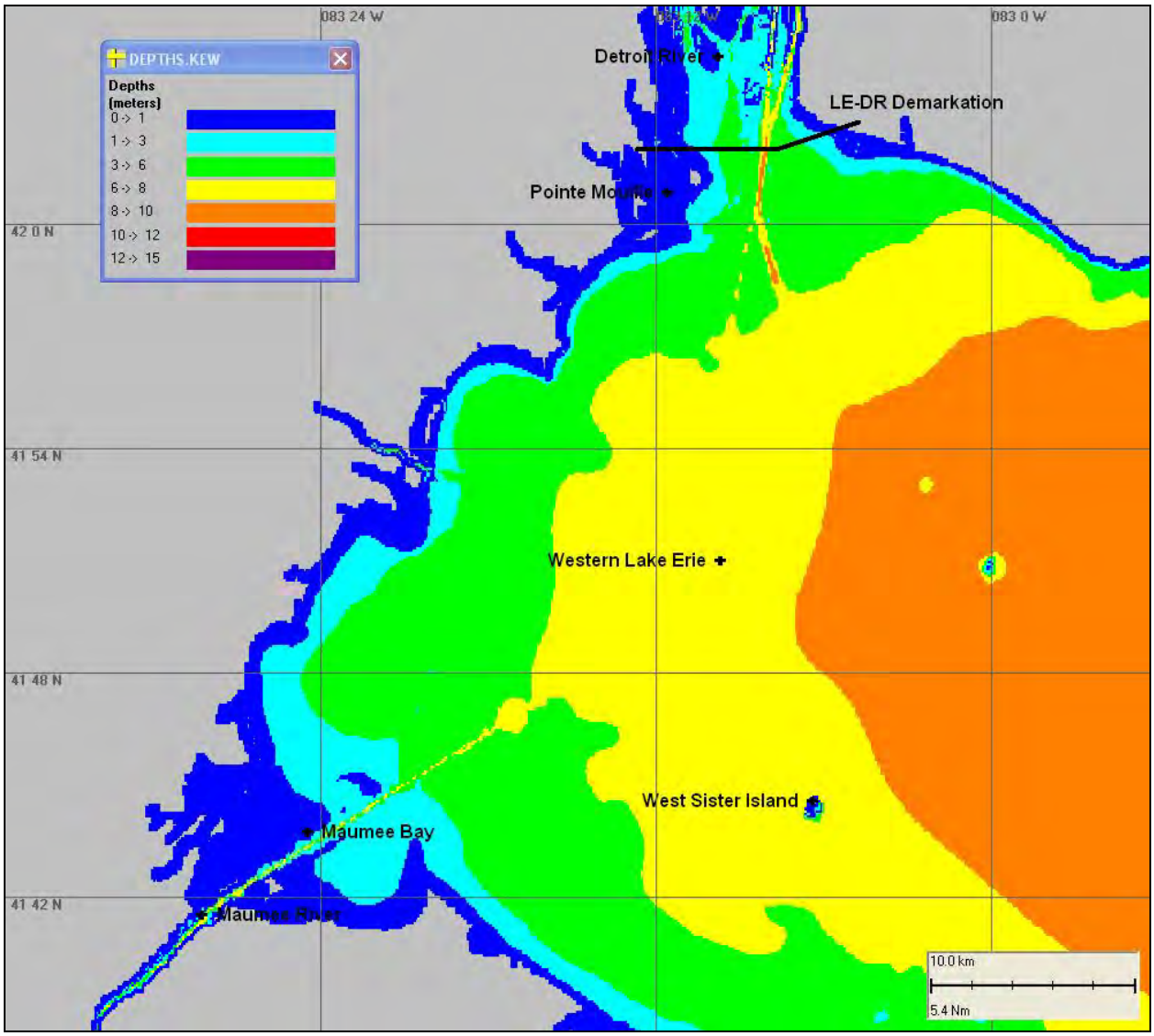

Figure 3-4. Depth grid developed for Western Lake Erie. The solid black line marks the delineation between the Detroit River and Lake Erie. Mapped depths are based on NGDC data.

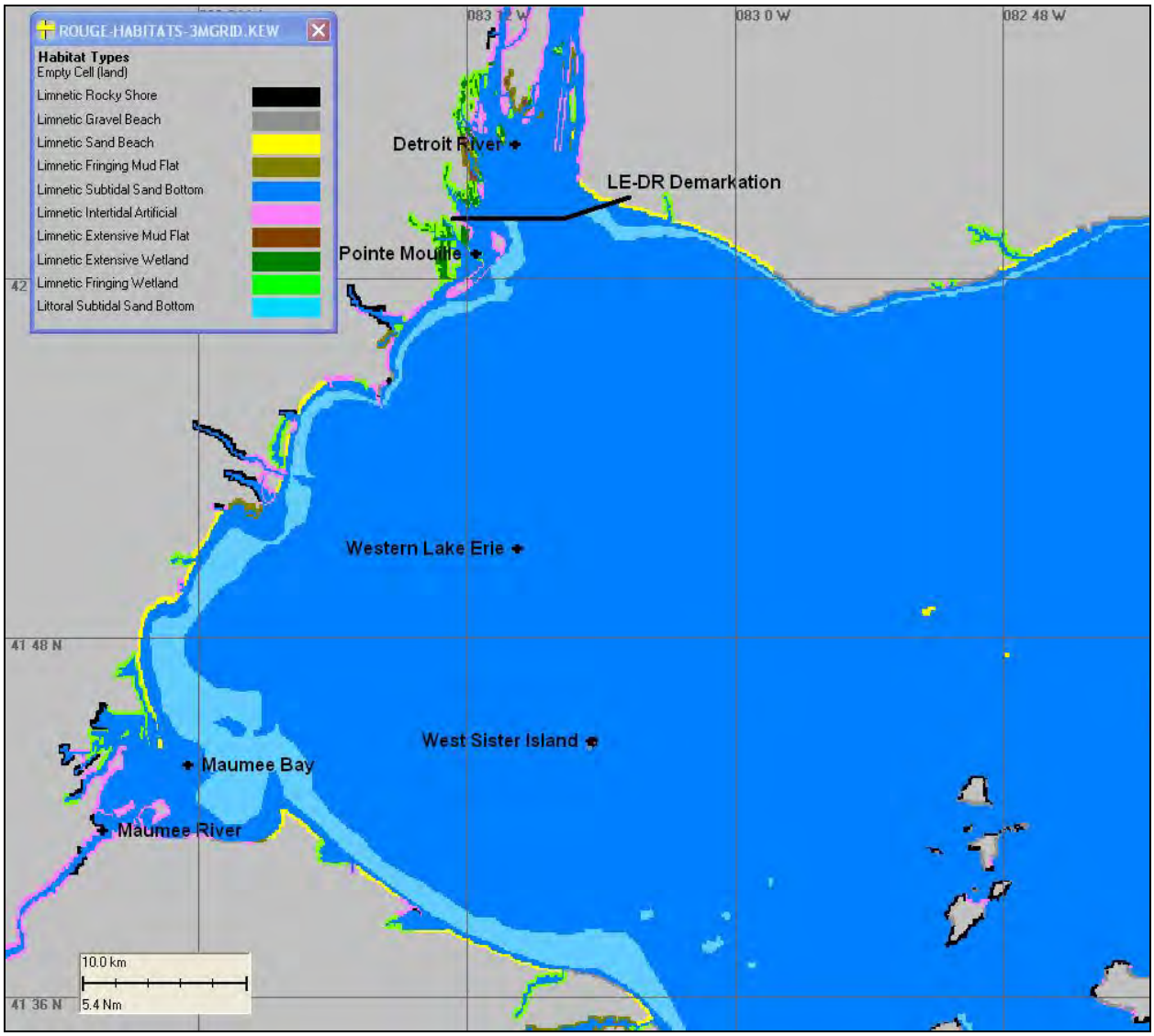

Figure 3-5. Habitat grid developed for Western Lake Erie in which scaup were applied to 1-3 meter deep water in Lake Erie. Mapped habitats based on ESI GIS data. The solid black line marks the delineation between the Detroit River and Lake Erie.

Most diving ducks feed in waters <6 meters deep (Bellrose 1980; Ewert et al. 2006). A 1-3 meter delineation for scaup habitat use (Figure 3-5) was assumed based on personal communications with Greg Souillere (USFWS). Regardless of the exact depth range in which scaups are found, it is known that they are not usually found very near shore, and that their primary diet is mollusks, particularly zebra mussels in the Great Lakes (Ewert et al. 2006). Therefore, the assumption of where scaups are found could be more based on where the zebra mussels are located in Lake Erie. In most lakes, zebra mussels are at a maximum density in waters 2-4 meters deep, and are not typically found in waters deeper than 6-8 meters (Nalepa and Schloesser 1993). Therefore, the assumption of scaups assigned to 1-3 meters within Lake Erie seems like an appropriate assumption based on their primary food source in the area. The demarcation line between the Detroit

River and Lake Erie (Figures 3-5) was made assuming scaup would not feed on either side of the main channel into the Detroit River due to ship traffic. It is possible that scaup were also not near the mouth of the Detroit River due to ship traffic, such that the line could be adjusted further out into Lake Erie (Figure 3-5). However, the mouth of the river has been noted as an important stopover point for scaups (Ewert et al. 2006), and the densities applied in the model (see below) were observed in the Pointe Mouillee area in April just after the spill, indicating the habitat delineation for scaups was appropriate.

3.2 Environmental Data

The model uses hourly wind speed and direction for the time of the spill and simulation. Wind data were acquired from the National Climatic Data center (NCDC) for the Detroit Metro Airport location (42.200001°N, 83.300003°W). Hourly mean wind speed and direction for 15 March to 30 June 2002 were compiled in the SIMAP model input file format. Figure 3-6 shows the location of the wind station used for modeling.

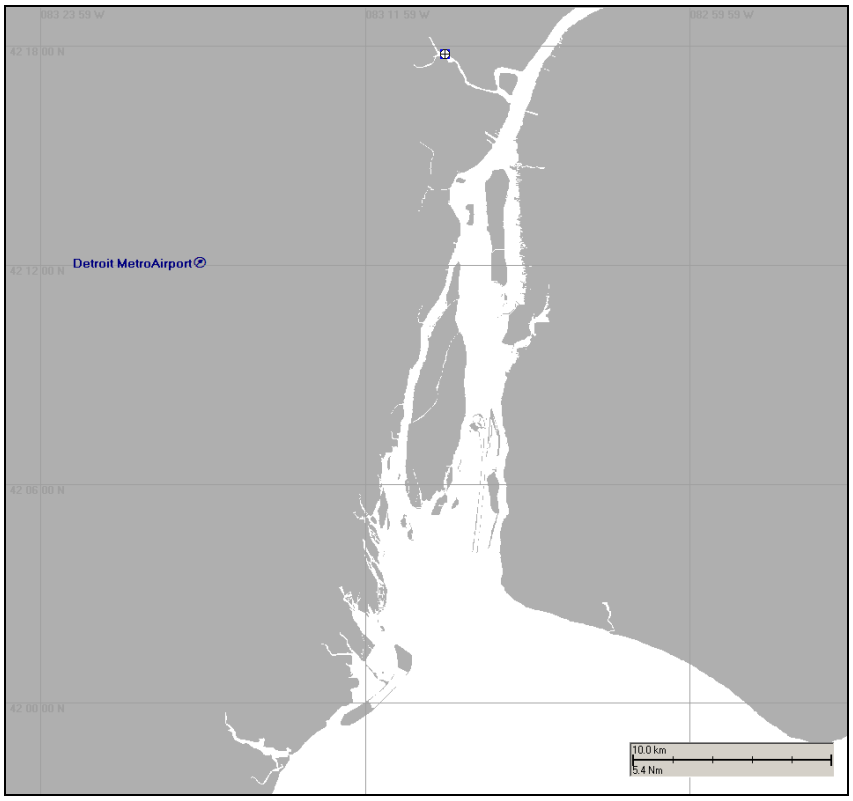

Figure 3-6. Locations of the wind station used for modeling.

Water temperature was held constant at 6°C for all model runs based on average April water temperature for West Lake Erie (41.676998°N, 82.398003°W) from NDBC. The air immediately above the water is assumed to have the same temperature as the water surface, this being the best estimate of air temperature in contact with floating oil.

The salinity was assumed to be 0 parts per thousand (French et al., 1996). 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 the oil evaluated had a density less than that of the water.

Suspended sediment was assumed to be 10 mg/l, a typical value for coastal and Great Lakes waters (Kullenberg, 1982). The sedimentation rate was set at 1 cm/day, which is the settling rate for oil-suspended sediment aggregates. Suspended sediment concentrations at this level have no significant affect on the model trajectory. Sedimentation of oil and PAHs becomes significant at concentrations greater than about 100 mg/L suspended sediment concentration. There is no indication that such high suspended sediment concentrations would occur in the areas where the spill was simulated.

The horizontal diffusion (randomized mixing) coefficient was varied for sensitivity analysis and model trajectory calibration, as described in detail in Section 4.0, below. The vertical diffusion (randomized mixing) coefficient is assumed to be 1 cm^2/sec. This is a reasonable value for nearshore and riverine waters based on empirical data (Okubo and Ozmidov, 1970; Okubo, 1971) and modeling experience.

3.3 Currents

Currents have significant influence on the trajectory and oil fate, and are critical data inputs. Wind-driven and background currents were input to the oil fates and biological effects models from a current file that was prepared for this purpose.

The Rouge River, located in southeast Michigan, is a tributary of the Detroit River that runs through the city of River Rouge and some of the most urban land in the state. The spill is located just below (downriver) the large turning basin[1]. Above the turning basin, the total river flow is well estimated by summing the flows of the lower Rouge, Middle Rouge and the Plymouth river gauges. During dry periods, the industrial inputs into the Rouge River add a significant input to the overall flow (personal communication, Ed Kluitenberg, Wayne County Rouge Program Office).

The surface oil was observed during a rainy period. Based on the river gauge data for early April, the Rouge was experiencing a relatively high flow of 70.99 m^3s^{-1} at the start of the first spill on 9 April. The second spill, observed on 13 April, occurred on another high flow day with readings of 76.17 m^3s^{-1}. Since the flow rates for both spill days were high, industrial inputs to the Rouge River are not a significant source of flow and were not considered. As mentioned above, the industrial inputs are only significant during dry periods.

The 2D circulation pattern for the Rouge and Detroit Rivers was developed using the NOAA Circulation Analysis for Trajectory Simulations (CATS) model. The Wind Analysis for Currents (WAC, Galt 1980) submodel was used, where the dynamics are dominated by shallow water wave theory, and is very applicable for river flow. River flow has faster water currents over the deeper waters depths, and shallow water wave

[1] An open area at the end of a canal that is large enough to allow vessels to turn around.

speeds are proportional to water depth. This diagnostic model has previously been used as primary tool for NOAA trajectory forecasting in this region. The model is a 2D, depth integrated model, that works well for surface currents associated with spill trajectories. CATS is a diagnostic model, which means the desired solution conditions (flow at the time of the spill) determine the flow field rather a prognostic model where the initial conditions start the model, then the model predicts the solution time period conditions. The CATS solution represents the model physics in combination with the data fields available at the time of the spill.

For scaling the CATS model, Rouge River flows from the three gauges for 9 April were used to develop an estimated total river current. Surface currents in the Detroit River were tuned to match overflight and SCAT information. The ratio of the surface currents in the Rouge River to those in the Detroit River was used to scale the CATS circulation model.[2] Once the ratio between the currents was determined, the water level boundary condition to the Rouge River was adjusted relative the water levels set at the ends of the Detroit River bathymetric domain. Figures 3-7 and 3-8 are examples of surface current vectors.

Because the SIMAP simulation utilizes a different (but overlaying) grid system for the river and western Lake Erie, the entire flow field was calibrated to match the observed transport of the oil downstream. This was a minor adjustment in the vector field, scaling the vectors up to a slightly higher rate, as explained in Appendix B on the sensitivity analysis.

[2] Rouge River width at bathymetry grid entrance: 65.9 m; Average depth of Rouge at bathymetry grid entrance: 2 m; Flow rate for Rouge river on 9 April: 70.99034 m^3/s; (70.99034 m^3/s) / (65.9 m x 2 m) = 53.86 cm/s flow; Detroit River scaling speed at scaling point (42 deg 16.18’ N, 83 6.37’ W) = 60 cm/s.

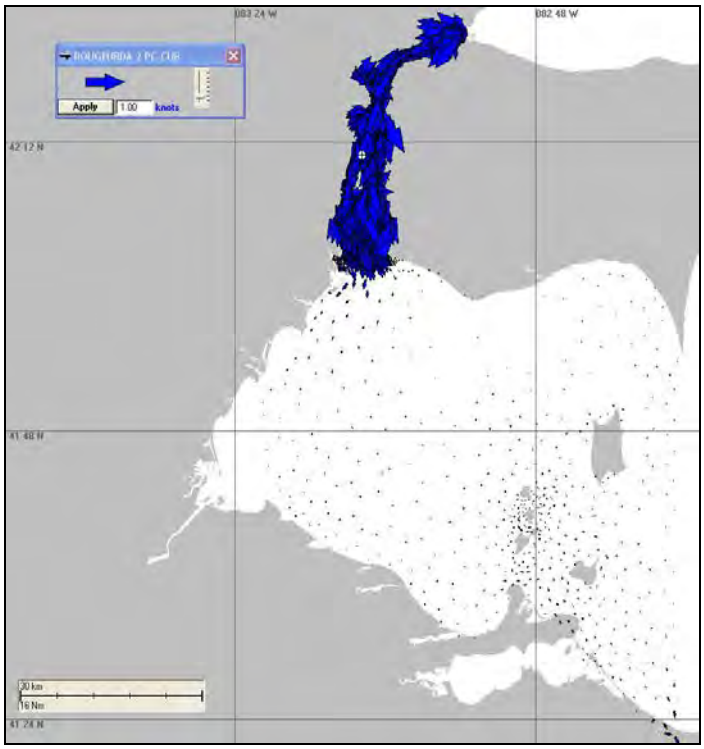

Figure 3-7. Current vector field generated by the CATS model developed for the Rouge and Detroit Rivers 9 April 2002.

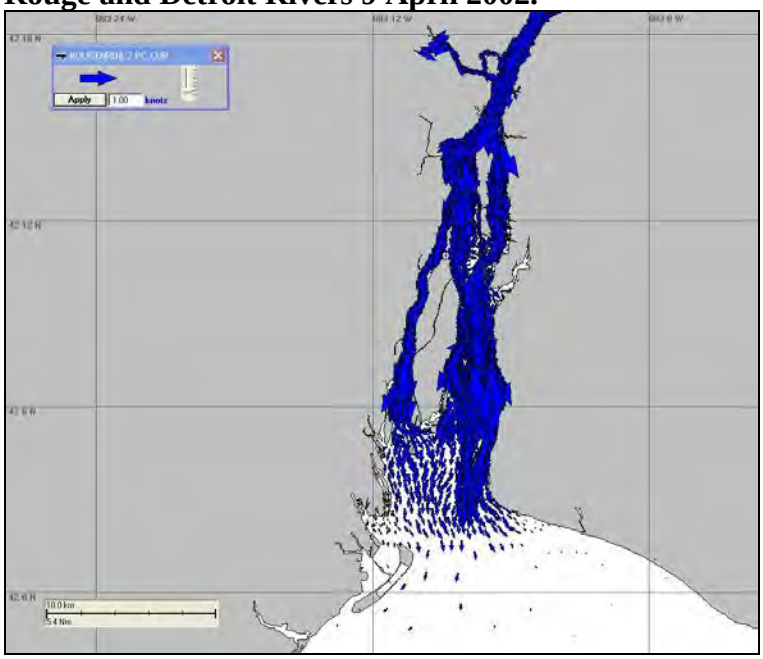

Figure 3-8. Current vector field generated by the CATS model developed for the Rouge and Detroit Rivers 9 April 2002.

3.4 Oil Properties and Toxicity

The spilled oil was a mix of diesel fuel oil and waste lubricating oil in an unknown ratio (Wang et al., 2004). Physical and chemical properties, except for BTEX and PAH concentrations, for diesel fuel oil were taken from the NRDAM/CME and NRDAM/GLE databases (French et al., 1996; Reed et al, 1996); and those for lubricating oil were taken from the Environment Canada database (Jokuty et al., 1999). Minimum oil slick thickness was assumed to be the same for both oils, 0.1mm, as they are of similar viscosity (based on McAuliffe, 1987). PAH and BTEX concentrations were taken from the oil sample measured by Wang et al. (2004) that was closest to the spill source and the least weathered (sample 44551). Weathering of oil and reduction of PAH and BTEX levels occur quickly; however, it is not technically feasible to back-calculate and estimate the initial concentrations of these compounds in the oils at the time of the spill, as the spill was for mixed waste oils of unknown initial composition. Thus, the values given for this sample, taken 24 hours after the initial report of the spill, were used in all model runs as the initial oil concentrations. For this reason, the water column contamination and resulting injuries are to some (likely small) degree underestimated.

EPA and USCG reported a total of 66,359 gallons of emulsified oil was removed from the environment. As diesel does not emulsify and assuming that lubricating oil emulsifies up to 60% in water (Jokuty et al., 1999), at least an estimated 40,000 gallons of lubricating oil was spilled. At these volumes, 12% of the 322,280 gallons spilled was lubricating oil and the remaining 88% was diesel fuel. Wang et al. (2004) examined two whole oil samples taken from the Detroit River on 10 April 2009 (9-10AM) using GC/MS analyses, finding that the oil contained <20% of weathered diesel. However, those samples were taken after the oil was in the environment for more than 24 hours, such that the diesel component might have been higher. Thus, oil properties were compiled for both oil types, and then calculated weighted mean properties for a range of assumed percentages of diesel. Because the two oils had similar properties, the mean properties were not sensitive to the relative weighing of the two oils. Thus, a 50-50 mix (equal weighing) was assumed for the model runs.

The $LC50_{mix}$ values assumed are for PAH concentrations in the water, because monoaromatics are less toxic, evaporate quickly, and contribute little to toxicity. To estimate $LC50_{\infty}$ values for dissolved PAHs in the water, the additive model described in French McCay (2002) was used. French McCay (2002) estimated $LC50_{\infty}$ at about 40-50 μg/L for typical fuels at infinite exposure time and for the average species. Ninety-five percent of species have $LC50_{\infty}$s between about 5 and 400 μg/L. Using the PAH data for the spilled oil, the average $LC50_{\infty}$ is 44 ppb, with 95% of species falling between 5 and 370 ppb. In the assessment of injuries, all species are assumed to be of average sensitivity to oil hydrocarbons, i.e., assuming $LC50_{\infty}$ = 44 μg/L. However, the range of potential injuries for the range of $LC50_{\infty}$s of 5 to 370 μg/L was also be evaluated in order to bound uncertainty associated with the toxicological properties of the spilled petroleum mixture. EPA and NOAA laboratory reports from 2002 have been identified and requested. Review of data in these reports may result in revised $LC50_{\infty}$ estimates.

3.5 Spill Observations

On Tuesday 9 April 2002 at 1000 local time the operator of the Fort Street Bridge, in Dearborn, MI, called in an observation of oil to the USCG. The impacted areas began at the Dix Street Bridge and continued for three miles of the Rouge River, and 17 miles of the US Detroit River coastline and 16 kilometers of the Canadian coastline. A second release was reported at 0700 on 13 April 2002 in the same original area as the first release. The entire spill volume was estimated at 322,280 gallons of a mix of diesel fuel and waste lubricating oil (Allen, 2002)

Oiling observational data were compiled from U.S. EPA pollution reports (EPA), U.S. Fish and Wildlife Service Reports (USFWS), U.S. Coast Guard press releases and pollution reports (USCG-Press and USCG-PolReps), NOAA SCAT maps, NOAA overflight maps, and material compiled by the Detroit Free Press (DFP). The following is a chronological outline of observations compiled from all data sources from 9 April to 26 April 2002.

<u>April 9th</u>

- 1000 – Fort Street Bridge operator contacts USCG and reports observed oil in the Rouge River (EPA)
- 1045 – Airsta Detroit conducts overflight of Rouge River (USCG-PolRep)
- 1115 – USCG arrives on scene and observes a slug (EPA)
- 1120 – Sheening observed at Fort St. Bridge from oil slug observed at Jefferson St. Bridge (USCG-PolRep)
- 1800 – Boom in water around Rough Steel's #6 outfall (USCG-PolRep)

Observations reported scattered patches of oil on the Rouge River and the Detroit River as far south as the Detroit River Light on Lake Erie (USCG-Press) (Figures 3-9 to 3-11).

<u>April 10th</u>

- 1025 – Helicopter reports oil patches extending southward past west bank of Livingston Channel in Detroit River (USCG-PolRep)
- 1054 – Rapid shoreline assessment at Black Lagoon, patches of oil are flowing past Trenton, MI (USCG-PolRep)
- 1152 – Booming off Rouge River (USCG-PolRep)
- 1545 – Humbug Marsh has not been affected, but Humbug Marina has (USCG-PolRep)
- 1618 – Deploying boom at Elizabeth Park in Trenton, MI (USCG-PolRep)
- 1648 – Oiled bird observed at Elizabeth Park (USCG-PolRep)
- Three zones of affected areas were identified (EPA):
    - Zone 1 – Contaminated area of the Rouge River (Figure 3-8)
    - Zone 2 – From the confluence of the Rouge and Detroit Rivers to Elizabeth Park, Trenton, MI (Figure 3-9)
    - Zone 3 – Elizabeth Park into Lake Erie (Figure 3-10)

The U.S. Coast Guard closed the Rouge River to boating traffic and reported that the mouth of the Rouge River had been boomed off (USCG-Press). With evidence of oily contamination on the Rouge River shoreline downstream of the Rouge Steel outfall

(EPA), several other sections of the Rouge and Detroit rivers were also outfitted with collection booms, including Humbug Marsh and Pointe Mouille with the intention of protecting these environmentally sensitive areas (USCG-Press).

April 11th

The Canadian Coast Guard reported that no free floating oil remained on the Canadian side, there was only shoreline oiling (USCG-PolRep). Citizens in Trenton, MI, located 7 miles downstream of the spill origin, complained of fuel smells (EPA).

The U.S. Coast Guard estimated 1,000-5,000 gallons of oil were discharged into the water (USCG-Press). Several measures were employed to gather further information about the spill. Dye tracers were used to try and identify source of spill but results were inconclusive and samples collected from the Detroit River (near Belanger Park and Trenton Riverside Marina) were sent for analysis (EPA).

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. At Elizabeth Park 12 Pekin ducks, 6 "wild ducks," 1 mallard, and one white goose were seen alive and oiled. On the Detroit River a fisherman reported oiled ducks to USFWS. At Lake Erie Metro Park one duck was found dead, but it was not known if the death was related to the spill. In Gibraltar three white geese were retrieved and taken to rehab. One Canada goose, alive and oiled, was spotted at the Woodmere cemetery and one at the mouth of the Rouge River. In Canada, three Canada geese and one duck were observed alive and oiled in Amherstburg.

April 12th

The U.S. Coast Guard received several citizen oil sighting reports from around the area. Oil was reported northwest of Lake Erie Metropark, at Dingell Park in Ecorse, MI, and at the Wyandotte Yacht Club, Wyandotte, MI. Additionally, impacted birds were observed and reported near Edmund Island (USCG-PolRep).

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. At Lake Erie Metropark, 2 ruddy ducks and 1 mallard were found dead, and 6 "wild ducks," 4 mallards, 6 Canada geese, and 5 great egrets were observed alive and oiled. One raptor was noted as possibly oiled. At Point Mouillee CDF, 12 ruddy ducks, 1 bufflehead and 1 pied-billed grebe were reported as oiled. The ruddy ducks were observed preening on shore and the bufflehead was retrieved for rehab. In Canada, 6 oiled Canada geese were observed on Boblo Island.

April 13th

- 0700 – A second spill in the same area as the initial spill was reported (EPA)
- New slick is concentrated north of the Jefferson Street Bridge along the south bank (USCG-Press)
- 0820 – Significant amount of additional oil in Rouge River observed (USCG-PolRep)
- 0915 – Rouge River closed to all traffic (USCG-Press)
- 1235 – USCG contractor reports a flow of oil from the Baby Creek Outfall on the Rouge River (EPA)
- 1250 – free standing oil/sludge discovered in sewer access point (EPA)

The new slick was concentrated north of the Jefferson Street Bridge along the south bank (USCG-Press), and three additional access points in a line from the Dearborn Pump Station were also found contaminated (EPA). Affected Zone 3 reported only significant residual shoreline contamination remained in Humbug Marina (EPA).

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. One oiled Canada goose was seen near the mouth of the Rouge River near Detroit Edison, and one oiled coot was seen further inland near BP Amoco.

April 14th

The U.S. Coast Guard reported and estimate of between 10,000 and 15,000 gallons of industrial oil was spilled and an estimated volume of recovered emulsified oil between 5,000 and 6,000 gallons. Additionally, the majority of Detroit River and Lake Erie had been cleaned (USCG-PolRep). A press release from the Coast Guard stated that preliminary testing indicated the oil did not contain PCBs or other hazardous chemicals (USCG-Press).

April 15th

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. At Lake Erie Metropark, 2 mallards and 1 turtle were found oiled and dead. One ruddy duck was seen oiled. On Fort Street near the Rouge River, one Canada goose was observed oiled and head bobbing. On Jefferson Avenue, also near the Rouge River, another Canada goose was observed to be heavily oiled. In Wyandotte at the Libra Marina, one oiled turtle was retrieved for rehab.

April 16th

The U.S. Coast Guard reported an estimated total volume of recovered emulsified oil at over 16,000 gallons and the whole spill is now estimated at more than 15,000 gallons (USCG-Press).

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. On private property in Trenton, one bird (coot or merganser) was found dead. In Gibraltar, on Bayview Street, one mallard was found dead.

April 17th

The U.S. Coast Guard reported an estimated total volume of recovered emulsified oil at over 26,000 gallons and that crews began the removal of oiled marsh flora in Lake Erie Metropark (USCG-PolRep). The Detroit Free Press also reported the oiled shoreline vegetation had been removed at Elizabeth Park (DFP).

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. At Elizabeth Park, one coot was dead and oiled. In Lake Erie Metropark, two mallards were seen lightly oiled, preening and washing. One map turtle near the Miller Road outfall in the Rouge River, and three Canada geese near block 13000 of Powell Street in the Rouge River were observed but not oiled.

April 18th

The U.S. Coast Guard reported an estimated total volume of recovered emulsified oil at 43,120 gallons (USCG-PolRep). An estimated 2,000 gallons were recovered from the sewers in the prior 24 hours, but additional releases into the Rouge River were still a potential risk (EPA). However, the Detroit River was protected by redundant containment booms (EPA). The Detroit Free Press reported additional booms placed at the mouth of the Huron River, around Pointe Mouillee State Game Area, and north and south of Humbug Island (DFP).

The U.S. Fish and Wildlife Service reported wildlife injuries at several area locations. At the Fort Street Bridge on the Rouge River, one merganser (red-breasted or common) was found dead and oiled. In Canada, 1 mute swan and 2 scaup were seen oiled, and 1 ruddy duck and 13 Canada geese were seen dead and oiled.

Additionally, crews reported to Lake Erie Metropark to remove oiled marsh vegetation and debris from shoreline (USFWS) and the Horse Island area and Humbug Marina have also been cleaned (DFP).

April 19th

The U.S. Coast Guard reported an estimated total volume of recovered emulsified oil at 43,868 gallons (USCG-PolRep). The Detroit Free Press reported that cleanup crews had recovered around 46,000 gallons of lube oil/diesel mix since April 12th (DFP). The U.S. Fish and Wildlife Service reported one oiled mallard or black duck in Garden City.

April 20th

The U.S. Coast Guard reported an estimated total volume of recovered emulsified oil at 49,423 gallons (USCG-PolRep). The U.S. Fish and Wildlife Service reported one oiled painted turtle at the Wyandotte Yacht Club and one dead duck, oiling unknown, at the Riverview Marina.

April 22nd

The Rouge River was reopened to shipping traffic and recovery efforts on the Detroit River are nearly complete (EPA).

April 23rd

The U.S. Coast Guard reported an estimated total volume of recovered emulsified oil at 67,749 gallons and all product in the Rouge River is contained (USCG-PolRep). Additionally, the Detroit River, from mouth of Rouge to Elizabeth Park, has been cleaned (USCGPolRep).

April 24th

To date, the U.S. Coast Guard had covered approximately 70,000 gallons of emulsified oil (EPA).

April 26th

The U.S. Coast Guard reported a revised estimated total volume of recovered emulsified oil at 66,359 gallons (USCG-PolRep). The Detroit River, from mouth of Rouge to Gibraltar, has been cleaned and the source of spill remains unknown (USCG-PolRep).

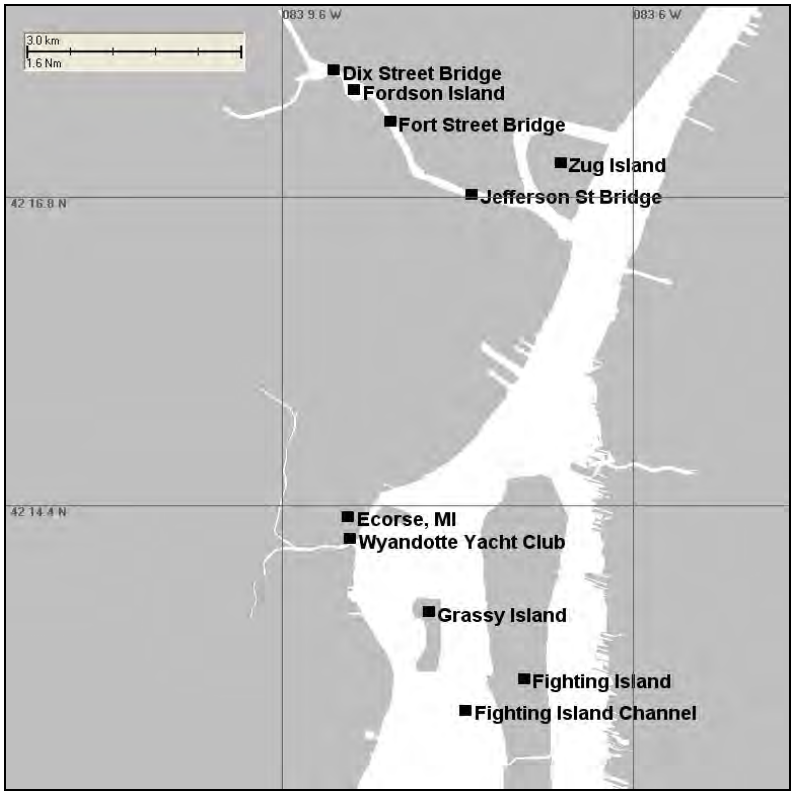

Figure 3-9. Detroit and Rouge Rivers, Assessment Zone 1.

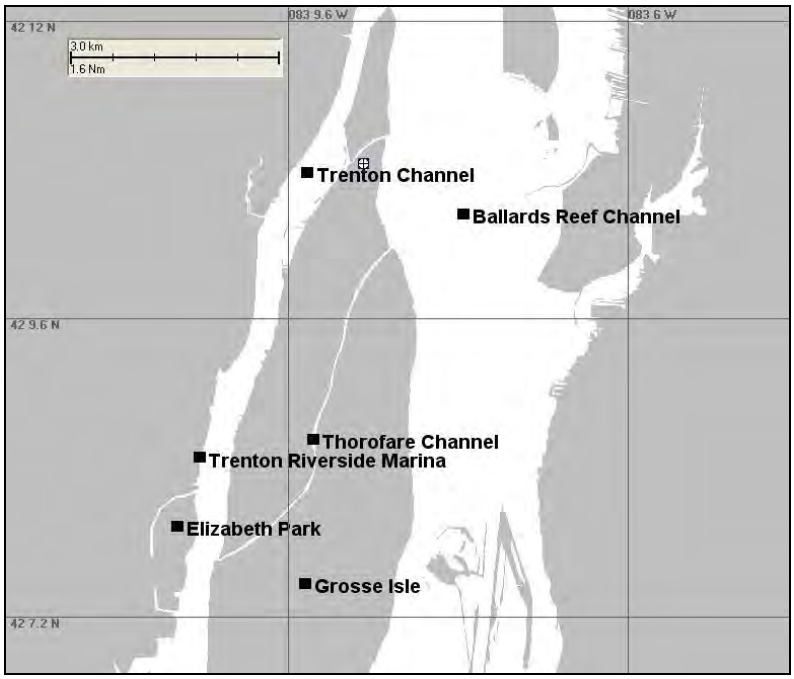

Figure 3-10. Detroit River, Assessment Zone 2.

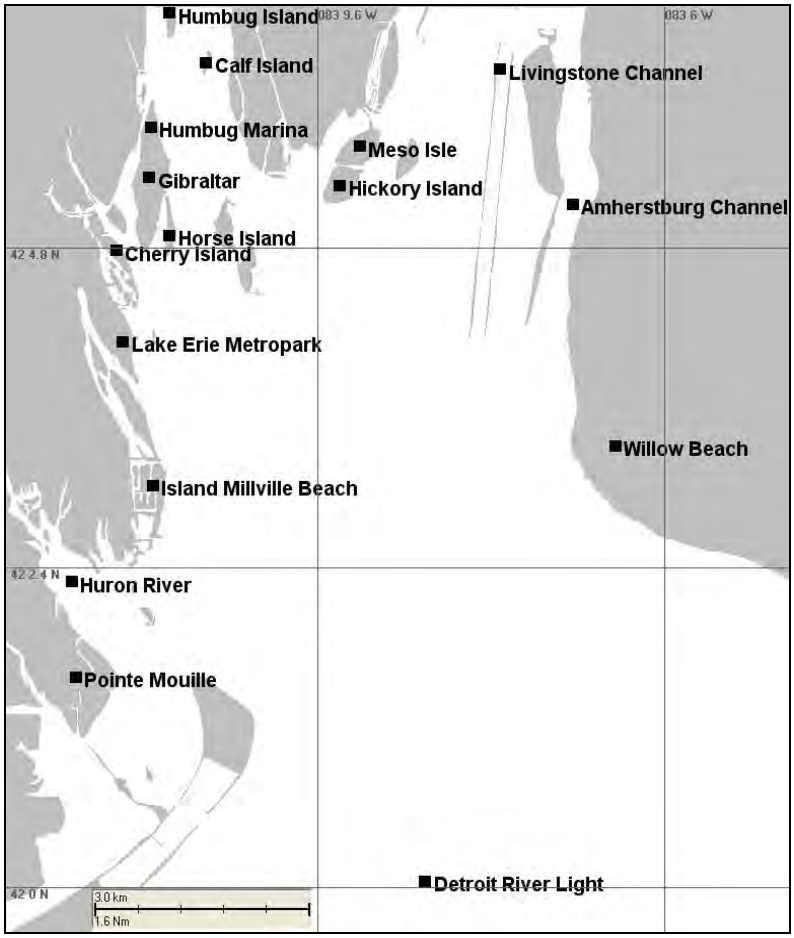

Figure 3-11. Detroit River and Northwest Lake Erie, Assessment Zone 3.

Table 3-2 provides a summary of the wildlife species that were either observed oiled, dead or alive in the vicinity of the Rouge River, Detroit River and western Lake Erie during the time of the spill, as reported above. There were a total of at least 110 birds and 3 turtles that were observed oiled or dead during the course of the oil spill.

Table 3-2. List of wildlife either observed oiled, dead or alive in the vicinity of the oil spill.

Date	Species Name	Location	Number Observed
10-April-2002	Bird, unspecified	Elizabeth Park	1
11-April-2002	Pekin duck	Elizabeth Park	12
	"Wild duck"	Elizabeth Park	6
	Mallard	Elizabeth Park	1
	White goose	Elizabeth Park	1
	Duck	Detroit River	>1
	Duck	Lake Erie Metro Park	1
	White goose	Gilbraltar	3
	Canada goose	Woodmere Cemetery	1
	Canada goose	Rouge River Mouth	1
	Canada goose	Amherstburg, Canada	3
	Duck	Amherstburg, Canada	1
12-April-2002	Bird, unspecified	Edmund Island	>1
	Ruddy duck	Lake Erie Metro Park	2
	"Wild duck"	Lake Erie Metro Park	6
	Mallard	Lake Erie Metro Park	5
	Canada goose	Lake Erie Metro Park	6
	Great egret	Lake Erie Metro Park	5
	Raptor	Lake Erie Metro Park	1
	Ruddy duck	Pt Mouillee CDF	12
	Bufflehead	Pt Mouillee CDF	1
	Pied-billed grebe	Pt Mouillee CDF	1
	Canada goose	Boblo Island, Canada	6
13-April-2002	Canada goose	Rouge River mouth near Detroit Edison	1
	Coot	Rouge River inland near BP Amoco	1
15-April-2002	Mallard	Lake Erie Metro Park	2
	Turtle	Lake Erie Metro Park	1
	Ruddy duck	Lake Erie Metro Park	1
	Canada goose	Fort St. near Rouge River	1
	Canada goose	Jefferson Ave. near Rouge River	1
	Turtle	Wyandotte at Libra Marina	1
16-April-2002	Coot or merganser	Trenton, private property	1
	Mallard	30014 Bayview St. in	1

Date	Species Name	Location	Number Observed
		Gilbraltar	
17-April-2002	Coot	Elizabeth Park	1
	Mallard	Lake Erie Metro Park	2
	Map turtle	Rouge River (Miller Rd outfall)	1 (alive, not oiled)*
	Canada goose	Rouge River (13207 Powell St)	3 (not oiled, but no longer feeding)*
18-April-2002	Merganser (red-breasted or common)	Fort St. Bridge on Rouge River	1
	Mute swan	Canada	1
	Scaup	Canada	2
	Ruddy duck	Canada	1
	Canada goose	Boblo Island, Canada	1
	Canada goose	Canada	12
19-April-2002	Mallard or black duck	Garden City	1
20-April-2002	Painted turtle	Wyandotte Yacht Club	1
	Duck	Riverview Marina	1
	Total birds observed oiled or dead		110+
	Total turtles observed oiled or dead		3

* These observations are not included in the total birds or turtles observed oiled or dead.

4. MODEL TRAJECTORY

4.1 Scenario

The model scenario involves two separate releases on 9 April and 12 April. The base scenario is a total of 339,810 gal of a mixture of diesel fuel oil and waste lubricating oil released over the course of several days from the Baby Creek Outfall (42°17'45.5" N, 83°9;4.3" W) that flows into the Rouge River.

The following assumptions were made to define the base case model scenario:

- Source of oil: 6-10 foot steel flow gate (with similar baffles upstream) that operated off hydraulic head. During the release from the outfall pipe to the Rouge River, the oil would have been mixed with water and sewage behind the gate until the pressure allowed the oil to flow and release below the gate.

- Droplet size distribution for release: assumed a droplet size distribution with a maximum of 1,000 µm diameter for base case scenario and varied between maximum of 500 µm and 5000 µm diameter for initial sensitivity analysis. These define typical droplet size distributions for releases under low ambient pressure, based on studies by Delvigne and Sweeney (1988) and Delvigne et al. (1994). The results were relatively insensitive to the range of these likely values for droplet size distribution; therefore, a range of 100-1,000 µm diameter was used.

- Volume of release: the total spill volume was set at 339,810 gallons.
  - The first component of 256,544 gal includes 255,544 gal (Allen 2002) that was observed on the waters of the Detroit River mid-day on 10 April and 1,000 gal reported cleaned from the Rouge River prior to the second release (US-PolRep).
  - The second component includes 66,276 gal, which is the volume of oil collected from the water (62,500 gal) and the banks of the Rouge River (4,776 gal) during the response (minus the 1,000 gal attributed to the first release).
  - The total spill volume of 322,820 gal based on observations was increased by 5% to account for evaporation by the time of the observation, which results in a total spill volume of 339,810 gal. This increase results in a first release on 9 April of 270,046 gal and a second release on 12 April of 69,764 gal.

- Emulsification:
  - The spill was reported as a mix of diesel and waste lubricating oils in an unknown percentage. Because samples of the oil were taken from the environment and more than 24 hours after the release, after some of the diesel had evaporated, degraded or dissolved, the original percentage of diesel is not known. When comparing the properties of diesel and

lubricating oils, the most significant difference with respect to controlling oil fate and resulting injuries is in the degree to which the oil can be emulsified into a mousse. Diesel does not emulsify and some (but not all) lubricating oils do form a mousse. From the spill observations and cleanup, it is clear that at least some of the lubricating oil emulsified to mousse containing 72% water. To simulate different ratios of diesel to lubricating oil and varying degrees of emulsification that may have occurred, the assumed maximum percent water in oil when fully emulsified as mousse was tested at three levels: 10%, 36%, and 60%. For the base case scenario, 36% maximum water content was used (50% diesel and 50% emulsifying lubrication oil), while 10% water indicates >50% diesel, an 60% water indicates >50% lubricating oil. Increasing percent water in mousse indicates a larger lubricating oil component in the spilled oil. The tests of these different percentages of water when fully emulsified in mousse provide additional sensitivity analysis of the bird injuries.

- Timing of releases:
  - Both releases to the river occurred as a result of rain runoff events when the steel flow gate overflowed.
  - Because these gates are designed to open during periods of increased outflow, the timing of the release was scaled to the timing of the precipitation. Total precipitation was added over each rain event, hourly rainfall in inches was converted to a percentage, and that percentage was used to scale the release using the two volumes mentioned above. Additionally, the timing was delayed (or lagged) for two hours to allow rain to runoff and reach the outfall (Tables 4-1 and 4-2).
  - An estimated 1,000 gal was removed from the Rouge River prior to the second spill. In order for the model to account for this, it was necessary to hold back 1% of the total spill volume and slowly release it between the end of the initial rain event and the installation of the booms at 1152 on 10 April (US-PolRep). Therefore, 100 gal were released each hour over the 27 hours between the end of the rain event and the installation of the booms. This slow release of 1% of the total spill volume simulates either oil released late or held along the shores of the Rouge River, and so not flushed out of the Rouge and into the Detroit River by 10 April.

Table 4-1. Timing of oil spill on 9 April 2002 based on hourly precipitation from Detroit Metro Airport.

Time of Day	Rain (inches)	Percent	Released Oil (gal)	Time of Release
1:00 AM	0.01	5	13,367	4:00 AM
2:00 AM	0.05	25	66,836	5:00 AM
3:00 AM	0.03	15	40,102	6:00 AM
4:00 AM	0.02	10	26,735	7:00 AM
5:00 AM	0.01	5	13,367	8:00 AM

Time of Day	Rain (inches)	Percent	Released Oil (gal)	Time of Release
6:00 AM	0.04	20	53,469	9:00 AM
7:00 AM	0.04	20	53,469	10:00 AM
8 am 4/9 – 10 am 4/10			100 gal/hr	10 am 4/9 – 12 pm 4/10
Total:	**0.2**	**100**	**270,046**	

Table 4-2. Timing of oil spill on 12-13 April 2002 based on hourly precipitation from Detroit Metro Airport.

Time of Day	Rain (inches)	Percent	Released Oil (gal)	Time of Release
5:00 PM	0.02	2	1,328	7:00 PM
6:00 PM	0.38	36	25,248	8:00 PM
7:00 PM	0.02	2	1,328	9:00 PM
8:00 PM	0	0	0	10:00 PM
9:00 PM	0	0	0	11:00 PM
10:00 PM	0	0	0	12:00 AM
11:00 PM	0	0	0	1:00 AM
12:00 AM	0	0	0	2:00 AM
1:00 AM	0	0	0	3:00 AM
2:00 AM	0	0	0	4:00 AM
3:00 AM	0.06	6	3,986	5:00 AM
4:00 AM	0.17	16	11,295	6:00 AM
5:00 AM	0.03	3	1,993	7:00 AM
6:00 AM	0	0	0	8:00 AM
7:00 AM	0.03	3	1,993	9:00 AM
8:00 AM	0.11	10	7,309	10:00 AM
9:00 AM	0.19	18	12,624	11:00 AM
10:00 AM	0.04	4	2,658	12:00 PM
Total:	**1.05**	**100**	**69,764**	

- Spill response:
  - According to Allen (2002), it is assumed that the bulk of the oil released into the Rouge River after mid-day on 10 April was contained and recovered. According to the USCG PolReps, a boom was placed across the Rouge River at 1152 on 10 April. According to NOAA overflight maps, a second boom was placed across the Rouge on 11 April, and another two booms were placed across the Rouge as of 15 April. Figure 4-1 shows the placement of all four booms. For the base case scenario, these booms were assumed to be 99% effective in stopping floating oil from entering the Detroit River.
  - Marine Pollution Control Corporation (MPC) recovered liquid oil and solid waste from Rouge and Detroit Rivers during the spill response. MPC reported 62,500 gallons of liquid product were removed in total from the surface of the Rouge River. An additional 500 gallons of liquid

product was recovered from the Detroit River (Allen 2002). A total 7,171 gallons of oil was recovered within the volume of solid waste (estimated at 5% of solid waste volume). Of this, 4,776 gallons were recovered from the banks of the Rouge and 2,395 gallons from the banks of the Detroit.

- The base case scenario only includes the removal of oil from the surface of the Rouge River between the first and second spills. The USCG PolRep mentions that MPC estimated 1,000 gal of oil had been removed from the system prior to the second spill.

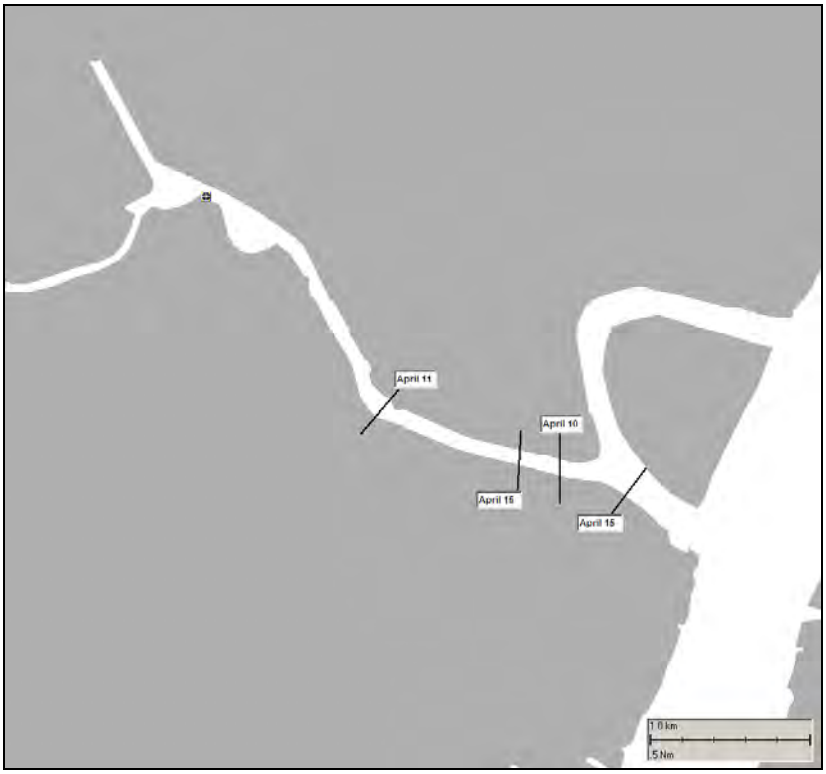

Figure 4-1. Placement of booms over the course of the two phase oil release.

4.2 Sensitivity Analysis

A sensitivity analysis was performed by varying several of the input parameters, as discussed below, and shown in Table 4-3 and Appendix B. Preliminary runs varying these parameters were used to narrow down the input assumptions that best fit the observations. Then a final set of simulations were performed for assumptions closest to best fit, to determine the best case and sensitivity to the input assumptions.

- Current flow speed was varied. A currents scaling factor affected the distribution of oil in the rivers at 12 noon on 10 April 2002 when the first overflights were recorded. For the base case scenario, a scaling factor of 1.1 was applied to the currents in order to match observations of approximately 256,000 gal of oil traveling out of the Rouge River and into the Detroit River

by noon on 10 April. As a sensitivity analysis, scenarios were also run using scaling factors for current flow of 1.0 and 1.2.

- Horizontal dispersion rate (coefficient) determines the randomized dispersion of the oil and affects the degree to which the oil will flow down the river or get stuck within cells (cul-de-sacs) of the habitat grid. For the base case scenario, a horizontal dispersion coefficient of 2 m^2/sec was applied to best fit oil spill observations. As a sensitivity analysis, scenarios were also run with horizontal dispersion coefficients between 1 m^2/sec and 5 m^2/sec. Scenarios with horizontal dispersion coefficients of 1 m^2/s to 3 m^2/s were carried throughout the sensitivity analysis because scenarios with higher horizontal coefficients did not distribute the oil sufficiently in the upper part of the Detroit River.

- Initial model runs showed no oil remaining in the Rouge River. In order to match reports that 1,000 gallons were removed from the river between 10 April and 12 April (before the start of the second release) the spill release had to be modified. Trial scenarios revealed that if 1% of the total volume of the first release (255,544 gal oil on the surface of the Detroit River, Allen 2002) was withheld and evenly released until noon on 10 April, approximately 1,000 gallons of oil was found on the surface of the Rouge River on 10 April just prior to when it would have been mechanically removed. The scenarios for 0% and 3% withholding were carried through the sensitivity analysis to show the effect, if any, this factor had on the trajectory of the oil.

Table 4-3 provides the matrix of scenarios that were used for sensitivity analysis, and highlights the base case scenario that was chosen. The base case scenario involved using 1.1 for the current scaling factor, 2 m^2/sec for the horizontal dispersion coefficient, and a 1 percent slow release of oil volume until noon on 10 April to match oil observations.

Table 4-3. List of scenarios used for sensitivity analysis based on input parameters varied from base case scenario.

Scenario name	Current scaling factor	Horizontal dispersion coefficient (m^2/sec)	Percent slow release (%)
RR-2PH -FV11-2HA-1PCT	**1.1**	**2**	**1**
Test: Scaling Factor			
RR-2PH -FV10-2HA-1PCT	**1.0**	2	1
RR-2PH-FV12-2HA-1PCT	**1.2**	2	1
Test: Horizontal Coefficient			
RR-2PH -FV11-1HA-1PCT	1.1	**1**	1
RR-2PH -FV11-3HA-1PCT	1.1	**3**	1
Test: Percent Slow Release			
RR-2PH-FV11-2HA-0PCT	1.1	2	**0**
RR-2PH-FV11-2HA-3PCT	1.1	2	**3**

5. 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).

The full model outputs of all model runs are available as *.avi files on CD and may be viewed with the Microsoft Windows Media Player or QuickTime software.

With the *.avi files, 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 (50 X 50 cells horizontally, 5 layers vertically) sized to just cover the plume at the time of the output. Table 5-1 displays what movie files are available and what data is contained in the movie files.

Table 5-1. Movie files (*.AVI) description.

Files Name	Model output
Rouge_trajectory	Model trajectory indicating where there is exposure to surface oil
Rouge_THC-max	Concentrations of total hydrocarbons in the water column over time (vertical maximum at each time step)
Rouge_float-oil	Amount of surface floating oil (g/m^2) over time
Rouge_diss-arom	Concentrations (ppb) of dissolved aromatics in the water column over time (vertical maximum at each time step)

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 Section 1, above. 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 C contains results for the best simulation, i.e., that simulation best agreeing with observed oil locations and shoreline oiling, and the two other simulations used for sensitivity analysis. Figure C-1 and Table C-2 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 in the water column. After 7 hours, 75% of the oil is on the water surface, 12% of the oil has been entrained into the water column, 13% has evaporated, 0.1% has decayed. After 21 hours (1200 on 10 April), 72% of the oil is on the water surface, 3% of the oil has been entrained into the water column, 20% has evaporated, and 0.6% has decayed. At the end of the simulation (30 days), 12% of the oil has been entrained into the water column, 37% has evaporated, 27% is on shore, and 17% has decayed.

The "Rouge_trajectory.avi" 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, as shown in Section 1, above.

"Rouge_THC-max.avi" shows the concentrations of total hydrocarbons (oil) in the water column over time. The animated movie shows the vertical maximum concentration on any given time step.

Figure C-2 in Appendix C shows the amount of oil accumulated on shorelines for the best 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 estimated in the model simulation as 32,800 m^2 of total shoreline, 27,900 m^2 of which is fringing marsh. No shoreline cleanup was simulated in the model. Thus, oil simply accumulates and remains on the shore.

"Rouge_float-oil.avi" shows the surface distribution of oil. For slicks on the water surface, 1 μm is approximately equivalent to 1 g/m^2. Table 5-2 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 5-2. 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

Black oil (with thicknesses greater than 1000 g/m^2) persisted for the first 21 hours after the start of the spill. Large areas of sheen (thicknesses greater than 10 g/m2) then persisted for 12 days (2200 on 21 April).

"Rouge_diss-arom.avi" shows the maximum concentration (ppb) of dissolved aromatics passing through each model grid cell.

6. ASSESSMENT OF INJURIES

A description of the data that were used as input to the biological model for densities of wildlife and fish is provided in Appendix D. Appendix E provides a list of biological injury results for the best base case scenario and the other scenarios performed as a sensitivity analysis.

6.1 Shoreline

Table 6-1 summarizes the shoreline oiled by more than 0.1 mm (>100 g/m^2) of oil. This threshold is the minimum (dose) in the model for impact to invertebrates in the littoral areas. Mortality of the vegetation in marshes occurs above about 14 mm of oil, according to literature reviewed in French et al. (1996), but marshes are generally lost (injured) at oiling levels above 1mm (French McCay, 2009). As the affected area is non-tidal, it is assumed that the invertebrate densities in the shoreline areas oiled were negligible, except for in wetlands, and so do not include biological injuries for non-vegetated shorelines in our injury assessment and compensatory restoration scaling. Wetland injuries are assumed compensable for areas where oiling exceeded 1mm oil (Table 6-2).

Table 6-1. Shoreline oiled by >0.1 mm (>100 g/m^2) of oil, for the scenario that best fit the observations of surface oil and shoreline oiling locations, and that was used for the injury quantification.

Habitat type	Length (m)	Area (m^2)
Rocky shore	6,132	6,132
Gravel beach	8,775	8,775
Sand beach	12,476	12,476
Wetland (marsh)	40,386	40,386
Mud shore	10,150	10,150
Artificial shore	0	0
Total shoreline oiled	**67,769**	**67,769**

Table 6-2 summarizes the oil exposure of shoreline and near shore habitats for all shorelines above a range of thresholds. Note that 1g/m^2 is approximately 1 micron thick oil, and 0.1g/m^2 is the thickness of oil sheen. No shoreline cleanup was simulated in the model. Thus, in the model, oil simply accumulates and remains on the shore until it is removed by natural processes (erosion and degradation).

Table 6-2. Area of shorelines oiled (m^2) with an average thickness greater than a threshold (1mm ~ 1kg/m^2) for base case scenario.

Shore type	>1 mm	>0.1 mm	>0.01 mm	>0.001 mm	>0.0001 mm
Rocky shoreline	3,066	6,132	7,929	8,352	8,352
Gravel beach	1,692	8,775	13,955	14,695	14,801

Shore type	>1 mm	>0.1 mm	>0.01 mm	>0.001 mm	>0.0001 mm
Sand beach	3,912	12,476	15,647	17,127	17,127
Wetland (marsh)	26,959	40,386	44,192	45,672	45,672
Mud shore	5,498	10,150	12,052	12,792	12,792
Artificial shoreline	0	0	740	1,163	2,115
Total shoreline	**41,127**	**77,919**	**94,801**	**99,801**	**100,859**

6.2 Wildlife

Table 6-3 provides the estimated total injury of wildlife, including birds, mammals, reptiles, and amphibians, for the best physical fate base case scenario for the three areas (Rouge River, Detroit River and Lake Erie) impacted by the spill. Species affected with a total injury of greater than 100 individuals per species or species group include muskrat, waterfowl, such as common merganser, greater scaup, and lesser scaup, and seabirds, such as Bonapartes gull, herring gull, and doublecrested cormorant (Tables E-2 and E-3 in Appendix E).

It should be noted that it is uncertain what the pre-spill densities of birds and other wildlife were before the spill. The density data used for the modeling, which was best available information, was from other locations and times (see Appendix D). However, the model results are directly proportional to the density data assumed. Therefore, if the densities assumed were a factor 2 lower, the injury results would also be a factor 2 lower. The counts of oiled animals observed oiled or dead in the field totaled 110 birds and 3 turtles. Thus, these model results suggest that one in 49 birds oiled were actually observed; whereas the rule of thumb for past spills has been about 1 in 10 might be observed. Yet, these ratios are highly uncertain, and dependant on the degree of search effort, losses to scavengers, and other factors. Estimates for the likelihood of observing oiled turtles are not available, but 1 in 100 is not unreasonable in this situation.

Table 6-3. Summary of estimated injuries to wildlife resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie.

Wildlife Group	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Waterfowl (other than scaup)	410	25	436
Scaup*	4,106		4,106
Seabirds	737	1	738
Wading birds	10	-	10
Shorebirds	58	-	58
Mammals (Muskrats)	308	0	308
Reptiles	114	0	114

Wildlife Group	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Amphibians	78	0	78
Total	**5,821**	**26**	**5,848**

* Scaups are assumed to be found in Lake Erie only in waters 1-3 meters deep.

Scenarios were also run for sensitivity to emulsification of the oil, since the exact proportion of diesel to lubricating oil in the mixture is unknown. The base case scenario used 36 as the maximum percent of water when fully emulsified as mousse. The two sensitivity analysis runs that were used to test this variable, and its effect on overall bird injuries, used 10 and 60 as the maximum percent of water when fully emulsified as mousse. The 10% indicated a spill with an oil mixture that was >50% diesel and the 60% indicated a spill with an oil mixture that was >50% lubricating oil. Overall, the results in bird injuries for these cases are not much different than those for the base case. The total number of birds, not including scaup, estimated to be killed for the 10% scenario was 956 birds, and for the 60% scenario was 1,443 birds, and compared to 1,242 birds for the base case scenario (Table 6-1). This low sensitivity is because the emulsification simply affects the thickness of oil, but has little effect on the area swept by the oil.

Tables 6-4 and 6-5 lists the equivalent losses for fledglings, hatchlings and age-one individuals, and the injury reported in equivalents losses for individual bird-, herptile- or mammal-years for the best base case scenario for the three areas (Rouge River, Detroit River and Lake Erie) impacted by the spill.

Table 6-4. Summary of estimated equivalent losses of bird fledglings, mammal age-zero (newly weaned) mammals, and herpetofauna hatchlings resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie.

	Equivalent Losses		
Wildlife Group	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Waterfowl (other than scaup) fledglings	1,401	84	1,485
Scaup fledglings*	14,332	-	14,332
Seabird fledglings	2,753	4	2,757
Wading bird fledglings	34	-	34
Shorebird fledglings	200	-	200
Muskrats (newly weaned)	940	-	940
Reptile hatchlings	1,700	-	1,700
Amphibian hatchlings	143,600	-	143,600
Total	**164,960**	**88**	**165,048**

* Scaups are assumed to be found in Lake Erie only in waters 1-3 meters deep.

Table 6-5. Summary of estimated injuries (interim loss) as individual bird-years, mammals-years and herptile years (all age classes combined for each group) resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie.

	Individual-years Lost (all ages)		
Wildlife Group	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Waterfowl (other than scaup)	1,057	78	1,135
Scaups*	8,855	-	8,855
Seabirds	11,977	16	11,992
Wading birds	31	-	31
Shorebirds	351	-	351
Muskrats	398	-	398
Reptiles	1,238	-	1,238
Amphibians	9,448	-	9,448
Total	**33,355**	**94**	**33,448**

* Scaups are assumed to be found in Lake Erie only in waters 1-3 meters deep.

6.3 Fish and Invertebrates

Table 6-6 lists the total injury (interim loss) of fish as the sum of direct kill plus production forgone (i.e., the net growth normally to be expected of the killed organisms over the remainder of their life spans, lifetime production), for the best base case scenario using an $LC50_{\infty}$ value of 44ppb for species of average sensitivity to the diesel and lubricating oil mixture that was released during the spill. Species affected with a total injury of greater than 40 kg per species (or species group) using an assumed $LC50_{\infty}$ value of 44ppb for species of average sensitivity included largemouth bass and large forage fish, which includes species such as common carp and buffalos.

Table 6-6. Summary of estimated injuries to fish resulting from the release of a diesel and lubricating oil mixture into the Rouge River, Detroit River and Lake Erie using a $LC50_{\infty}$ value of 44ppb for species of average sensitivity for the base case scenario.

Fish species:	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Herrings	2.2	0.0	2.2
Marsh forage fish	0.0	0.0	0.0
Rainbow smelt	0.0	0.0	0.0
White bass	2.0	1.4	3.4
White perch	6.5	5.8	12.3
Bowfin	3.6	0.0	3.6
Bullhead catfish	1.4	1.4	2.8
Freshwater drum	1.0	1.3	2.3
Large forage fish	18.7	23.0	41.8
Largemouth bass	19.8	21.2	41.0
Longnose gar	9.1	0.0	9.1
Medium forage fish	9.8	12.7	22.5
Northern pike	0.8	0.9	1.6
Rainbow trout	0.3	0.3	0.5
Rock bass	12.2	11.3	23.4
Small forage fish	1.7	1.1	2.8
Smallmouth bass	18.6	20.1	38.7
Sunfishes	4.4	3.9	8.3
Walleye	5.2	5.4	10.5
Yellow perch	1.5	0.0	1.5
Total small pelagic fish	2.2	0.0	2.2
Total large pelagic fish	8.4	7.2	15.6
Total demersal fish	108	102	211
Total demersal invertebrates	0.0	0.0	0.0
Total mollusks	0.0	0.0	0.0
Total	**119**	**110**	**228**

Scenarios were also run for $LC50_{\infty}$ values of 5ppb (for sensitive species) and 370ppb (for insensitive species) to bound these estimates, with the total range representing 95% of sensitivities to oil hydrocarbons based on species to date. The results indicate that the fish injuries computed by the model are somewhat affected by the assumed percentage of the oil released slowly and after the majority of the first oil release had moved out of the Rouge River, which was one of the parameters varied as part of the sensitivity analysis. The total injuries to fish for the 0 percent, 1 percent and 3 percent slow release scenarios, using an $LC50_{\infty}$ value of 44ppb for species of average sensitivity, are 153 kg, 228 kg and

258 kg, respectively. The total injuries to fish for the base case (1 percent slow release) scenario with oil containing 10 percent and 60 percent water when fully emulsified in mousse, using an $LC50_{\infty}$ value of 44ppb for species of average sensitivity, are 214 kg and 155 kg, respectively. Variation in species sensitivity to oil hydrocarbons induces a factor of 20 change in injuries. Thus, the fish injuries are not very sensitive to variation in the fates model inputs assumed, but are sensitive to the toxicity parameter range tested. Note, however, that most species would be close to average in sensitivity to oil hydrocarbons. In this system, it is unlikely that any of the species present would be highly sensitive to oil hydrocarbons (PAHs), given the historical and present levels of background contamination.

7. REFERENCES

Allen, A., 2002. Detroit River "Mystery Oil Spill" – April, 2002. Surface Volume Estimates. Prepared for U.S. Environmental Protection Agency, Region V, May 10, 2002.

Anderson, J.W., 1985. *Toxicity of dispersed and undispersed Prudhoe Bay crude oil fractions to shrimp, fish, and their larvae*. American Petroleum Institute, Publication No. 4441, Washington, D.C., USA, August, 1985, 52 p.

Bellrose, F. C. 1980. Ducks, geese, and swans of North American. Stackpole Books, Harrisburg, PA.

D'Avanzo, C., J.A. Jusler, and M.E. Kentuka (eds.), 1989. Long-term evaluation of wetland creation projects. pp. 75-84 in: Wetland Creation and Restoration: The Status of the Science, Vol. II Perspectives, EPA/600/3-89/038B, October 1989, 172p.

Delvigne, G.A.L. and C.E. Sweeney, 1988. Natural Dispersion of Oil. Oil and Chemical Pollution 4: 281-310.

Delvigne, Gerald A. L. and Hulsen, Lamber J. M., 1994. Simplified laboratory measurement of oil dispersion coefficient - Application in computations of natural oil dispersion. In: Proceedings of the Seventeenth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, Vancouver, B.C., Environmental Protection Service, Emergencies Science Division, Environment Canada, Ottawa, ON, Canada, pp.173-187.

Dunn, W.J. and G.R. Best, 1983. Enhancing ecological succession. 5. Seed bank survey of some Florida marshes and role of seed banks in marsh reclamation. pp. 365-370 in: D.H. Graves (ed.), Proceeding of the Symposium on Surface Mining Hydrology, Sedimentation and Reclamation, University of Kentucky, Lexington.

Electric Power Research Institute (EPRI). 2004. Extrapolating Impingment and Entrainment Losses to Equivalent Adult and Production Foregone. *EPRI Report No. 1008471*.

Ewert, D.N, G.J. Souillere, R.D. Macleod, M.C. Shieldcastle, P.G. Rodewald, E. Fujimura, J. Shieldcastle, R.J. Gates. 2006. Migratory bird stopover site attributes in the Western Lake Erie basin. Final report to The George Gund Foundation.

French, D., M. Reed, K. Jayko, S. Feng, H. Rines, S. Pavignano, T. Isaji, S. Puckett, A. Keller, F. W. French III, D. Gifford, J. McCue, G. Brown, E. MacDonald, J. Quirk, S. Natzke, R. Bishop, M. Welsh, M. Phillips and B.S. Ingram, 1996. The CERCLA type A natural resource damage assessment model for coastal and marine environments (NRDAM/CME), Technical Documentation, Vol. I - V. Final Report, submitted to

the Office of Environmental Policy and Compliance, U.S. Dept. of the Interior, Washington, DC, April, 1996; Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, PB96-501788.

French, D.P., and H. Rines, 1997. Validation and use of spill impact modeling for impact assessment. In: *Proceedings, 1997 International Oil Spill Conference*. Fort Lauderdale, Florida, American Petroleum Institute Publication No. 4651, Washington, DC, pp.829-834.

French, D.P., H. Rines and P. Masciangioli, 1997. Validation of an Orimulsion spill fates model using observations from field test spills. In: *Proceedings of 20th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*. Vancouver, Canada, June 10-13, 1997, Emergencies Science Division, Environment Canada, Ottawa, ON, Canada, pp. 933-961.

French McCay, D.P., 2002. Development and Application of an Oil Toxicity and Exposure Model, OilToxEx. *Environmental Toxicology and Chemistry* 21(10): 2080-2094, October 2002.

French McCay, D.P., 2003. Development and Application of Damage Assessment Modeling: Example Assessment for the *North Cape* Oil Spill. *Marine Pollution Bulletin* 47 (9-12): 341-359.

French McCay, D.P., and J.J. Rowe, 2003. Habitat restoration as mitigation for lost production at multiple trophic levels. *Marine Ecology Progress Series* 264:235-249.

French McCay, D.P., C.H. Peterson, J.T. DeAlteris and J. Catena, 2003a. Restoration that targets function as opposed to structure: replacing lost bivalve production and filtration. *Marine Ecology Progress Series* 264:197-212.

French McCay, D., J. J. Rowe, and N. Whittier, 2003b. Final Report, Estimation of Natural Resource Damages for 23 Florida Cases Using Modeling of Physical Fates and Biological Injuries. (23 volumes). Prepared for Florida Department of Environmental Protection, May 2003.

French McCay, D.P., and J.J. Rowe, 2004. Evaluation of Bird Impacts in Historical Oil Spill Cases Using the SIMAP Oil Spill Model. In: *Proceedings of the 27th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Emergencies Science Division, Environment Canada, Ottawa, ON, Canada, pp. 421-452.

French McCay, D.P., 2004. Oil spill impact modeling: development and validation. *Environmental Toxicology and Chemistry* 23(10): 2441-2456.

French McCay, D.P., 2009. State-of-the-art and research needs for oil spill impact assessment modeling. *2009 AMOP Proceedings*, in prep.

Galt, J.A. 1980. A finite element solution procedure for the interpolation of current data in a complex region. *Journal of Physical Oceanography* 10:1984-1997.

Holcombe, T.L., J.S. Warren, L.A. Taylor, D.F. Reid, C.E. Herdendorf. 1997. Lakefloor geomorphology of Western Lake Erie. *Journal of Great Lakes Research* 23(2): 190-201.

Holcombe, T.L., L.A. Taylor, J.S. Warren, P.A. Vincent, D.F. Reid, C.E. Herdendorf. 2005. Lake-floor geomorphology of Lake Erie. National Geophysical Data Center, publication RP-3.

Jensen, A.L., R.H. Reider, and W.P. Kovalak. 1988. Estimation of production forgone. *North American Journal of Fisheries Management* 8: 191-198.

Jokuty, P., S. Whiticar, Z. Wang, M. Fingas, P. Lambert, B. Fieldhouse, and J. Mullin. 1999. A catalogue of crude oil and oil product properties (1999 edition). Report # EE-165, Emergencies Science Division, Environment Canada, Ottawa, Canada.

Kullenberg, G. (ed.), 1982. *Pollutant Transfer and Transport in the Sea*. Volume I. CRC Press, Boca Raton, Florida. 227 p.

Malins, D.C. and H.O. Hodgins. 1981. Petroleum and marine fishes: a review of uptake, disposition, and effects. *Environmental. Science & Technology* 15(11): 1272-1280.

McAuliffe, C.D., 1987. Organism exposure to volatile/soluble hydrocarbons from crude oil spills – a field and laboratory comparison. In: *Proceedings of the 1987 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp.275-288.

Nalepa, T.F., and D.W. Schloesser, 1993. *Zebra Mussels: Biology, Impacts, and Control*. Lewis Publishers.

National Oceanic and Atmospheric Administration (NOAA). 1994. ADIOS, Automated Data Injury for Oil Spills, User's Manual, NOAA/Hazardous Materials Response and Assessment Division, Seattle, Washington.

National Oceanic and Atmospheric Administration (NOAA). 1997. Natural resource damage assessment guidance document: scaling compensatory restoration actions (Oil Pollution Act of 1990), NOAA Damage Assessment Center, Silver Spring, MD

National Oceanic and Atmospheric Administration (NOAA). 1999. Habitat Equivalency Analysis: An Overview. NOAA Damage Assessment Center, Silver Spring, MD, 23p.

National Research Council (NRC), 1985. *Oil in the Sea: Inputs, Fates and Effects*, National Academy Press, Washington, D.C. 601 p.

National Research Council (NRC), 2002. *Oil in the Sea III: Inputs, Fates and Effects*, National Academy Press, Washington, D.C. 446 p.

Neff, J.M., J.W. Anderson, B.A. Cox, R.B. Laughlin, Jr., S.S. Rossi, and H.E. Tatem, 1976. Effects of petroleum on survival respiration, and growth of marine animals. In: *Sources, Effects and Sinks of Hydrocarbons in the Aquatic Environment*, Am. Institute of Biological Sciences, Washington, DC, pp. 515-539.

Neff, J.M. and J.W. Anderson, 1981. *Response of Marine Animals to Petroleum and Specific Petroleum Hydrocarbons*, Applied Science Publishers Ltd., London and Halsted Press Division, John Wiley & Sons, NY, 177p.

Odum, E.P., 1971. *Fundamentals of Ecology*. W.B. Saunders Co., Philadelphia, 574 p.

Okubo, A. 1971. Oceanic diffusion diagrams. *Deep-Sea Research* 8: 789-802.

Okubo, A. and R.V. Ozmidov, 1970. Empirical dependence of the coefficient of horizontal turbulent diffusion in the ocean on the scale of the phenomenon in question. *Atmospheric and Ocean Physics* 6(5):534-536.

Rago, P.J. 1984. Production foregone: An alternative method for assessing the consequences of fish entrainment and impingement at power plants and water intakes. *Ecological Modeling* 24: 79-111.

Reed, M., D.P. French, S.Feng, F.W. French III, E. Howlett, K, Jayko, W.Knauss, J. McCue, S. Pavignano, S. Puckett, H. Rines, R.Bishop, M. Welsh, and J. Press, 1996. The CERCLA type a natural resource damage assessment model for the Great Lakes environments (NRDAM/GLE), Vol. I - III. Final report, submitted to Office of Environmental Policy and Compliance, U.S. Department of the Interior, Washington, DC, by Applied Science Associates, Inc., Narragansett, RI, April 1996, Contract No. 14-01-0001-88-C-27.

Rice, S.D., J.W. Short and J.F. Karinen, 1977. Comparative oil toxicity and comparative animal sensitivity. In: D.A. Wolfe (ed.)., *Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms*, Pergamon Press, NY, pp. 78-94.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. *Bulletin of Fisheries Research Board Canada* 191, 382 p.

U.S. Environmental Protection Agency (USEPA), 2004. Final Rule, Clean Water Act §316(b), National Pollutant Discharge Elimination System, Final Regulations to Establish Requirements for Cooling Water Intake Structures at Phase II Existing Facilities, July 2004

Wang, Z., M. Fingas, P. Lambert, G. Zeng, C. Yang, and B. Hollebone. 2004. Characterization and identification of the Detroit River mystery oil spill (2002). *Journal of Chromatography A*. 1038: 201-214.

Attachment A: State-of-the-Art and Research Needs for Oil Spill Impact Assessment Modeling

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State-of-the-Art and Research Needs for Oil Spill Impact Assessment Modeling

Deborah French-McCay
Applied Science Associates, Inc.
South Kingstown, RI, USA
dfrenchmccay@asascience.com

Abstract

Modeling can be a powerful tool for oil spill impact quantification as part of environmental risk assessments, contingency planning, and natural resource damage assessments. Historically, oil spill models have focused on trajectory and fate in aquatic environments, with impacts being assessed in most cases by evaluating the presence of biota in the area exposed to floating or shoreline oil. A few models have addressed subsurface oil concentrations to which water column biota are exposed, but most of these simply overlay fates model concentration results on maps or grids of biological distributions to assess "impact". This paper describes the state-of-the-art of biological effects modeling for the most comprehensive approach to date, a model that evaluates dose and resulting impact of oil hydrocarbons on aquatic biota including birds, mammals, reptiles, fish, invertebrates, and plants. The biological effects model is coupled to an oil trajectory and fates model that supplies required spatial and temporal quantification of oil distributions and hydrocarbon component concentrations. Model development and validation studies are reviewed, strategies for applying the model for hindcasts and risk assessments are discussed, and research and data needs are identified.

1 Introduction

There is a growing demand by both government and industry for oil spill fates and biological effects modeling to address the potential environment impacts of spills and oil-related activities. This demand is driven by government regulations, the limits of data collections from field and laboratory work, and the growing power of computers for performing data analyses and modeling calculations. Models use knowledge of physical, chemical, and biological relationships along with environmental data to simulate pollutant transport, fate and biological effects. This analysis is useful for risk assessment, contingency planning, cost-benefit analysis and natural resource damage assessment (NRDA). Modeling may be applied to investigate a single spill event, to evaluate the probable consequences of a hypothetical spill, or to determine impacts of a worst-case spill scenario. Examples of these applications include risk assessment in support of permit application, comparison of response strategies for contingency planning, and analysis of maximum liabilities for accidental spills.

A number of oil trajectory and fates models are available around the world. Several reviews of the state-of-the-art in oil spill trajectory and fate modeling have been performed over the past two decades (Huang, 1983; Spaulding, 1988; ASCE, 1996; Reed et al., 1999) to assess the state of the practice, to summarize key developments, and to project future capabilities. The reader is referred to these papers and the literature (e.g., Mackay et al., 1982; Kirstein et al., 1987; Lehr et al.,

1995, 2000; Jones, 1997; Galt, 1998; Reed et al., 2000; French McCay, 2004; Boufadel et al., 2007) for descriptions of these and other oil fate models, as well as research needs.

In contrast, few model developers have carried out the analysis to quantitatively address biological impacts of oil spills in aquatic environments. In most cases, impacts are assessed by evaluating the presence or densities of biota in the areas exposed to floating or shoreline oil. In some cases, the oil fate model used for the assessment is three-dimensional, such that subsurface concentrations are considered. However, the assessment of impact is generally performed by establishing a threshold for concern and then mapping or quantifying the area "impacted". The problem with this approach is that an impact is assumed if there is an intersection of some amount of oil with biological "receptors", without consideration of dose, uptake, duration of exposure, or measurable effect.

Early modeling efforts for wildlife impact assessment relied on calculating the intersection of oil trajectories with birds or marine mammals, assuming an impact threshold (Reed et al., 1989; Jayko et al., 1990). In some cases, wildlife population and migration models were used to simulate the distribution, behavior and recovery of the affected species, in conjunction with their intersection with oil trajectories (Samuels and Lanfear, 1982; Ford, 1985, 1987, Ford et al., 1982; Brody, 1988; French and French, 1989; French et al., 1989; Seip et al., 1991). In these modeling efforts, the impact threshold for wildlife was appropriately based on a threshold oil thickness or mass for lethal or sublethal effects, although quantitative information definitively indicating what dose would be lethal was not available.

Both subsurface oil droplets and dissolved hydrocarbons must be explicitly simulated (in addition to surface floating oil and associated processes) in an oil fates model in order to be able to evaluate exposure of aquatic biota to oil hydrocarbons and biological effects. A prime case example is the *North Cape* oil spill of January 1996, which occurred during a severe winter storm where 2682 metric tons (828,000 gallons) of home heating oil (No. 2 fuel oil) spilled into the surf zone on the south coast of Rhode Island, USA. Most of the oil was entrained into the water column by heavy surf, resulting in high concentrations of dissolved components in shallow water, which took weeks to disperse, killing millions of water column and benthic organisms (French McCay, 2003). Moreover, because the many hydrocarbons in oil have varying physical-chemical properties (most significantly those related to solubility and volatility), the oil fates model must separately track chemical classes or pseudo-components of the whole oil with characteristics typical of the chemical group to simulate their separate fates (Payne et al., 1984, 1987; Kirstein et al., 1987; French et al., 1996; Jones, 1997; Reed et al., 2000; French McCay, 2004). Most oil fates models employ a Lagrangian particle approach, which enables the modeler to track physical and chemical property changes as oil weathers. This is particularly needed when oil is released over time under varying conditions. The Lagrangian methodology is also useful for biological modeling to track organisms' movements and exposure to oil (French et al., 1996; French McCay, 2003, 2004).

Potential and documented impacts of oil in aquatic environments have been reviewed by the National Research Council (NRC, 1985, 2002) as well as others (Neff et al., 1976; Neff and Anderson, 1981; Engelhardt, 1983, 1987; Teal and Howarth, 1984; Capuzzo, 1987; Geraci and St. Aubin, 1990; Rice et al., 1996; Sloan,

1999; Kingston, 2002). A biological effects model that considers all impacts of oil should include evaluation of: exposure considering movements and amounts of both oil and biota; duration of exposure and degree of accumulation in tissues; acute effects and direct impacts (lethal and sublethal) in the short-term; sublethal effects of chronic contamination; behavioral changes resulting in reduced growth, survival or reproductive success; indirect effects via reduction in food supply, habitat, or other changes in the ecosystem; impacts of spill response activities; and population level impacts caused by mortality and sublethal effects. Supporting research and information is available to quantify some but not all of these effects, as discussed below.

Herein, the state-of-the-art of biological effects modeling for use in impact and risk analyses is described, as developed by French and French (1989), French et al. (1996), and French McCay (2002, 2003, 2004), and on-going research and case analyses for NRDA and risk assessments. A biological effects model requires physical and environmental inputs including (1) wind data as time- and (optionally) spatially-varying velocities; (2) current data as time- and spatially-varying velocities; (3) environmental conditions such as temperature and salinity; and (4) physical fates model outputs that quantify spatial distributions, physical-chemical characteristics, and concentrations over time of floating oil, entrained oil droplets, dissolved hydrocarbon components, oil in sediments, and oil on shorelines. Typically, a biological effects model is coupled to an oil fates model capable of providing the needed information, such as that described by French McCay (2004). However, in the future, models could be modularized and fates models could provide standardized outputs that could be used as input to biological effects models.

This paper provides background for current research being supported by the Coastal Response Research Center at the University of New Hampshire. Previous model development, modeling approaches, available information, potential algorithms, and data needs for developing the next-generation oil spill biological effects model are being reviewed. Processes being considered in the biological effects modeling review include (1) oil hydrocarbon exposure (to floating oil, entrained droplets, dissolved hydrocarbons, oil in sediments, and oil on shoreline) for habitats, wildlife, fish and invertebrates, including consideration of behavior (i.e., normal, avoidance and attraction); (2) pathways and rates of uptake of hydrocarbons into biota; (3) lethal and sublethal effects levels for mechanical, smothering, thermal, and/or toxicological effects of (whole) oil on wildlife and aquatic biota; (4) acute and chronic toxicity of hydrocarbons on aquatic biota, including consideration of duration of exposure and long-term effects on development, growth, reproduction, etc.; (5) phototoxicity of polynuclear aromatic hydrocarbons (PAHs) on aquatic biota; and (6) population and ecosystem level effects and recovery rates. This paper focuses on model development to date: that addressing acute toxic effects resulting from short-term exposure. Long-term effects of oil hydrocarbon exposure have not been addressed in oil spill models to date, due to the complexity, site-specificity required, and paucity of quantitative information to develop such a model.

2 Coupled Physical Fates Model

The SIMAP (Spill Impact Model Application Package) physical fates model (French McCay, 2004), to which the SIMAP biological effects model is coupled

(Figure 1), is described briefly here to illustrate the needed capabilities for input to the biological effects model calculations. The SIMAP models were derived from the physical fates and biological effects submodels in the Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME), which were developed for the U.S. Department of the Interior (USDOI) as the basis of Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) Natural Resource Damage Assessment (NRDA) regulations for Type A assessments (French et al., 1996). The SIMAP physical fates model is described in detail in French McCay (2004).

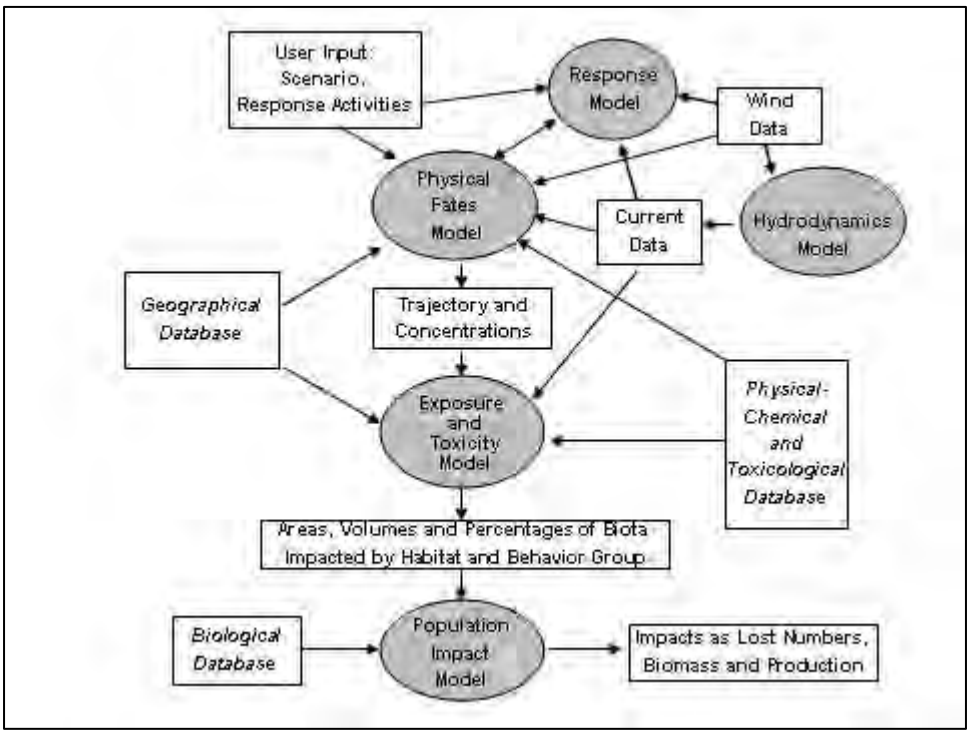

Figure 1. Diagram of the SIMAP Model System

The transport model in SIMAP (French McCay, 2003, 2004, also the earlier version in French et al., 1996) and other oil spill models (Mackay et al., 1982; Spaulding et al., 1983; Spaulding, 1988; Lehr et al., 1995, 2000; Galt, 1998; Reed et al., 1999, 2000) utilize similar algorithms for calculating advective movements and turbulent dispersion, i.e., Lagrangian elements ("LEs" or "spillets") are used to track the oil movements and weathering. The SIMAP physical fates model (French McCay, 2004) uses wind data, current data, and transport and weathering algorithms to calculate the mass of oil components in various environmental compartments (water surface, shoreline, water column, atmosphere, sediments, etc.), oil pathway over time (trajectory), surface oil distribution, and concentrations of the oil components in water and sediments over time. The distribution of oil in space and time is expressed as mass per unit area on the water surface, mass per unit area on shorelines, concentration in the water column, and mass loading per area of the sediments.

Processes simulated in the physical fates model include slick spreading, evaporation of volatiles from surface oil, transport on the water surface and in the

water column, randomized dispersion, emulsification, entrainment of oil as droplets into the water column, resurfacing of larger droplets, dissolution of soluble components (i.e., lower molecular weight aromatics), volatilization from the water column, partitioning of semi-soluble components between sediments and the dissolved form, sedimentation, stranding on shorelines, and degradation. Oil mass is tracked separately for lower-molecular-weight aromatics (1 to 3-ring aromatics), which are soluble and so cause most acute toxicity to aquatic organisms (French McCay, 2002, see below), other volatiles, and non-volatiles. The lower molecular weight aromatics dissolve both from the surface oil slick and whole oil droplets in the water column, and they are partitioned in the water column and sediments according to equilibrium partitioning theory (French et al., 1996; French McCay, 2003, 2004).

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

Concentrations in the water column are calculated in SIMAP by summing mass (in the spillets) within each grid cell of three-dimensional grid scaled each time step to just cover the dimensions of the plume. This includes all potential contamination in the water column, while maximizing the resolution of the contour map at each time step to reduce 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 and $2D_zt$ 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. Concentrations of particulate (oil droplet) and dissolved aromatic concentrations are calculated in each cell and time step and saved to files for later viewing and calculations. These data are used by the biological effects model to evaluate exposure, toxicity, and effects.

In summary, the fates model quantifies, in space and over time:

- The spatial distribution of oil mass and volume on the water surface (including flooded intertidal areas and lands) over time;
- Oil mass, volume and thickness on shorelines of varying types over time;
- Subsurface (in-water) oil droplet concentrations, as total hydrocarbons, in three spatial dimensions over time;
- Dissolved aromatic concentrations in water in three spatial dimensions over time; and
- 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) floating on water surfaces,
- Oil loading (g/km and g/m^2) on shorelines,

- Subsurface oil droplet concentrations in water (ppb), as total hydrocarbons,
- Dissolved aromatic concentrations in water (ppb),
- Total hydrocarbon loading on sediments (g/m^2), and
- Dissolved aromatics concentrations in sediment pore water (ppb).

The SIMAP transport model has been validated with more than 20 case histories, including the *Exxon Valdez* and other large spills (French McCay, 2003, 2004; French McCay and Rowe, 2004), as well as test spills designed to verify the model's transport algorithms (French et al., 1997; French McCay et al., 2007). It has been used in many NRDA cases in the US, as well as in ecological risk assessments for potential spills world wide.

3 Biological Effects Model

The biological exposure model estimates the area or volume where organisms are adversely affected by surface oil, concentrations of oil components in the water, and/or sediment contamination. The area or volume impacted may be multiplied by organism density to calculate an impact or evaluated as a portion of a stock or population affected. The biological effects model (Figure 2) estimates losses resulting from acute exposure after a spill (i.e., losses at the time of the spill and while floating oil and 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. The model first estimates percentage losses in discrete habitat areas or volumes by behavior group (e.g., aerial seabirds in areas, pelagic fish in volumes), translating these to equivalent areas and volumes of 100% loss (i.e., by summing the percent loss times area or volume affected). These equivalent areas and volumes are then multiplied by biological density data to estimate direct losses of species or species groups of fish, invertebrates (i.e., shellfish and non-fished species) and wildlife (birds, mammals, reptiles). Lost production of aquatic plants (microalgae and macrophytes) and lower trophic levels of animals are also estimated in the direct loss model calculations. Lost production of prey species are translated to losses higher in the food web using a food web model. Future losses are calculated using a population model, accounting for lost future growth as well as natural and harvest mortalities for each life stage and annual age class.

The area potentially affected by the spill is represented by a rectangular grid with each grid cell coded as to habitat type. The same 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. Pre-spill densities of fish, invertebrates, and wildlife (birds, mammals, reptiles, and amphibians) are assumed evenly distributed across each habitat type defined in the application of the model. Habitat types may be defined to resolve areas of differing density for each species, and the impact in each habitat type is then separately computed. 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, a reasonable assumption for the few weeks following oil release that are modeled. Aquatic organisms are modeled using Lagrangian particles representing schools or groups of individuals. Benthic organisms remain stationary on or in the bottom. Planktonic stages, such as pelagic fish eggs and larvae are transported by the currents (input to the model).

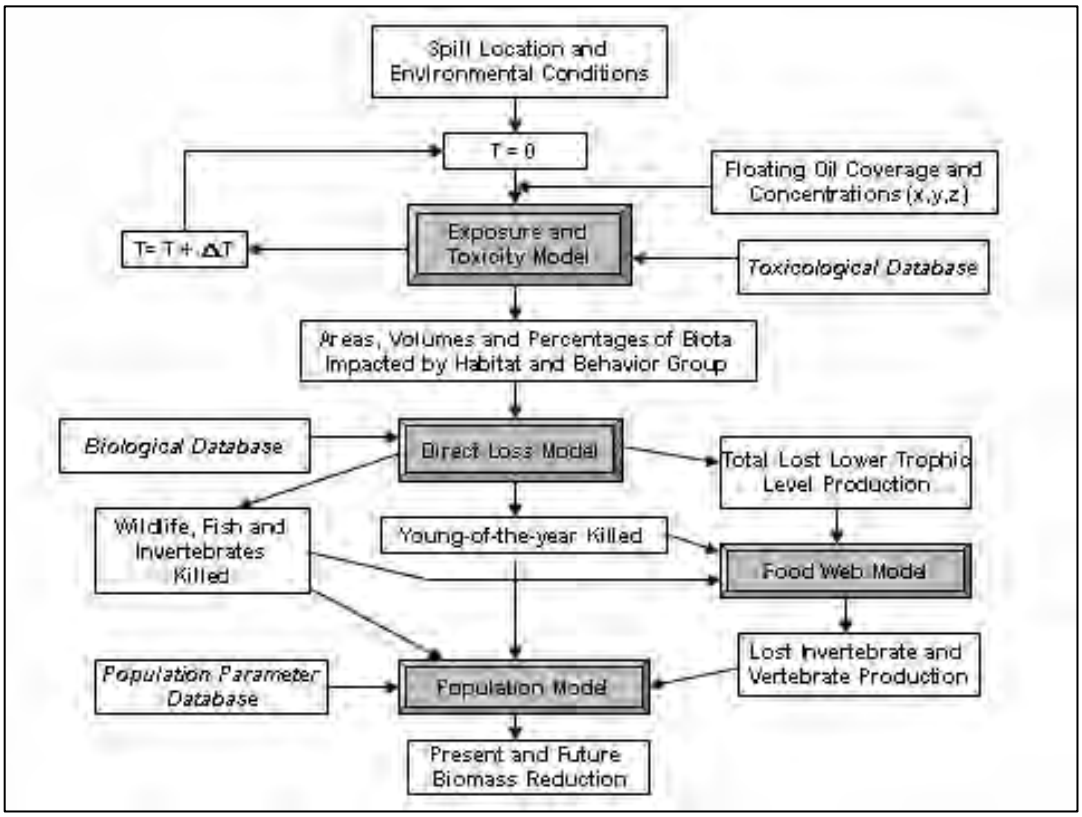

Figure 2. Diagram of the Biological Effects Model

Habitats include open water, invertebrate reef, wetland (marsh, swamp), seagrass, macroalgal bed, and shoreline environments. Habitat types are defined by depth, salinity regime, proximity to shoreline(s), bottom/shore type, dominant vegetation type, and the presence of invertebrate reefs. With respect to salinity and proximity to shoreline(s), habitats are designated as landward or seaward. 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). Thus, the landward-seaward designation is operational and tailored to the needs for a particular assessment in an oil-affected area. The SIMAP model has been applied to marine, estuarine and freshwater environments, with habitats defined accordingly.

Wildlife (i.e., air-breathing vertebrates) individuals that move through the area swept by floating oil are assumed to be oiled based on probability of encounter. Those oiled above a threshold dose are then assumed to die.

Fish, shellfish, their eggs and larvae, and other plankton are affected by dissolved concentrations of hydrocarbons in the water or sediment. Mortality is

calculated using laboratory acute toxicity test data (LC50, concentration lethal to 50% of test individuals) corrected for temperature and time of exposure, and assuming a log normal relationship between percent mortality and dissolved concentration. The model accounts for the uptake, accumulation and additive effects of the mixture of hydrocarbons to which the organisms are exposed. Organisms killed are integrated over space and time and by habitat type to calculate a total short term kill. This total short term kill occurs from the time of the spill until the time the contaminants are dispersed to the point where concentrations are below toxic levels.

Lower trophic level biota are generally not evaluated by species or species group, and impacts are quantified as lost production in each habitat affected. Lost primary (plant) and secondary (herbivore) production due to sublethal concentrations of dissolved hydrocarbons is estimated using the EC50, the concentration where growth rate is 50% of the clean control, correcting it for temperature and assuming a log normal relationship between percent of uninhibited growth rate and concentration. Primary and secondary production losses are integrated over space and time and by habitat to calculate the total biomass not produced during the spill. For areas affected by sublethal concentrations, the rates of production are assumed to return to normal immediately following the dispersion of the contamination to non-toxic concentrations.

For microalgae (phytoplankton and benthic microflora), concentrations which reduce production to near zero are essentially lethal. The above calculation procedure covers these losses. Reseeding of these groups into affected habitats which are no longer toxic is so rapid that recovery may be assumed immediate following dispersion of toxic concentrations. However, for macrophytes, recovery following exposure to lethal concentrations is not immediate. In habitats dominated by macrophytes (e.g., marshes, swamps, kelp beds, seagrass beds), complete mortality of plants is assumed if a lethal threshold is reached (in water concentrations or in oil coverage). Losses from the direct kill and over the period of natural recovery after the toxicity is gone are included in the tabulation for macrophytes and for animals (wildlife, fish, shellfish, eggs, larvae and benthos) dependant on the affected habitat for food or development.

Biomass which is not produced as a result of a loss of food resources is estimated using a simple food web model. The portion of the lost primary production which would have produced primary consumer (secondary producer or herbivore) biomass is estimated based on observations of ecological efficiency made on representative ecosystems. The fractions of the lost secondary production which would have been consumed by each of their predators are assumed to be proportional to the biomass of that predator relative to the sum of its competitors. The output of this part of the model is lost production of the various fish, shellfish, and wildlife species as a result of the spill. This is added to the total direct kill to yield a total loss of biomass by habitat as a short term result of the spill.

In addition to the direct kill and food web losses of eggs, larvae and juveniles, these young-of-the-year may be lost via habitat disruption. This is included in the model for macrophyte-dominated habitats affected by lethal oiling. Losses are assumed proportional to the macrophyte loss. Thus, recovery of spawning and nursery habitat in wetlands, kelp beds, and seagrass beds follows recovery of

macrophyte biomass and production. Similar assumptions are made for coral reefs based on the same arguments.

Potential long term losses (losses realized after the spill has dissipated) which can result from a spill of a toxic substance include: (1) lost recruitment to a fishery of the larvae and juveniles killed at the time of the spill; (2) lost future growth of the adults killed at the time of the spill; (3) changes in food web structure and, therefore, productivity of specific trophic levels and populations; and (4) chronic effects of sublethal levels of contaminants in tissues or the environment, such as reduced growth rate or loss of reproductive potential. The first two effects are typically the most dominant following an acute event such as an oil spill. The latter two effects have not been included in any model to date, both due to the complexity of developing such models, which necessitates that they be site specific, and to the lack of quantitative information required to apply these models (e.g., see Hansen, 1984). Thus, the impacts estimated in the biological effects model are the results of acute toxicity and resulting direct effects on long term productivity and yield: lost recruitment and lost growth. As such, the model does not consider any indirect (chronic) effects or feedbacks after the spill has dissipated, such as changes in mortality due to density dependent effects, changes in food web structure and predator prey relationships, or changes in reproductive potential. The modeled spill impact extends only for the life span of the species considered, and growth and reproduction are assumed to return to normal after the effects of the spill have dissipated.

For fish and invertebrates (juveniles over the age of one year and adults of a species), it is assumed that a constant natural mortality rate (due to natural causes) applies; juveniles (over age one) and adults inhabit the same habitat at the same time; there is a constant fishing mortality rate for animals past the age of recruitment to the fishery; and that growth follows the von Bertalanffy relationship (Ricker, 1975). Using these assumptions and standard steady state fisheries models, the age structure of a population and long term losses in yield as the result of the spill may be estimated (Ricker, 1975). The direct kill, in numbers by age, is calculated from biomass killed, weight as a function of age, and natural and fishing mortality rates. For each year following the spill, the lost catch, calculated from fishing mortality, weight by age and average number alive during that year, is calculated. Thus, only those individuals which would have been caught in present and future years, and not those which would have died naturally, are included in the quantification of the future production and catch losses due to the incident.

The relatively high mortality rates of eggs and larvae are considered in the biological effects model, since a high number killed at the time of the spill would have died regardless of the spill. The young-of-the-year (eggs, larvae, and juveniles less than one year old) of each fishery species category are tracked as percents of the age one population. Young-of-the-year and older age classes are not assumed to inhabit the same environment concurrently, and their losses are calculated separately.

For waterfowl and mammals, losses to hunting are calculated assuming constant natural and hunting mortality rates over time after the spill. For all wildlife, population losses are calculated as the number not left alive in present and future years as the result of the spill, after constant natural mortality (and hunting mortality) is subtracted.

The biological effects model is designed to be generally applicable, while restricting the data and parameter requirements to information which is generally available. As part of the development of the NRDAM/CME (French et al., 1996), biological data were compiled for a series of habitat types within each of 77 regions of U.S. coastal and marine waters, as opposed to site specific information for every possible geographic location. A similar approach has been taken when applying the model to other locations outside US waters. In addition, freshwater databases have been developed for the Great lakes and other inland waters. Site- and event-specific databases have been developed for specific case investigations or risk assessments.

Required biological data for applying the model to obtain biomass and numerical losses by species are: estimates of fish and invertebrate biomass per area (kg wet weight/km^2), numbers of wildlife (birds, mammals, reptiles) per unit area (#/km^2), and rates of production for lower trophic levels (plants and invertebrates, g C m^{-2} day^{-1}). These data may be specific for the time of a spill or, if a biological database is developed, seasonal or monthly means in each habitat type.

Parameters required for the population model include estimates of natural and fishing (hunting) mortality rates, available from the fisheries and wildlife literature; age specific growth rates, available from length or weight at age catch data; and age at recruitment and life span. The spawning areas and times for fish and invertebrate species and development information for the young of all species groups are also compiled when evaluating these losses. All of these estimates are specific to habitat within each geographic region.

3.1 Wildlife: Air-Breathing Vertebrates

3.1.1 Model Algorithm

For wildlife (air-breathing vertebrates: birds, mammals, and reptiles, and adult amphibians), the number or fraction of a population suffering oil-induced effects is proportional to the water-surface area swept by oil (slicks, emulsions, or other floating forms such as tar balls) of sufficient quantity to provide a lethal dose to an exposed animal. Wildlife populations are assumed to be in equal density across each ecosystem (each grouping of like habitat grid cells) and to remix within each ecosystem each day. For each day of the simulation, those oiled above a threshold dose are assumed to die, and the remainder may be oiled in subsequent days if oil is still present on the water surface.

Wildlife individuals are assumed to move at random within the ecosystem for the period of the simulation of the spill. Studies have shown that while birds and mammals may sometimes try to avoid oil once they have experienced it, for the most part animals respond to overriding desires of obtaining food or other behaviors such that avoidance is negligible (Varoujean et al., 1983; Geraci and St. Aubin, 1988, 1990). While the majority of fulmars near an experimental spill were observed by Lorentsen and Anker-Nilssen (1993) to avoid oil, 4% entered oil sheen because they were attracted to food remains thrown overboard from the research vessel. Avoidance (or attraction) is simulated in the model by adjusting the probability of intersecting oil (see below).

For each of a series of surface spillets, the physical fates model has estimated the location and size (radius of circular spreading spillet) as a function of time. This information is input to the biological exposure model where 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. The areas swept by all spillets are summed over all (physical fates model) time steps in a given day, 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 by oil greater than a threshold thickness in each 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. The calculations are summarized as follows:

$$N' = P_w \sum_{t=0}^{t=\infty} A_s N_t \Delta t \qquad (1)$$

where N' is the total number killed of a wildlife species in a given ecosystem, P_w is the probability of oiling and dying given that a surface slick is encountered for the wildlife behavior group of the species, A_s is the portion of the ecosystem area swept by oil (greater than a threshold thickness or g/m^2 such that animal would obtain a lethal dose) over the time interval Δt = 1 day, and N_t is the number remaining alive at time t (of the species and ecosystem of concern).

3.1.2 Threshold Thickness for Lethal Dose

The threshold thickness of oil that would impart a lethal dose to an intersecting wildlife individual is 10 microns (~10 g/m^2), based on the following review. See Engelhardt (1983), Clark (1984), Geraci and St. Aubin (1988), and Jenssen (1994) for reviews of the literature on oil effects on aquatic birds and marine mammals.

Varoujean et al. (1983) cite that, when confined to oil, 1 g/m^2 is 100% lethal to birds oiled by such a slick, while 0.1 g/m^2 is not enough to cause acute mortality. Peakall et al. (1985) state that blue sheen (which is < 1 µm thick, National Research Council, 1985) is not harmful to seabirds. Jenssen and Ekker (1991a,b) studied the effects of exposure of eiders to oil of varying doses. Greater than 20 ml of (crude) oil was the required dose for an effect on metabolism. However, their review of the literature revealed that an order of magnitude more oil is the required dose for significant and potentially lethal effects.

Birds incubating eggs can transfer oil to the egg from their plumage (Albers and Szaro, 1978; King and Lefever, 1979; Albers, 1980). Clutches of common eider eggs treated with 20 µl of fuel oil had significantly greater embryonic mortality than control clutches (Albers and Szaro, 1978). Hatching success was significantly reduced for mallards with plumage exposed to 100 ml/m^2 (0.1 mm) of Prudhoe Bay crude oil for 48 hours while incubating eggs (which were oiled by transfer from the adult plumage), whereas the reduction in hatching success was not significant at 5 ml/m^2 of oil exposure. However, survival rates of newly hatched ducklings and adults exposed to up to 100 ml/m^2 oil were not significantly lowered (Albers, 1980). Mortality of mallard (*Anas platyrhynchos*) eggs treated with 1 and 5 µl South Louisiana crude oil was 35% and 91%, respectively. For chicken (*Gallus gallus*)

eggs, mortality was 38%, 80% and 98% with applications of 1, 5 and 10 µl of oil, respectively (Hoffman, 1978).

Wolfe and Esher (1981) exposed rice rats (*Oryzomys palustris*) to 200 ml/m^2 (~200 g/m^2) and 20 ml/m^2 (~20 g/m^2) of crude oil on the water surface in laboratory test chambers with 1 m^2 water and two islands. In both exposures, willingness to enter the water and swim was reduced, whereas survival 24 hours later was significantly lowered in the higher exposure treatment. Survival rate was not measured beyond 24 hrs after exposure. These results suggest that mortality would occur for other semi-aquatic mammals, such as muskrat (*Ondatra zibethicus*), nutria (*Myocastor coypus*), mink (*Mustela vison*), and otter (*Lutra canadensis*) that swim through oil. River otters were observed to be killed by *Exxon Valdez* oil (Spies et al., 1996).

Little research is available to quantify oil exposure effects on sea turtles. Much of what is available is synthesized by Vargo et al. (1986). In addition to direct mechanical and toxic effects, impacts include reduced hatching rates and developmental deformities (Milton et al. 2003). For turtles of all ages, ingestion of tarballs is a major issue because turtles eat anything that appears to be the same size as their preferred prey. Ingestion can result in starvation from gut blockage, decreased absorption efficiency, absorption of toxins, buoyancy problems from buildup of fermentation gasses, and other effects (Milton et al. 2003). Inhalation of vapor is of concern for turtles since when they prepare for a dive they inhale a large volume of air before submerging. They thus have prolonged exposures to any inhaled hydrocarbons. Sea turtles have not been shown to exhibit avoidance behavior when surrounded by petroleum fumes (Milton et al. 2003).

The model utilizes an estimate of the minimum (external) dose of oil that is lethal. While there is one observation of a 70 ml dose causing a significant change in metabolic rate, 200-500 ml has been observed as a lethal dose when applied to the plumage of ducks (Jenssen, 1994). In the model, 350 ml is assumed to be the lethal dose for all wildlife. Assuming swimming bird has a width of 15 cm, it would need to swim through 23 m of oil of 100 µm thickness, 230 m of oil of 10 µm thickness, or 2300 m of oil of 1 µm thickness, to obtain a dose of 350 ml. This distance spent in oil need not be in a straight line. If an animal swims 10 m/min., 23 m would be covered in about 2 minutes; 230 m in 23 min; and 2300 m in 230 min (3.8 hrs).

To determine a dose obtained by a wildlife individual swimming through oil, the area and thickness of the oil intersected need to be estimated. The SIMAP physical fates model provides an estimate of slick size (radius of a "spillet" treated as a circle) and thickness at any given time and location. If the volume of the spillet is less than 20 ml, no effects are assumed. Spillets with greater than 20 ml of oil are assumed to oil birds sufficiently to affect hatching success (if within the nesting season for the species). If the diameter of the spillet is less than 230 m, a thickness of 100 µm is assumed as a threshold thickness for oiling mortality of wildlife. If the spillet is larger than 230 m in diameter, 10 µm is assumed as a threshold thickness for oiling mortality.

3.1.3 Probability of Encounter with Oil and Mortality

The behavior of species influences the likelihood of their being oiled. Characteristics which make certain bird species more susceptible to oiling include:

spending large periods of time on the water, weak flying capability such that they dive often, having flightless feather-molting stages, diving foraging behavior, and roosting at night on water (Speich et al., 1991). Birds that roost on land (e.g., gulls, cormorants) would have a lower probability of oiling (integrated over a daily time step). Thus, the probability of encounter with the slick is related to the percentage of the time an animal spends on the water or shoreline surface, including any diel or oil avoidance behavior.

Birds, mammals, reptiles, and amphibians (wildlife) are categorized by behavior patterns, i.e.,:

- Dabbling waterfowl and surface seabirds: surface divers (ducks, geese, swans, coots, murres) spend most of their time on the surface of the water and fly from place to place only occasionally.
- Aerial nearshore divers: birds that fly over the habitat most of the day time and dive for food (e.g., gulls, terns, osprey).
- Aerial seabirds: birds that fly over the habitat most of the time and dive occasionally (e.g., albatross) or have demonstrated oil avoidance behavior (e.g., fulmar).
- Wetland wildlife: wading birds, shorebirds, muskrats, and other wildlife typical of wetlands and shallow water habitats that walk, wade or swim in shallow water, wetlands, and intertidal or shoreline habitats.
- Terrestrial wildlife: Animals which typically walk and forage in shoreline or wetland habitats, and do so only a small percentage of their time.
- Marine wildlife: Marine mammals and sea turtles swim on the surface or live under it some percentage of the time.

Once oiled, it is generally agreed that birds have a very low survival rate, even when rescue and cleaning is attempted (Bourne et al., 1967; Holmes and Cronshaw, 1977; Croxall, 1977; Ohlendorf et al., 1978; Chapman, 1981; Ford et al., 1982; Samuels and Lanfear, 1982; Varoujean et al., 1983; Ford, 1985; Evans and Nettleship, 1985; Fry, 1987; Seip et al., 1991; Anderson et al., 2000). Death may be due to loss of body heat, toxicity through the skin, and/or ingestion of toxins via grooming. Also, death may not be immediate. Samuels and Lanfear (1982) estimated that 95% of oiled seabirds die while most of the other authors cited above estimate the probability of dying near 100%. Thus, the probability of mortality once oiled is assumed 100% for birds and fur-covered mammals (assuming they are not successfully treated) and much lower for other wildlife.

The estimated products of the two probabilities for various wildlife behavior groups are in Table 1. Estimates for the probabilities are derived from information on behavior and field observations of mortality after spills. Table 2 contains generic category estimates, also calculated in the model.

Table 1. Combined probability of oil encounter and mortality once oiled assumed for species groups, if present in the area swept by oil exceeding a threshold thickness. Area swept is calculated for the habitats occupied.

Wildlife Group	Probability	Habitats Occupied
Surface divers: dabbling waterfowl	99%	Intertidal, wetland, near-shore waters, bays, lakes, ponds, rivers/streams

Wildlife Group	Probability	Habitats Occupied
Surface divers: seabirds	99%	All intertidal and waters
Nearshore aerial divers	35%	Intertidal, wetland, near-shore waters, bays, lakes, ponds, rivers/streams
Aerial seabirds	5%	All intertidal and waters
Wetland birds (waders, shorebirds)	35%	All wetlands, shorelines, seagrass beds
Terrestrial mammals in wetlands and on shorelines	0.1%	All wetlands, shorelines
Raptors (other than eagles and osprey)	0.1%	Intertidal, wetland, near-shore waters, bays, lakes, ponds, rivers/streams
Cetaceans	0.1%	All subtidal marine waters
Furbearing marine mammals	75%	All intertidal and marine waters
Furbearing aquatic mammals	75%	All shorelines and nearshore waters (freshwater and estuarine systems)
Non-fur-bearing pinnipeds, manatee	1%	All marine intertidal and waters
Sea turtles (juvenile, adult)	5%	All subtidal marine waters
Sea turtles (hatchlings)	50%	All subtidal marine waters*
Terrestrial reptiles and amphibians	75%	All shorelines and waters (typically freshwater systems)

* Oiling on nesting beaches is evaluated geographically, based on mapped information.

Table 2. Combined probability of encounter with oil and mortality once oiled for generic behavior categories, if present in the habitats listed and area swept by oil exceeding a threshold thickness.

Wildlife Group	Probability	Habitats*
Surface birds in seaward habitats only	99%	All seaward intertidal and subtidal
Surface diving birds in seaward habitats only	35%	All seaward intertidal and subtidal
Aerial divers in seaward habitats only	5%	All seaward intertidal and subtidal
Surface birds in landward habitats only	99%	All landward intertidal and waters
Surface diving birds in landward habitats only	35%	All landward intertidal and waters
Aerial divers in landward habitats only	5%	All landward intertidal and waters
Surface diving birds in water habitats only	35%	All waters
Aerial divers in water only	5%	All waters

* Intertidal includes all between-tide or terrestrial areas flooded by tides or by storm surges; seaward and landward designations are operationally defined for the area modeled, e.g., marine = seaward and estuarine = landward or estuarine = seaward and freshwater = landward.

Documentation of the probability of oiling and the mortality of wildlife which have been oiled is not readily available due to difficulties in obtaining estimates. Accurate beach counts of dead animals are not enough, since many dead individuals sink or are consumed before being washed ashore (National Research Council, 1985). In studies of the *Puerto Rican* and *Apex Houston* spills (Point Reyes Bird Observatory, 1985; Page and Carter, 1986; Page et al., 1990; Carter et al., 2003), 20 to 52 percent of oiled birds recovered from beaches were dead or died following recovery. In order to estimate the total mortality of birds attributable to each of the spills, the Point Reyes Bird Observatory scientists estimated how many birds died but were not observed. From observations of the trajectory and path width of each spill, the density of birds in the area and estimates of daily carcass deposition and survival rates for beached oiled birds, they estimated the number of birds killed by the spill for seabird species groups. The estimated mortalities averaged 90% in the *Puerto Rican* spill and 68% in the *Apex Houston* spill. These rates would be overestimates to the extent that some oiled birds survived oiling but were not observed. However, they are underestimates to the extent that oiled birds flew off to other areas before dying.

This approach (termed the Beached Bird Model, Page et al., 1990; Carter et al., 2003) of estimating total mortality from counts of oiled animals has been utilized in several large oil spill cases in the US (e.g., *Puerto Rican, Apex Houston, Exxon Valdez, Kure, New Carissa, Stuyvesant, Luckenback).* The calculations include corrections for losses at sea, losses on shorelines after beaching, background non-spill-related beaching rates, and observational effort and search success (Carter and Page, 1989; Ford, 1987; Ford et al., 1996). Results of these and similar detailed studies provide data for estimating probability of oiling if a bird is present in the area swept by oil.

Studies of the *Exxon Valdez* incident provide such estimates. Gundlach et al. (1991) give an estimate of 30,000 km^2 of water surface swept by oil slicks and sheen. Within this area Piatt et al. (1990) estimated that 283,000 – 370,000 seabirds were present in April 1989 when mortalities occurred. Piatt et al. (1990) estimate 100,000 – 300,000 seabirds were killed or 61% percent of those present using the midpoints. U.S.A. (1991) estimated bird kills at 260,000 – 580,000, which is 78% using the midpoints. Later reports were that about 250,000 seabirds were oiled (Spies et al., 1996; Ford et al., 1996), inferring 77% of those birds present in the area were oiled. Of these, 74% were murres.

Wilhelm et al. (2007) observed 50% of murres and 8% of dovekies on the sea surface at any given time, as opposed to flying, in the area of a crude oil spill off Newfoundland. Their mean estimate of birds oiled assumed 50% of the flying birds and all the birds on the water would intersect the oil, i.e., 75% of the murres and 54% of dovkies. However, for the flying birds Wilhelm et al. (2007) simply picked the mid-point of a range of up to 100% that would likely be oiled.

The above estimates are for seabirds of a variety of species, some of which are surface swimming and would have a high probability of contacting surface slicks (e.g., murres), while other species are aerial divers and would have a lower probability of oiling (Holmes and Cronshaw, 1977; King and Sanger, 1979; Varoujean et al., 1983; Ford et al., 1982; Samuels and Ladino, 1984; Holmes, 1984; Ford, 1985; Evans and Nettleship, 1985; Seip et al., 1991). Ford (1985) estimates the probabilities of slick encounter and subsequent mortality for several bird species. His

estimates average 90% for surface swimmers and 35% for aerial divers, assuming no avoidance of slicks. These values are consistent with estimates derived from spill observations cited above. Values assumed for P_w in the present model are in Table 1. For surface swimming birds, 99% is used because the majority of evidence shows that oiled birds do not survive.

Aerial seabirds spend much of their time flying above the water surface. They are not oiled in large numbers in oil spills. A probability of 5% is reasonable (Table 1). This group would also include species known to avoid oil, such as fulmars (Lorentsen and Anker-Nilssen, 1993).

For waders and shorebirds, little information is available for estimation of probability of oiling and mortality given a slick's presence. Chapman (1981) observed shorebirds along the South Texas coast as the *Ixtoc* blowout oil came ashore there. He observed up to 10% of shorebirds present were oiled on average. At the time of maximum shoreline oiling, 40% of royal terns were observed oiled, this being the most vulnerable species. However, the oil was present as mousse and tar balls over 2 months old, in scattered patches. Chapman (1981) did observe avoidance behavior, but the availability of clean beach may have facilitated this. Thus, 10% or even 40% would be too low an estimate for probability of oiling on a beach covered with fresh oil. Since these species do contact the surface much like surface swimming birds, and oil on feet was observed by Chapman (1981) to be transferred to plumage and so be ingested, probabilities of oiling and dying are most likely near the high end of this range for waders and shorebirds. A value of 35% is assumed in the model (Table 1) and applied when oil on shorelines exceeds 100 g/m^2. At this oil thickness, a bird would need to move along a path 35 m long and 10 cm wide to obtain a lethal dose of 350 ml. Thus, the assumed threshold thickness is reasonable, as more scattered oil on a shoreline would require proportionately longer distances where birds would be in contact with oil.

For mammals, the evidence is that oiling most often causes mortality for semi-aquatic furbearers (e.g., muskrat, otter, mink, beaver) and for those marine mammals which have a fur pelage used for retaining body heat (e.g., sea otters and fur seals). This was born out in the *Exxon Valdez* incident where sea otters were the mammal species most heavily impacted (U.S.A., 1991). It was estimated that 3500 – 5500 sea otters were killed by *Exxon Valdez* oil (Spies et al., 1996). The cause of mortality for fur bearing mammals is both due to loss of body heat (exposure) and to ingestion of toxins via the frequent grooming of the pelage (Wragg, 1954; McEvan et al., 1974; Geraci and Smith, 1976; Engelhardt, 1983, 1987; Geraci and St. Aubin, 1988). It is reasonable to assume that marine and semi-aquatic furbearers will have similar sensitivity to oil (Engelhardt, 1983; and by comparison of the results of Wragg, 1954, McEvan et al., 1974, and Wolfe and Esher, 1981, for muskrats to those of the other citations above). Ford (1985) has estimated a probability of an oiling encounter plus subsequent mortality for furbearing mammals (fur seals) at 75%. This value is assumed for all swimming furbearers in the model.

It was estimated that 200 harbor seals were killed by *Exxon Valdez* oil (Spies et al., 1996). Other non-fur-bearing marine mammals could not be definitively documented as having been killed by the *Exxon Valdez* oil, although inferences from circumstantial evidence were made (Loughlin et al., 1996). Similarly, in an earlier spill in the Santa Barbara Channel, sea lions did not appear to suffer high mortality

rates from oiling (Simpson and Gilmartin, 1970; Brownell and LeBoeuf, 1971; LeBoeuf, 1971). For non-furbearing pinnipeds, a low probability of oiling and mortality of 1% is assumed; while for cetaceans 0.1% is assumed (Table 1).

No estimates are available for raptors. Since bald eagles and osprey behave as aerial divers, diving for fish in the near-shore area, the estimated probability of dying of oiling is assumed to be 35%, as for other aerial diving birds. For other raptors (hawks, owls, etc.) the probability of oil mortality would be much lower because of lower encounter frequency. An estimate of 0.1% is assumed (Table 1).

Sea turtle behavior and likelihood of exposure to oil are reviewed by Vargo et al. (1986) and Shigenaka (2003, see especially Milton et al., 2003). A summary of the major spills where impacts to turtles were observed is available in Yender and Mearns (2003). Turtles do not exhibit avoidance behavior when encountering an oil slick (Milton et al. 2003). Hatchlings are the most vulnerable stage because only a small amount of oil is needed to completely coat them. Also, since smaller turtles have more limited motility, they are often caught in the same currents as oil slicks and can end up in convergence zones more frequently than juveniles or adults. Finally, hatchlings spend more time on the surface than older turtles, thus increasing the potential for contact with oil slicks (Milton et al. 2003). Once oiled, hatchlings may not be able to swim as well, thereby increasing their predation risk.

The oiling probabilities for sea turtles were derived from the following. Data from small, attached time-depth-location data logger devices, and miniature video-cameras, indicate that adult and juvenile sea turtles at sea spend only 1 to 10 % of their time at the surface, and each dive duration is generally between 30-70 minutes (Blair Witherington, Fish and Wildlife Conservation Commission, Florida Marine Research Institute, Sea Turtle Research Station, Melbourne, FL, and David Bernhart – NOAA/NMFS Southeast Region Office of Protected Resources, St. Petersburg, FL, personal communication, September 2001). Regarding the effects of oil, literature indicates a moderate to high short-term survival rate if oiling occurs (Vargo et al., 1986). There are few definitive data regarding the long term effects of oil on any reptile. The value of 5% for this combined factor is reasonable for adult and juvenile sea turtles, based on the available information.

Field observations of hatchling sea turtle behavior at sea were described by B. Witherington (pers. comm., September, 2001). Hatchlings are very buoyant and have little ability to dive (estimated maximum dive depths are 6-7 meters and less than 1 minute duration), and may dive only to avoid predation by birds. Hatchlings spend most (~99%) of their in-water time at the surface. Their size and anatomy that would make them susceptible to passing oil and potentially dying from suffocation as a result of this exposure. Hatchlings are small (41-78 mm SCL, 18-50 g, mostly less than 25 g), can only lift their head 1 or 2 cm above the surface, and have very tiny nares, about 0.5 mm diameter. The literature indicates hatchlings are injured by both fresh and weathered oil, but can survive in the short term (several weeks) after acute (2 day) exposure to weathered oil (Vargo et al., 1986). The likely range of probability for oiling and dying is 10-100%, with 50% as a best estimate.

Other aquatic reptiles are modeled using information for sea turtles, as these are the only reptiles where such information related to behavior and vulnerability to oil is available. Impacts to terrestrially-based turtles and snakes present in oiled habitats would likely occur at oil doses similar to those for sea turtles. However, probability

of oiling of these animals (when oil is present in the habitat occupied) is likely higher than for sea turtles that spend much of their time underwater. Thus, the probability of oiling for terrestrially-based reptiles present in oiled habitats is assumed 75%, similar to fur-bearing mammals. The probability of oiling for terrestrial stages of amphibians (e.g., frogs, toads) present in oiled habitats is also assumed 75%.

In addition, any reptile eggs laid in an oiled habitat would likely be lost, as evidence shows that sea turtle eggs are killed by small doses of oil (Vargo et al., 1986). The evidence from studies on bird eggs (reviewed above) are supportive that reptile eggs should be vulnerable at low oil doses as well.

In the model, area swept is calculated for the habitats occupied by each of the behavior groups of wildlife listed in Table 1. A species or species group is assigned to a behavior group to evaluate its loss, which is calculated as the area swept multiplied by the combined probability (Table 1) and the density at the time of the spill.

The wildlife mortality model applied to birds and sea otters was evaluated 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). Insufficient data are available to evaluate the model algorithms for other wildlife groups.

Wildlife mortality is directly proportional to abundance per unit area and the percent mortalities in Table 1. Note that the abundance of a species should be specific to the affected area at the time of the spill. For example, in the case of severe storm events such as the hurricanes, bird abundance may be lower than normal due to avoidance of the storm. Thus, the density data used for impact estimations should reflect this behavior if it is known or assumed to occur. Model uncertainty is decreased when field data are used to estimate bird density and to calibrate the probability of an at-risk bird becoming oiled.

If densities are unknown, area affected by sufficient oil to cause a lethal dose can be used as an index of potential for impacts to any wildlife present in the areas oiled. The exposure index we have used for seabirds and other offshore wildlife is the water area swept by more than 10-μm thick (> 10 g/m^2) oil, which is sufficient to provide a lethal dose, as discussed above. The probability of exposure is related to behavior: i.e., the habitats used and percentage of the time spent in those habitats on the surface of the water. For shorebirds and other wildlife on or along the shore, an exposure index is length of shoreline oiled by > 100 g/m^2. Areas of exposure above these thresholds have been used in environmental risk assessment studies (French McCay et al., 2003a, 2004, 2005a,b,c).

3.2 Aquatic Biota: Fish, Invertebrates, and In-Water Stages of Amphibians

The most acutely toxic components of oil to water column and benthic organisms are low molecular weight compounds, which are both volatile and soluble in water, especially the aromatic compounds (Neff et al., 1976; Rice et al., 1977; Neff and Anderson, 1981; Malins and Hodgins, 1981; National Research Council, 1985, 2002; Anderson, 1985; McAuliffe, 1987; and French McCay, 2002). This is because organisms must be exposed to hydrocarbons in order for uptake to occur and aquatic biota are exposed primarily to hydrocarbons (primarily aromatics) dissolved in water. Thus, exposure and potential effects to water column and bottom-dwelling aquatic

organisms are related to concentrations of dissolved aromatics in the water. Exposure to microscopic oil droplets may also impact aquatic biota either mechanically (especially filter feeders) or as a conduit for exposure to semi-soluble hydrocarbons (which might be taken up via the gills or digestive tract).

The effects of the uptake and accumulation of the dissolved hydrocarbon components in tissues are additive. Thus, an additive acute toxicity model and available LC50 data for individual compounds (under known temperature and duration of exposure conditions) may be used to estimate the LC50 (lethal concentration to 50% of exposed organisms) of the mixture of monoaromatic hydrocarbons (MAHs) and PAHs in oil to which aquatic organisms are exposed. Note that the LC50 is a proxy measurement for the concentration that leads to sufficient uptake into tissues for lethal effects to occur for 50% of individuals exposed. (See French McCay (2002) for a detailed explanation of the derivation of the LC50-based model commonly used in aquatic toxicology, which is briefly summarized below). Oil toxicity is a function of MAH and PAH content and composition in the oil. The toxicity of oils and refined products has been estimated and verified with available bioassay data. The verified oil toxicity model may be used to estimate toxicity of untested oils under varying environmental conditions (French-McCay, 2002).

Hydrocarbons accumulate in lipids (such as in the cell membranes) and disrupt cellular and tissue function. The more hydrophobic is the compound, the more accumulation in the tissues and the more severe the impact. However, the more hydrophobic the compound, the less soluble it is in water, and so the less available it is to aquatic organisms. Thus, impact is the result of a balance between bioavailability (dissolved-component exposure) and toxicity once exposed (see review in DiToro et al., 2000).

PAHs are more hydrophobic than MAHs, and so are more toxic. There is a continuum from the most soluble and least toxic benzene (simplest MAH) through the naphthalenes (2-ring PAHs) to the 3- and 4-ring PAHs. The more complex 4-ring PAHs are so insoluble that they are not dissolved or (acutely) bioavailable to a significant extent. This functional relationship can be described by a regression model using available data on a variety of compounds and species (French-McCay, 2002). A similar approach has been used to develop US Environmental Protection Agency (USEPA) water and sediment quality criteria for PAHs (DiToro et al., 2000; DiToro and McGrath, 2000).

Because of the relative solubility and volatility of various MAHs and PAHs, and the relative concentrations of the various compounds in oil, most of the acute toxicity is caused by the PAHs, and specifically the substituted naphthalenes (C2- and C3-naphthalenes). However, all the compounds in the mixture contribute to toxicity (French-McCay, 2002).

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). This is due to the accumulation of toxicant over time up to a critical tissue concentration that causes mortality. The accumulation is slower for more hydrophobic compounds. The accumulation is also slower at colder temperature. Thus, for brief exposures at low temperature, toxic effects require a higher concentration than would be necessary at higher temperature or for instances where

exposure times are longer (see Figure 3). At a given concentration after a certain period of time, all individuals that will die have done so. The incipient LC50 ($LC50_\infty$) is the asymptotic LC50 reached after infinite exposure time (or long enough that the asymptotic level is approached, Figure 3). At a given exposure duration, percent mortality is a log-normal function of concentration, with the LC50 the center of the distribution.

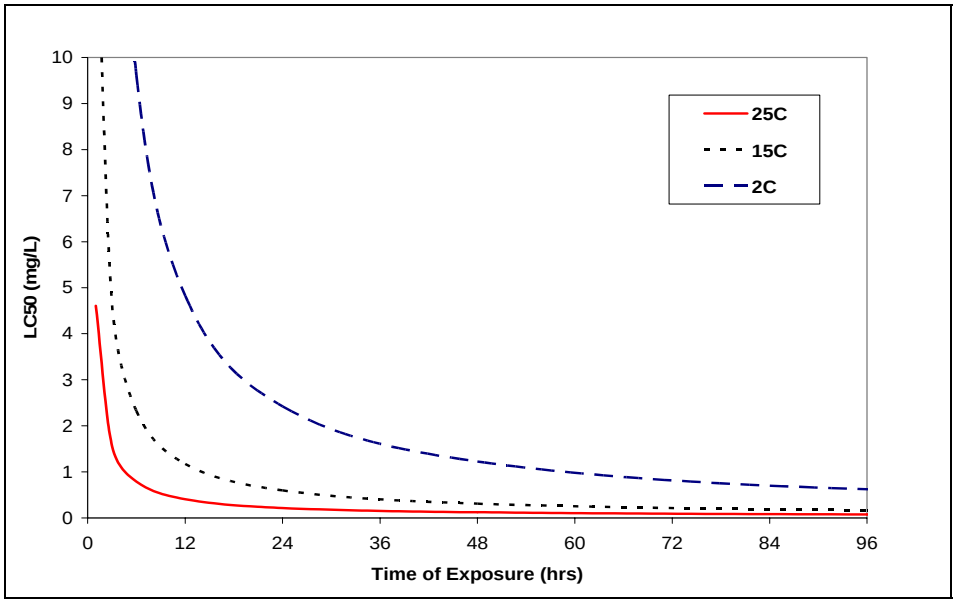

Figure 3. LC50 of dissolved PAH mixtures from oil, as a function of exposure duration and temperature (French McCay, 2002).

For most fuel and crude oils (where PAHs cause most of the toxicity), the value of $LC50_\infty$ ranges from 5-400 μg/L for 95% of species (Figure 4) exposed to dissolved PAH mixtures for over 96 hrs (which is sufficient time to approach the asymptote, as seen in Figure 3; French McCay, 2002). The $LC50_\infty$ for the average species is about 40-50 μg/L (ppb) of dissolved PAH (varying slightly among oils and fuels by percent composition of the PAH mixture). These $LC50_\infty$ values have been validated with oil bioassay data (French McCay, 2002), as well as in an application of SIMAP to the *North Cape* oil spill where field and model estimates of lobster impacts were within 10% of each other (French McCay, 2003).

Mortality of fish, invertebrates, and their eggs and larvae is computed as a function of temperature, concentration, and time of exposure. Percent mortality is estimated for each of a large number of Lagrangian particles representing organisms of a particular behavior class, i.e., planktonic, demersal (on the bottom), and benthic (in bottom sediments), or fish (or invertebrate nekton) that are classed as small pelagic (slower swimming), large pelagic (faster swimming), or demersal (near bottom) and occupying specific habitats (open water, wetland or reef; varying by seaward and landward habitats, as defined above). For each Lagrangian particle, the model evaluates exposure duration to dissolved hydrocarbons, and corrects the $LC50_\infty$ for time of exposure and temperature (Figure 3; see French McCay (2002) for equations). Percent mortality is then calculated from the mean exposure concentration, *C*, and the corrected $LC50_t$ using a log-normal function (with 50%

mortality at $C = LC50_t$, 1% mortality at $C = LC50/100$, and 99% mortality at $C = 100 \times LC50_t$). The percent mortalities are summed, weighed by the area represented by each Lagrangian particle to estimate a total equivalent volume for 100% mortality. In this way, mortality is estimated on a volume basis, rather than necessitating estimates of species densities to evaluate potential impacts. In addition to the mortality estimates, the volume exceeding 1 μg/L total dissolved aromatics may be used as an index for exposure for fish, invertebrates, and plankton. The algorithms for these calculations are described in French McCay (2002, 2003, 2004).

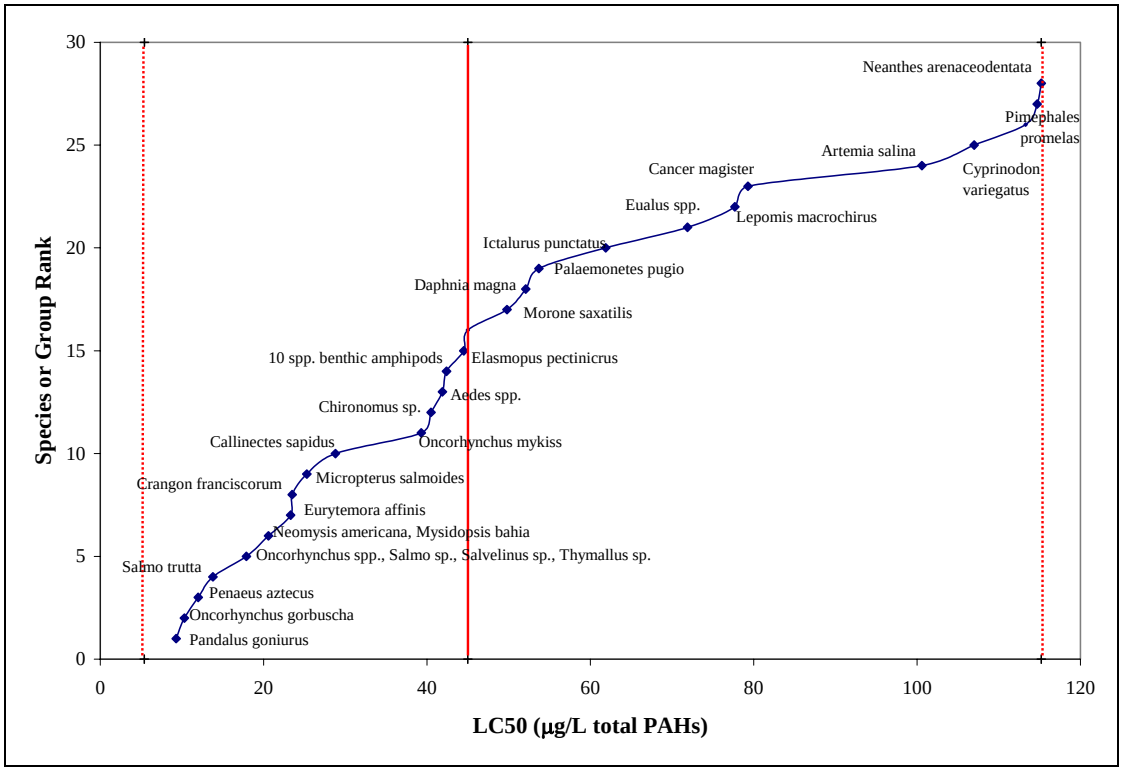

Figure 4. Variation in $LC50_\infty$ for dissolved PAH mixtures from a typical oil, by species in rank order of sensitivity (French McCay, 2002).

3.3 Sublethal Effects on Primary and Secondary Producers

Three primary producer categories are designated in the model: phytoplankton, benthic microalgae and macrophytes (macroalgae and/or angiosperms). Secondary and tertiary producers (primary and secondary consumers) which are not evaluated except through the food chain are divided into eight trophic categories: zooplankton, benthos, the air-breathing stages of insects, planktivorous forage fish, herbivorous forage fish, benthic forage fish, insectivores (e.g., moles, shrews) and small herbivorous mammals (e.g., rodents). Early life stages of insects which are aquatic are considered part of the benthos or zooplankton.

Estimates of primary production and secondary production are included in the biological database input to the model for each habitat type. Since organic carbon accumulation in sediments is less than 10% of supply in most environments, all primary production by phytoplankton and benthic microalgae is assumed to be consumed by the water column organisms and benthos (Hargrave, 1973).

Phytoplankton are assumed to inhabit the upper water column (or entire water column in shallow water or if it is mixed to the bottom) and to be uniformly distributed with depth. Thus, their exposure is to the concentration field in the surface water layer. Zooplankton are assumed to be distributed throughout the water column and are exposed to contaminant concentrations at all depths. Macrophytes, present only in shallow-water habitats, are assumed to be exposed to the average concentration over the entire water column. Benthic microalgae and the benthos are assumed to be exposed to sediment pore water concentrations.

For each time step and for each of the concentration grid cells output by the physical fates model, lost primary, zooplankton and benthic production (P_L) is calculated as follows:

$$P_L = (1- F_k)\, P_i\, V\, \Delta\, t \qquad (2)$$

where F_k is the fraction of the uninhibited rate of production which is realized at the contaminant concentration, P_i is the rate of production (g dry weight m^{-3}/day^{-1}), V is volume contaminated (m^3), and Δt is the number of days contaminated. [Appropriate conversion factors for biomass and production are 12.5 from g C to g wet weight, and 40-45% of dry weight is carbon (Odum, 1971).] This calculation is performed for each habitat grid cell and vertical section of the water column affected by toxic concentrations, at each time step ($\Delta\, t$). Total production loss is summed over time and space.

The value of F_k is calculated from the EC50 for growth, corrected for temperature, using the log-normal toxicity model (Section 3.2) relating cumulative response (in this case, percent growth rate, F_k) to concentration. However, unlike for $LC50_\infty$'s, the EC50 is not corrected for exposure time, i.e., reduction in growth rate is assumed to be uniform over time. Since P_i is a rate per time, multiplication by Δt accounts for exposure time.

Concentrations from the spill are assumed to either be toxic (if the concentrations are high enough) or to have no effect on productivity. Although stimulation of phytoplankton primary production has been noted in a few studies, in the vast majority of studies, negative effects have been observed (National Research Council, 1985).

Biomass of upper trophic level biota which is not produced as a result of a loss of food resources from affected lower trophic levels (i.e., P_L) is estimated using a simple food web model. The portion of the lost primary production which would have produced primary consumer (secondary producer or herbivore) biomass is estimated based on observations of ecological efficiency made on representative ecosystems. Angiosperm biomass passes up the food web primarily via detritivores consuming the plant material and (more importantly) the attached microbial communities (Teal, 1962; Odum and de la Cruz, 1967; Thayer et al., 1984; Howes et al., 1985; Newell and Porter, 2000). The detritivores are then prey for larger animals (e.g. in marshes: decapods, such as grass shrimp, *Palaemonetes pugio*, and small fish, such as the mummichog, *Fundulus heteroclitus*, and other killifishes) and ultimately support production of recreationally and commercially important finfish, shellfish, waterfowl and wading birds (Teal, 1962). The ecological efficiency of detritivore production per unit primary producer production is low because a high percentage of

biomass produced by the plant is broken down by microorganisms (primarily fungi at a transfer efficiency of 55%: Newell and Porter, 2000) before it can be assimilated by detritivores. Benthic meiofauna and macrofauna also directly consume benthic and epiphytic microalgae directly. French McCay and Rowe (2003) estimated the transfer efficiencies from plants to detritivores as 3.4% in (*Spartina*-dominated) saltmarsh and 7.2% in seagrass beds. Transfer efficiencies for woody vegetation would be lower than these values. As a general value, 4% is assumed in the model.

Values for production of predator per unit production of prey (i.e. ecological efficiency) for invertebrate and fish consumers of animal prey have been estimated to be 10-30% in both freshwater and marine environments by a number of authors (e.g. Slobodkin, 1960; Odum, 1971; Steele, 1974; Cohen et al., 1982; Pimm, 1982; Pauly and Christensen, 1995; Jennings et al., 2002). In the model, the transfer efficiency of fish and invertebrates consuming animal prey is assumed 20%.

For birds and mammals (which as homeotherms are less efficient), ecological efficiency is much lower, with estimates ranging from 1-5% (McNeill and Lawton, 1970; Steele, 1974; Whittaker, 1975; Grodzinski and Wunder, 1975; Pimm, 1982). In the model, the ecological efficiency of birds and mammals feeding on fish or invertebrate prey is assumed to be 2%.

Figure 5 shows the food web compartments used in the model. The fractions of the lost secondary production which would have been consumed by each of their predators are assumed to be proportional to the biomass of that predator relative to the sum of its competitors. The fraction of prey compartment *j*'s production which is consumed by predator *i*, a_{ij} is:

$$a_{ij} = (\rho_i B_i^{3/4}) / \sum_k (\rho_k B_k^{3/4}) \qquad (3)$$

where B_i is biomass per unit area of predator *i*, B_k is the biomass per unit area of predator *k* which preys on *j*, where *k* represents all predators of prey *j* (including *i*), and ρ_i or ρ_k represents the ratio of consumption to biomass of the predator (*i* or *k*) relative to consumption to biomass of fish.

The correction factor ρ is based on the fact that homeotherms (birds and mammals) have higher metabolic rates at a given body size than poikilotherms (fish and invertebrates) and so have a higher consumption to biomass ratio (Zeuthen, 1953; Hemmingsen, 1960; Fenchel, 1974). Respiration rate has been shown to be proportional to body weight (W) to the 3/4 power (Kleiber, 1947; Zeuthen, 1953; Hemmingsen, 1960; Fenchel, 1974). Fenchel (1974) showed that the ratio of respiration rate to $W^{3/4}$ (where W = body weight) between homeotherms and poikilotherms is 28 (on average). Assuming food consumption is proportional to respiration rate, wildlife consumption per $W^{3/4}$ is 28 times fish consumption per $W^{3/4}$. In the biological submodel, all fish and invertebrates are assumed to have the same consumption to biomass ratio. Birds and mammals each are assumed to have 28 times higher consumption to biomass ratios at a given body size.

The total production of compartment *i* (P_i) is then equal to the sum of its consumption of prey production times the ecological efficiency, ε_i for the predator *i*.

$$P_i^{pred} = \varepsilon_i \sum_j a_{ij} P_j^{prey} \quad (4)$$

where P_j is the production for prey compartment j. If the predator has no competitors, it consumes 100% of that prey's production.

Production rate estimates of primary producers (angiosperms and algae) and benthos are input to the model. Production rates of zooplankton, forage fishes, insects and secondary consumers not evaluated by individual species are calculated from their prey production rates and the trophic transfer efficiencies described above. For upper trophic level fish, invertebrate and wildlife species, biomass estimates are input to the model. Thus, in order to estimate production loss via a prey compartment where only biomass is known, i.e., for all upper trophic level losses resulting from lost primary and secondary production, the ratio of annual production to biomass (P/B) is assumed to be as derived by Banse and Mosher (1980), as follows: P/B = 0.65 $M_k^{0.37}$ for invertebrates, P/B = 2.75 $M_k^{0.26}$ for fish; and P/B = 12.88 $M_k^{0.33}$ for birds and mammals; where M_k is body mass in kcal (1 kcal/g wet weight for invertebrates, 1.3 kcal/g wet weight for fish, and 1.5 kcal/g wet weight for birds and mammals).

In calculating lost production of consumers in the food web, a proportionate loss of lower trophic level production is translated to a proportionate loss higher in the food web. For example, a 30% loss in phytoplankton is translated to a 30% loss in all of the upper trophic level production rates which are dependent ultimately on phytoplankton production. However, in the case where toxicity has reduced zooplankton, benthic or forage fish production to a greater degree than the reduction of primary production, consumers of zooplankton and benthos and forage fish are assumed to suffer proportionate losses to the losses for these food resources. Thus, zooplankton, benthos and forage fish are assumed either food limited or toxicant limited, whichever is greater.

Larvae of fish and invertebrates are assumed to feed entirely on zooplankton and to be food-limited. Feeding studies on fish larvae have shown that survival of larvae is dependent on finding high enough densities of food (Munk and Kiorboe, 1985). Thus, in the model it is assumed that reduced zooplankton production causes a proportionate reduction in larval (young-of-the-year) numbers. This is termed "indirect kill," as opposed to the direct kill via toxicity to larvae.

The output of this part of the model is lost production at lower trophic levels translated into losses of upper trophic level species (fish, invertebrates, and wildlife) as a result of the spill. This is added to the total direct kill to yield a total loss of biomass by habitat as a short term result of the spill.

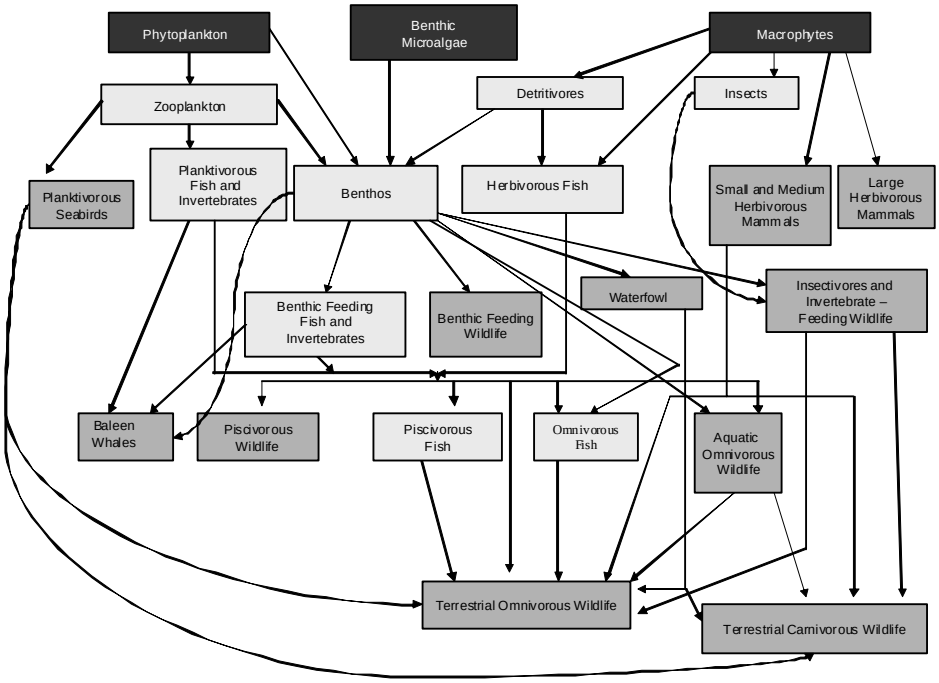

Figure 5. Food web compartments used in the model.

3.4 Intertidal, Wetland, and Terrestrial Plants and Invertebrates

In addition to the quantifying impacts in water habitats, the oiling of intertidal (wetland, rocky shore, gravel and sand beach, and mudflat) and temporarily flooded habitats with enough oil to impact plants and invertebrates may be evaluated. This is calculated as the area oiled above threshold(s) for injury times the habitat- and species-specific density or production rate of biota in that habitat and area.

Alexander and Webb (1985, 1987), Cubit et al. (1987) and Moody (1990) document mortality or other impacts on wetland vegetation by oiling in significant quantities. For submerged macrophyte and seagrass beds, dissolved concentrations of oil hydrocarbons are assumed to affect production, not surface floating oil. Exposure to floating oil is assumed lethal at the thresholds established below if the habitat area is not flooded with water at the time of exposure. No data are available to quantify effects thresholds for sunken oil on macrophytes.

Based on review of the literature performed in the late 1980s, French et al. (1996) assumed a threshold of 14 mm as lethal to wetland vegetation in the Type A model (NRDAM/CME). Alexander and Webb (1985) reported that 0.35 gal./ft^2 had a detrimental effect on Texas saltmarsh plants (*Spartina* spp), which is equivalent to about 14 mm-thick oil. The review by Moody (1990) supported the 14 mm threshold level. The Ile Grande marsh oiled by 50-200 mm of crude oil after the *Amoco Cadiz* spill was completely killed (Johnson and Pastorok, 1985). However, other data suggests the threshold for effects is lower than 14 mm. Baker (1971) reported that 0.5 mm of fresh Kuwait crude (a light oil) spread over saltmarsh vegetation was lethal when applied during the growing season (May or August), but if applied in November, growth in the following season was not affected. Baca et al. (1987) measured oil thickness in marshes where vegetation was killed by a heavy fuel spill in the Cape Fear River (NC) in 1982, finding 0.25-0.5 mm of heavy fuel oil coat on

leaves of *Spartina* saltmarsh plants to be lethal and that the surface area of the affected marsh was covered with about 10 mm of oil. The reviews by Johnson and Pastorok (1985) and Shigenaka (2002) summarize other literature and case histories, and indicates that coating of the leaves is necessary for plant mortality.

Lin and Mendelssohn (1996) applied south Louisiana crude oil to natural marsh sods at rates of 0, 4, 8, 16 and 24 L/m^2 (1 L/m^2 is approximately 1 mm of oil), observing reduction in plant biomass above 4 L/m^2. The year following oil application, no regrowth of *Spartina patens* and *S. alterniflora* occurred at oil levels above 8 L/m^2. Lin et al. (2002) performed additional experiments with No. 2 fuel oil (diesel) applied to *S. alterniflora,* finding a significant decrease in total (above- plus below-ground) plant biomass at concentrations above 57 mg/g dry soil (= 2.5 L/m^2 = 2.5 mm) of oil. A significant decrease in below-ground biomass compared to the control was identified at a dosage as low as 29 mg/g dry soil (= 1.2 L/m^2 soil = 1.2 mm), but not at 14 mg/g (= 0.6 L/m^2 soil = 0.6 mm).

Based on these observations, it appears that more than 1 mm of oil during the growing season would be required to impact marsh or mangrove plants significantly. Thus, 1 mm is the assumed lethal threshold for wetland vegetation.

Numerous reports document suppression of intertidal invertebrate densities on visibly oiled shorelines and that invertebrates are more sensitive to oiling than intertidal macrophytes (e.g., Stirling, 1977; Boucher, 1980, 1985; Gilfillan et al., 1981; Cubit et al., 1987; Jackson et al., 1989; McGuinness1990; Garrity and Levings, 1993; Burns et al., 1993; Clarke and Ward, 1994; Ansari and Ingole, 2002; Yamamoto et al., 2003; Teruhisa et al., 2003; Anderson et al., 2008). However, specific measurements of the amount of oil required to lethally impact invertebrates are lacking. Owens and Sergy (1994) define oil “stain/film” as <0.1mm, oil “coat” as 0.1-1mm, and oil “cover” is 1-10mm. For benthic epifaunal invertebrates living in intertidal habitats on hard substrates, a threshold of 0.1 mm oil thickness would be enough to coat the animal and likely impact its survival and reproductive capacity, while stain (<0.1 mm) would be less likely to have an effect. Thus, 0.1 mm (100 g/m^2) of oil is assumed as the lethal threshold for invertebrates on hard substrates (rocky, artificial/man-made, rip-rap, etc.) and sediments (mud, silt, sand, or gravel) in intertidal habitats.

The impact thresholds are 1 kg/m^2 (1 mm) for vegetation and 100 g/m^2 (0.1 mm) for invertebrates. Injuries to wetland and intertidal biota oiled at these levels or higher are calculated as the product of the normal production rate (g dry weight m^{-2} day^{-1}) and the m^2-days of loss realized over a recovery period where production hyperbolically increased back to the pre-spill level over a specified number of years (based on literature documenting such recovery rates). 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 (i.e., for the year of the spill) is calculated as $(1+d)^{-n} = 1/(1+d)^n$, where d=0.03.

The recovery of plant or invertebrate production in an oiled habitat is assumed to follow a sigmoid function described by:

$$\frac{dP_R}{dt} = a_r P_R (1 - P_r) \qquad (5)$$

where P_R is portion recovered, t is time, and a_r is a constant. The sigmoid function was chosen since, at first, recovery is slow while seeding/settlement and early succession takes place. Later recovery speeds up as filled-in vegetation and new settlers grow rapidly, but the final establishment of the mature habitat proceeds at a slower rate. The value of the constant a_r is derived from solution of the equation assuming P_R at $t = 0$ is 0.01 and P_R at $t = t_{rec}$ is 0.99, where upon the above equation may be solved using

$$P_R = 1/(1 + 99\ exp(-a_r t)) \tag{6}$$

What is needed is one data point of P_R at some time t. At $t = t_{rec}$, $a_r = 9.19/t_{rec}$.

In the model, losses are integrated over time using this recovery curve equation. The loss in the time interval t to $t+\Delta t$ (P_L) is calculated as follows:

$$P_L = (1-P_R)\ P_i\ A\ \Delta t \tag{7}$$

where P_i is the normal (pre-spill) production rate in the habitat, A is the area affected, and Δt is the time step.

Literature regarding the recovery rate of vegetation or other habitat structure after the structural organisms are killed or severely damaged is reviewed below and summarized in Table 3. Assumed values of t_{rec}, the time to 99% recovery, are specific to habitat type and are based on experiences from observations of natural recovery following disturbance (including spills) and from habitat creation projects. Much of the wetlands creation and restoration literature emphasizes that correct hydrology be established on the site before planting, that soils are fertile, and that the site must be properly maintained and monitored (Mancini, 1989). If these conditions are met, recovery of structure and function is much more rapid and successful. As the recovery in the model is for areas which are naturally those habitats, it is assumed that the hydrology and soils remain, and that recovery is as rapid as could be expected.

Time for recovery (to 99% function) for intertidal invertebrates (based on a natural recovery curve) is estimated as 3-5 years (French et al., 1996; Table 3; also see review below). It is assumed that the affected areas are not cleaned in a manner that would slow recovery.

Table 3. Recovery rates for vegetation or other structural organisms in habitats, and for benthic invertebrates where habitat structure is not impacted (based on review below).

Habitat	Description	Vegetation or Structure: Years to 99% Recovery	Benthic Invertebrates : Years to 99% Recovery
Rocky Shore	Rocky shore (including rock seawalls) without significant seaweed cover	-	3
Artificial Shore	Vertical piers, seawalls made of artificial, man-made materials	-	3
Gravel Beach	Gravel or cobble beach without significant seaweed cover	-	3
Sand Beach	Coarse- or fine-grained sand beach	-	3
Mud Flat	Silty-mud intertidal flats	-	3
Submerged Aquatic Bed	Seagrass or other submerged angiosperm-dominated habitats	10	3
Wetland: Emergent Marsh	Saltmarsh dominated by *Spartina* spp.; brackish marsh; intermediate marsh	15	5
Wetland: Swamp	Forested wetlands; shrub-scrub wetlands	20	5
Macroalgal Bed	Kelp or other seaweed	15	5
Coral Reef	Reefs dominated by coral	30	30
Mollusk Reef	Oyster or mussel reef	3	2

Rocky, Man-made and Artificial Shores

The *Esso Bernicia* spill in 1978 oiled rocky shorelines of the Shetland Islands and recovery was monitored for nine years. Shores which were left untreated had nearly recovered by one year later, whereas those shores which were cleaned and where the biota were obliterated had not recovered after nine years (Rolan and Gallagher, 1991). Houghton et al. (1991) observed that Prince William Sound rocky shores which were cleaned after the *Exxon Valdez* spill would take many years to recover. Broman et al. (1983) also observed that hot water cleaning after an oil spill in the Baltic Sea did more harm than good and slowed recovery dramatically. From Southward and Southward (1978), recolonization and recovery of rocky shores in Cornwall, England after the *Torrey Canyon* spill took 5-8 years if the shores were lightly oiled and received light dispersant treatment. Recovery took 9-10 years or more if the shore received repeated dispersant treatment. No sites were observed (or available) that were left untreated.

Baker et al. (1990) reported that rocky shores in the Baltic Sea had nearly recovered by one year after the *Tsesis* spill of 1977. As cited by Ganning et al. (1984) cleaning slows recovery: recovery from a medium fuel oil spill followed by

mechanical cleaning in the Baltic Sea took four years, recovery from a Bunker C spill in Nova Scotia took greater than six years, and recovery from a No. 2 fuel oil spill in Baja California took over ten years. In contrast, Keller and Jackson (1991) summarize recovery of intertidal rock reefs in Panama following a medium crude oil spill as complete by one year. Yamamoto et al. (2003) and Teruhisa et al. (2003) documented decreased densities of invertebrates and vegetation in areas heavily oiled by the *Nakhodka* spill in Japan (but not cleaned). The flora and fauna recovered in 3 years. Jones et al. (1998), based on their own observations and data in Sell et al. (1995), estimate 2-5 years for recovery of rocky intertidal communities.

In the model, three years is assumed for 99% recovery (Table 2-2). Artificial shores, and rock and gravel beaches are assumed to have the same recovery rates.

Sand Beaches and Mud Flats

Keller and Jackson (1991) summarized recovery of sand beaches in Panama following oiling as being complete by 1 year, except for certain species. Bodin (1988) observed recovery of three sand beaches in Brittany, France after the *Amoco Cadiz* oil spill over the years 1978 to 1984, stating recovery of the meiofauna was complete by 1983 (5 years). Thomas (1978) observed recovery of invertebrates after 3 years on beaches oiled by the 1970 *Arrow* spill of Bunker C oil. Baker et al. (1990) cite evidence from the Baltic Sea after a 1970 spill of medium and heavy fuel oil with mechanical cleanup where recovery took four years. Judd et al. (1991) observed that Texas dune vegetation took 2-3 years to recover from removal experiments.

Thus, recovery rate is variable, depending on conditions and initial disturbance during the spill response. A median value of three years is assumed in the model (Table 3). Mud flats are assumed to recover at the same rates as sandy beaches.

Seagrass and Submerged Aquatic Beds

If seagrasses are not killed, and only leaves are injured, recovery can be rapid. Jacobs (1980) observed that eelgrass oiled by the *Amoco Cadiz* oil spill had blackened leaves and returned to normal productivity almost immediately. However, there were massive kills of invertebrates. The invertebrate community had mostly recovered by 2 years. In Panama, oil did not induce a total kill of seagrass beds, and they had recovered by 7 months after the spill (Keller and Jackson, 1991). Zieman and Zieman (1989) reviewed recovery rates for Florida seagrass beds. Their estimates are 6 months to 1 year for leaf damage, and 5 years to decades if rhizome damage is severe and no replanting is performed. They estimate it takes 2-5 years for invertebrates to recolonize a *Thalassia* bed.

In the model, if the vegetation is lost, it is assumed that replanting is performed, eliminating the recolonization lag. Recovery of the seagrass bed is assumed to take 10 years. Recovery of freshwater wetlands dominated by grasses or submerged angiosperms is assumed to take 10 years as well. If seagrass or other vegetation is not lost, invertebrates are assumed to recover in 3 years. Three years is assumed to be the recovery time for benthos in other benthic habitats.

Saltmarsh and Other Emergent Wetlands

Getter et al. (1984) state that recovery of saltmarshes after oiling takes 5-20 years, assuming no cleanup or restoration actions are performed. With cleanup and

restoration (replanting), they estimate three years to vegetative cover. Baca et al. (1987) observed that marshes oiled by the *Amoco Cadiz* spill, but not cleaned or treated, had mostly recovered by 8 years.

Joy Zedler and colleagues (Pacific Estuarine Research Laboratory, PERL) followed recovery of experimentally created saltmarsh in Southern California for 7 years. In PERL (1990), they reported 60% recovery by 5 years. Two years later, recovery has not progressed significantly further (Joy Zedler, personal communication). Using the recovery model above, t_{rec} = 13 years if 60% recovery is in 5 years and t_{rec} = 18 years if 60% recovery is in 7 years.

The 130 acre Muzzi marsh in San Francisco Bay was observed for 10 years of natural recolonization. *Spartina* was dense in the channels by 5 years. In the marsh plain, it was still developing after 10 years. Species composition changed over time (Faber, 1991).

Blair (1991) reported that a saltmarsh created in Chesapeake Bay in 1984 was successful. He stated that it was nearly 100% recovered by 7 years to "almost" like a natural marsh.

Broome et al. (1986) reported on a created marsh along an eroding shoreline in North Carolina. *Spartina alterniflora* was transplanted and monitored for 10 years. The vegetation was equal to a natural marsh by 4 years. Other saltmarsh biota were not monitored.

Dunn and Best (1983) reported natural reestablishment of emergent freshwater marshes in Florida in 4-5 years. D'Avanzo et al. (1989) reports variable rates for freshwater marshes with recovery taking 2-5 years in some cases, but 15-30 years in others where soils used had no initial organic matter content.

Given the variability of recovery rates and of criteria used to estimate them, the literature does not provide a consensus of recovery time estimates. Where saltmarsh structure is lost, 15 years is assumed required for full recovery of all parts of the ecosystem (not just the vegetation). If the vegetation is not lost, 5 years is assumed for recovery of other functions, including invertebrate populations.

Forested and Shrub Wetlands (Swamps)

In examining a 6 ha mangrove forest killed after a JP-5 jet fuel spill, recovery was estimated as requiring 10 years after replanting (Ballou and Lewis, 1989). Lewis (1983) reviewed case histories of oil spills in mangroves. For one example, after a crude oil spill on St. Croix, U.S. Virgin Islands, there was no recolonization after 7 years. Recovery was estimated to require 10-50 years. Getter et al. (1984) estimated recovery after oil spill at 25-30 years if restoration were performed. Research Planning, Inc. (RPI, 1987) estimated 20 years for recovery of an oiled mangrove forest. Keller and Jackson (1991) speculated that for mangroves oiled and killed in Panama "full recovery may require many decades". Mature trees are 50-70 years old. Cubit et al. (1987) summarizes mangrove mortality and the more severe mortality of associated animals in these Panama habitats. Recovery was not complete after 5 years of monitoring. Additional review of literature on recovery of mangroves after oil spills is available in Hoff (2002).

In the model, it is assumed that replanting is performed (Section 5), eliminating the recolonization lag. Recovery of the mangrove swamp is assumed to take 20 years.

Macroalgal Beds

The most important macroalgal bed habitat is the kelp bed of the Pacific coast (*Macrocystis* spp.). Moody (1990) estimated that oiled kelp beds had 90% recovered in 3-4 years. However, after 14 years they had not fully recovered to pre-spill diversity. Foster and Schiel (1985) reviewed a 1957 oil spill in Baja California. There was massive mortality of invertebrates, but vegetation damage was less obvious. Vegetation increased rapidly (due to reduce grazing) by one year later. By four years later, most animal populations had recovered, but a few had not by six years. In the model, recovery time for the vegetation is assumed 15 years and for invertebrates where vegetation is unaffected, 5 years.

Coral Reefs

It is generally agreed that recovery of coral reefs after total destruction of the reef is very slow, but small scale impacts may take much less time for recovery. Brock et al. (1979) performed defaunation experiments on patch reefs in Hawaii. With all (and only) fish removed from small reefs, recovery took one to two years. Fucik et al. (1984) estimates that recovery after small scale localized destruction requires less than ten years. After heavy destruction, recovery takes 10-20 years. Severe impacts require several decades for recovery.

Keller and Jackson (1991) summarized observations on oiled coral reefs in Panama. At 0.5-3.0 m depth, 76% of coral was killed. At 3-6 m depth, 56% of coral was killed. Recovery was speculated to require more than a decade. There was no recovery after two years of observations. Additional review of literature regarding impacts and recovery of coral reefs after oil spills is available in Shigenaka (2001).

In the model, it is assumed that recovery following mortality of a reef requires 30 years (to 99% recovery).

Oyster Reef

Lenihan et al. (2001) found that the fish community compositions and species abundances on oyster reefs restored 6 years before sampling were largely indistinguishable from those on natural oyster reefs. Peterson et al. (2003) evaluated changes in abundance of fish and large mobile crustaceans on oyster reefs over time, finding that for reefs constructed in summer, development of fish and mobile crustacean abundance is virtually complete by the next spring-summer season. Densities do not increase in successive years (Grabowski, 2002). Thus, recovery of reef invertebrates, given structure already present, requires 1-2 years, depending on the timing of the spill impacts. Two years is assumed in the model.

However, if the reef structure is destroyed (e.g, during storms, Livingston et al., 1999), recovery of oyster reefs would take more time. Three years is assumed in the model.

3.5 Quantification of Fish and Invertebrate Impact as Lost Production

3.5.1 Approach

The biomass (kg) of fish and invertebrates killed represents biomass produced before the spill. In addition to this impact, 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 to calculate the total production foregone. The loss is expressed in "present day" (i.e., year of the spill) values using a 3% annual discount rate for future losses.

In a natural resource damage assessment (NRDA, based on US regulations and practice), 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 injury (impact) inflated to the year restoration occurs or the restoration discounted back to the year of the spill.

Interim losses are 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 used here is that the total loss 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 impacts 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 potentially 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 lost ecological services.

This injury estimation approach was developed and used previously in the injury quantification for the *North Cape* spill of January 1996 (French McCay et al., 2003b, French McCay and Rowe, 2003) and many other spill cases (e.g., French McCay et al., 2003c). The method makes use of the population model in 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 production foregone).
3. Future interim losses are calculated in "present day" (year of the spill) 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. Production forgone is then estimated using the model of Jensen et al. (1988), which is commonly used in fisheries science (see below).

It should be noted that compensation would be 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.

3.5.2 Equations

The production foregone population model as described by the U.S. Environmental Protection Agency in its 316(b) rule (USEPA, 2004) is used. This approach is recommended by fisheries scientists and the models are those typically used for entrainment and impingement fisheries impact evaluations (EPRI, 2004). The equations are based on fisheries model development described in Ricker (1975).

The production foregone population model makes use of survival rates from one stage to the next. For eggs, survival to age one (S_{e1}) is calculated as:

$$S_{e1} = 2\ S_e\ e^{-\ln(1+Se)}\ S_L\ S_j \tag{8}$$

where S_e, S_L, and S_j are the survival rates for each stage: egg, larvae, and juvenile. For larvae, survival to age one (S_{L1}) is calculated as:

$$S_{L1} = 2\ S_L\ e^{-\ln(1+S_L)}\ S_j \tag{9}$$

Natural and fishing mortality rates for annual age classes are used to estimate numbers that would remain alive by each age class. The number remaining alive at age t (years), N_t, is:

$$N_t = N_1\ e^{(-Z_a\ (t-1))} \tag{10}$$

$$Z_a = M_a + F_a \tag{11}$$

where N_1 is the number at age one, Z_a is annual instantaneous total mortality, M_a is annual instantaneous natural mortality, and F_a is annual instantaneous fishing mortality, for age class a. The annual survival rate for age t (S_t) is thus:

$$S_t = e^{(-Z_t)} \tag{12}$$

The fraction dying in a year is 1-S_t.

Yield foregone (Y_k) (i.e., equivalent yield, or lost catch) may be calculated using the Thompson-Bell equilibrium yield model (Ricker, 1975) where the harvest at each age class is calculated from number starting the class multiplied by fishing mortality rate, $(F_a/Z_a)(1-e^{-Za})$:

$$Y_k = \sum_j \sum_a L_{jk} S_{ja} W_a (F_a/Z_a)(1-e^{-Za}) \tag{13}$$

where:

Y_k = foregone yield (kg) in year k
L_{jk} = losses of individual fish of stage j in the year k
S_{ja} = cumulative survival fraction from stage j to age a
W_a = average weight (kg) of fish at age a
F_a = instantaneous annual fishing mortality rate for fish of age a
Z_a =instantaneous annual total mortality rate for fish of age a

Total natural mortality (TM_k) is calculated using an analogous model:

$$TM_k = \sum_j \sum_a L_{jk} S_{ja} W_a (M_a/Z_a)(1-e^{-Za}) \tag{14}$$

where M_a is the instantaneous annual natural mortality rate for fish of age a.

For this analysis, the losses are for eggs and larvae translated to 1 year of age, i.e., one stage where j=1.

Production foregone (USEPA, 2004, Chapter A-5; based on Rago, 1984 and Jensen et al., 1988) which includes yield (harvest) and the production consumed in the food web, is estimated using:

$$Y_k = \sum_j \sum_a [\, G_a L_{jk} W_a (e^{Ga-Za} - 1) \,]/[\, G_a - Z_a \,] \tag{15}$$

where G_a is the instantaneous growth rate for individuals of age a.

Length and weight at age are estimated using the von Bertalanffy equation and a power curve of weight versus length following methods in Ricker (1975). The equations used are as follows. For length (mm) at age t (years):

$$L_t = L_\infty [1 - e^{(-K(t - t_o))}] \tag{16}$$

where L_t is length (mm) at age t (years), L_∞ is the asymptotic maximum length (mm), K is the Brody growth coefficient, and t_o is a constant. Weight as a function of length (mm) is:

$$W_t = \alpha L_t^{\beta} \tag{17}$$

where W_t is wet weight (g) at age t years and α and β are constants.

Discounting at 3% per year (NOAA, 1997) 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 (i.e., for the year of the spill) is calculated as $(1+d)^{-n} = 1/(1+d)^{n}$, where d=0.03. Thus, the losses in future years have a discounted value at the time of the spill. In this analysis, all discounting will be calculated based on the number of years from the year of the spill. Thus, additional discounting is needed to translate all the injuries to compensatory equivalents for the year the restoration is performed. The multiplier for this calculation is $(1+d)^{m}$, where *m* is the number of years after the spill when restoration is accomplished.

4 Discussion

Validation

The 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. Field and model estimates of lobster impacts were within 10% of each other (French McCay, 2003).

Hindcasts and NRDA

The model has proved useful in numerous hindcast studies as part of NRDAs. The most accurate approach for using a model in an NRDA is to obtain sufficient field data to provide input to the model and calibrate the results.

In the event of an oil spill, in order to fully characterize the impact by field sampling, water and sediment samples would be needed at frequent time intervals over the first few weeks after the release (and especially in the first 24-48 hours), and with enough spatial coverage to characterize the extent of contamination. In addition, comprehensive sampling of each of the species affected is needed in the exposed and unaffected areas. Because marine organisms are so patchy in their distribution, large numbers of stations and samples within stations are needed to accurately map abundance. Such extensive sampling of all (or even selected) species affected is often not feasible, given the rapidity at which the evidence disappears (by scavenging of killed organisms and by migration of animals into the impacted area). Thus, in practice, the needed sampling would require a considerable effort, which is usually both infeasible and too costly to be justifiable by the expected impact of the spill. In spite of these obstacles, historically, attempts at quantification have primarily been made by collecting field data. A more practical and realistic approach is to combine field sampling with modeling.

Biological sampling should be designed to establish pre-spill baseline (by number and weight for each species and life stage and by size classes, as appropriate) and what types of organisms were exposed. Biological effects modeling may then be used to quantify impacts. If it is feasible, field data collections could be focused on exposed species of particular concern, such that enough data might be collected to indicate and possibly quantify the impacts. If this is possible, such data may be used to verify the modeling results.

Modeling may be used to estimate the range of potential injuries, given the range in species sensitivity and acute toxicity values that have been observed in laboratory-based bioassays performed and reported previously (French McCay, 2002). Given the large variation in sensitivity of various species and life stages (Figure 4), and that many important species have not been tested, acute toxicity bioassays should be performed on exposed organisms of concern to provide more accurate estimates of impact. To simplify this and avoid artifacts of whole-oil bioassays, the toxicity tests can be performed for single hydrocarbon exposures and the toxicity of the dissolved hydrocarbon mixture resulting from oil exposure can be calculated from the bioassay results using the modeling approach described in French McCay (2002).

Risk Assessment Consequence Analyses

In environmental risk assessment studies (e.g., French McCay et al., 2003a, 2004, 2005a,b,c) the objective is to assess potential consequences if a spill were to occur. Hence, multiple model runs and conditions need to be evaluated to develop an expectation of risk of oil impacting each resource of concern. To evaluate the distribution of potential impacts resulting from variation in environmental conditions, the model is run many times, randomizing the start date and time. In addition or alternatively, various other model inputs may be varied within specified ranges or according to probability distributions, such as the spill volume, location, release depth, release duration, density of biota of concern, toxicity values, and assumed parameters for model algorithms. The multiple model runs provide a frequency distribution of model results, for which statistics (e.g., mean, standard deviation, maximum) are calculated and plotted, such as for probabilities of exceeding effects endpoints, areas impacted above these thresholds, or numbers of animals killed. Response strategies (i.e., removal from clean up, booming) may be incorporated into the model and considered in the assessment.

The potential spill conditions causing the median or the worst-case impacts to specific resources may be identified using the probabilistic model results. For example, a worst case for sensitive resources along the coast may be those wind and current conditions which would maximize exposure to those resources. The individual worst case scenario may then be examined in more detail, forecasting it using the 3-dimensional fates and biological effects models, quantifying the worst possible exposure for that resource of concern. Sensitivity analysis provides measures of uncertainty for these predictions. Other worst case scenarios may be identified for additional resources of concern, such as seabirds, marine mammal, sea turtles, fish, etc; and examined in detail with fates and biological effects model analyses. Alternatively, the range of potential impacts may be identified.

Research Needs

The above-described model represents the state-of-the-art for oil spill biological effects modeling. Research needs for informing model parameterization and developing new algorithms are outlined below.

- **Wildlife oiling probabilities**: For wildlife the probabilities of exposure to oil, given presence in the area swept by oil, would be less uncertain with additional quantitative observational data from spills. For example, counts by

species in an area oiled could be followed up by counts of oiled birds recovered (with necessary corrections for losses and search effort).

- **Avoidance or attraction behavior**: Wildlife may avoid oil or learn to avoid oil. Alternatively, wildlife may be attracted to biota impacted by oil and become oiled. While many anecdotal observations have been reported, quantitative information to include such behavior in a model is lacking. Alternatively, the issue can be addressed by altering densities of animals exposed.
- **Fish and invertebrate behavior**: Behavioral detail for fish and invertebrates, both in general and in the presence of oil (e.g., avoidance, attraction), could potentially improve accuracy of the modeled movements. Data needed are the details of vertical distribution on a diel basis and overall migration speed of these organisms (as opposed to localized or temporary swimming speed).
- **Effects of suspended oil droplets**: To date, modeling has only quantified acute effects of dissolved hydrocarbon components. While anecdotal information exists to indicate that suspended oil droplets impact aquatic biota, data quantifying the dose-response relationship are lacking. In SIMAP, the fates and concentrations of suspended oil droplets are simulated, such that concentration estimates are available for such evaluations.
- **Impacts on neuston**: The sea surface environment provides an important habitat for many organisms commonly referred to as neuston. Fish eggs, fish larvae and crustacean larvae, including several commercially important species, have been found to encompass significant portions of neustonic communities (Grant, 1986). Besides the permanent invertebrate inhabitants of the surface layer, commonly referred to as euneuston, the larvae of several macroinvertebrates including various families of corals, crabs and spiny lobster have been observed to be concentrated in the surface layer. Larval fish of some species appear to actively seek the surface layer by adjusting their swim bladder to become buoyant (e.g., sardines, Santos et al., 2006). Certain species of fish are noted as having larval stages which are completely neustonic or surface dwelling (i.e. gurnards, (Dactylopteridae)) (Cowen, 2002). Floating fish eggs are particularly vulnerable to the impacts of oil (Longwell, 1977; Longwell and Hughes, 1980). These neustonic assemblages are subject to surface contamination, such as floating oil and oil entrained by breaking waves in the surface wave-mixed layer. Ignoring the presence of neuston has lead to underestimation of oil spill impacts in the past (Grant, 1986). Observational and experimental information is needed to support model algorithm development and parameterization.
- **Impacts on surfacing fish**: In addition to larvae and zooplankton, there are several species of adult fish which utilize the sea surface habitat, e.g., flying fish, halfbeaks and needlefish spend a significant amount of time swimming and breaking the sea surface. Many fish species come to the surface to fill their swim bladders. Oil spills which sweep pelagic areas where these and other surface-dwelling species are found likely impact these species. Injury due to physical interaction between adult fish at the sea surface and floating oil/tar has not been assessed to date for lack of information with which to address the issue.

- **Acute toxicity for short-term (several hour) exposures**: Research and the literature have well-documented that the uptake of semi-soluble organics such as hydrocarbons in oil continues for days to weeks until the tissue concentrations reach effects levels (see reviews in DiToro et al., 200; French McCay, 2002). Indeed, standard acute toxicity tests are performed for 96 hours or longer on this basis (Sprague, 1969; Swartz et al., 1995). The relationship of effects level (LC50) versus duration of exposure is based on uptake modeling and what data is available for short-duration (i.e., hours) exposures. Additional bioassay data for exposures of a few hours are needed to calibrate and verify these relationships.
- **Phototoxicity**: It is well understood that UV light induces phototoxic effects for some PAHs in oil (Barron et. al., 2003, 2004; Lee, 2003; Kirby et al., 2007). UV light intensity decreases with increasing latitude and depth into the water column. However, organisms in shallow water and in the neuston could be significantly affected by phototoxicity of PAHs accumulated in their tissues if they lack pigmentation for protection from these effects (Lee, 2003; Barron et al., 2005). The magnitude of this effect should be evaluated and phototoxicity included in modeling assessments if significant.
- **Chronic effects of oil**: Long-term effects of PAHs from oil are well documented in the literature. Such effects have not been formally included in biological effects models to date. However, the physical fates modeling to support such inclusion would need to be very comprehensive and accurate for such inclusion to be reasonably accurate. Alternatively, and more accurately, long-term biological effects modeling could be driven by observational data of sediment and shoreline concentrations of PAHs. This latter approach is recommended, given the duration of exposure and feasibility of sampling sediments. Concentrations in the water column are of short duration and, thus, do not result in chronic exposures in that habitat.
- **Population and ecosystem level impacts** result from acute and chronic effects on individuals. Modeling of such effects can rely on the extensive literature related to effects of disturbance and recovery. Such modeling has not been attempted for impacts of oil spills to date, due to the magnitude of the task and uncertainties involved.

Finally, it should be noted that the level of detail required in a model varies by the circumstances and needs of the assessment. For example, if water column contamination from a spill results in minimal or negligible toxicity, the accuracies of input density data, algorithms governing water column organism behavior, and population level modeling for fish and invertebrates are inconsequential to results. Also, if an ecological risk assessment is being performed, such that the analysis involves comparisons among alternatives, use of organism density data may not be required; rather comparisons of areas or water volumes impacted can be used. Sensitivity analysis, varying inputs within the range of uncertainty, is used to quantify and convey the uncertainties of model results. This elucidates important assumptions and data inputs for a particular application of the model. Calibration may be used to improve accuracy for specific hindcasts.

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6 References

Albers, P.H., "Transfer of Crude Oil from Contaminated Water to Bird Eggs", *Environmental Research*, 22:2, pp. 307-314, 1980.

Albers, P.H. and R.C. Szaro, "Effects of No. 2 Fuel Oil on Common Eider Eggs", *Marine Pollution Bulletin*, 9, pp. 138-139, 1978.

Alexander, S.K. and J.W. Webb, "Seasonal Response of *Spartina alterniflora* to Oil", in *Proceedings of the 1985 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., API Publ. 4385, pp. 355-258, 1985.

Alexander, S.K. and J.W. Webb, Jr., "Relationship of *Spartina alterniflora* Growth to Sediment Oil Content Following an Oil Spill", in *Proceedings of the 1987 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., API Publ. 4452, pp. 445-449, 1987.

Andersen, L.E., F. Melville, and D. Jolley, "An Assessment of an Oil Spill in Gladstone, Australia – Impacts on Intertidal Areas at One Month Post-Spill", *Marine Pollution Bulletin*, 57, 607–615, 2008.

Anderson, D. W., S.H. Newman, P.R. Kelly, S.K. Herzog, and K.P. Lewis, "An Experimental Soft-Release of Oil-Spill Rehabilitated American Coots (*Fulica americana*): I. Lingering Effects on Survival, Condition and Behavior", *Environmental Pollution*, 107, pp. 285-294, 2000.

Anderson, J.W., *Toxicity of Dispersed and Undispersed Prudhoe Bay Crude Oil Fractions to Shrimp, Fish, and Their Larvae*, American Petroleum Institute, Washington, D.C., API Publ. 4441, 52 p., 1985.

Ansari, Z.A. and B. Ingole, "Effect of an Oil Spill from M V *Sea Transporter* on Intertidal Meiofauna at Goa, India", *Marine Pollution Bulletin*, 44, 396–402, 2002.

ASCE Task Committee on Modeling Oil Spills, "State-of-the-art Review of Modeling Transport and Fate of Oil Spills", *Journal of Hydraulic Engineering*, 122:11, pp. 594-609, 1996.

Baca, B.J., T.E. Lankford, and E.R., Gundlach, "Recovery of Brittany Coastal Marshes in the Eight Years Following the *Amoco Cadiz* Incident", in *Proceedings of the 1987 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., API Publ. 4452, pp. 459-464, 1987.

Baker, J.M., "Seasonal Effects of Oil Pollution on Salt Marsh Vegetation", *Oikos*, 22, pp. 106-110, 1971.

Baker, J.M., R.B. Clark, P.F. Kingston and R.H. Jenkins, "Natural Recovery of Cold Water Marine Environments After an Oil Spill", in *Thirteenth Annual Arctic and Marine Oil spill Program Technical Seminar*, Environment Canada, Ottawa, ON, 111 p., 1990.

Ballou, T.G., and R.R. Lewis, "Environmental Assessment and Restoration Recommendations for a Mangrove Forest Affected by Jet Fuel", in *Proceedings of the 1989 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 407-414, 1989.

Banse, K. and S. Mosher, "Adult Body Mass and Annual Production/Biomass Relationships of Field Populations" *Ecological Monographs*, 50, pp. 355-379, 1980.

Barron, M.G., M.G. Carls, J.W. Short, and S.D. Rice, "Photoenhanced Toxicity of Aqueous Phase and Chemically Dispersed Weathered Alaska North Slope Crude Oil to Pacific Herring Eggs and Larvae", *Environmental Toxicology and Chemistry*, 22, pp. 650–660, 2003.

Barron, M.G., M. G. Carls, R. Heintz, and S.D. Rice, "Evaluation of Fish Early Life-Stage Toxicity Models of Chronic Embryonic Exposures to Complex Polycyclic Aromatic Hydrocarbon Mixtures", *Toxicological Sciences*, 78, pp. 60–67, 2004.

Barron, M.G., M. G. Carls, J. W. Short, S. D. Rice, R. A. Heintz, M. Rau, and R. Di Giulio, "Assessment of the Phototoxicity of Weathered Alaska North Slope Crude Oil to Juvenile Pink Salmon", *Chemosphere*, 60, pp.105–110, 2005.

Blair, C., "Successful Tidal Wetland Mitigation in Norfolk, VA", in *Coastal Wetlands*, H.S. Bolton (ed.), Proceedings of Coastal Zone '91, American Society of Civil Engineers, New York, NY, pp. 463-476, 1991.

Bodin, P. "Results of Ecological Monitoring of Three Beaches Polluted by the *Amoco Cadiz* Oil Spill: Development of Meiofauna from 1978 to 1984", M*arine Ecology Progress Series*, 42, pp.105-123, 1988.

Boucher, G., "Impact of *Amoco Cadiz* Oil Spill on Intertidal and Sublittoral Meiofauna", *Marine Pollution Bulletin*, 11, pp. 95-101, 1980.

Boucher, G., "Long-Term Monitoring of Meiofauna Densities After the *Amoco Cadiz* Oil Spill", *Marine Pollution Bulletin*, 16, pp. 328-333, 1985.

Boufadel M. C., K. Du, V. J. Kaku, and J. Weaver, "Lagrangian Simulation of Oil Droplets Transport Due to Regular Waves", *Environmental Modelling & Software*,22, pp. 978-986, 2007.

Bourne, W.R.P., J.D. Parrack and G.R. Potts, "Birds Killed in the *Torrey Canyon* Disaster", *Nature*, 215, pp. 1123-1125, 1967.

Brock, R.E., C. Lewis, and R.C. Wass, "Stability and Structure of a Fish Community on a Coral Patch Reef in Hawaii", *Marine Biology*, 54, pp. 281-292, 1979.

Brody, A., "A Simulation Model for Assessing the Risks of Oil Spills to the California Sea Otter Population and an Analysis of the Historical Growth of the Population", in *Population Status of California Sea Otters*, D.B Siniff and K. Ralls (eds), Report to U.S. Department of the Interior, Minerals Management Service, Pacific Outer Continental Shelf Region, Los Angeles, CA, Contract No. 14-12-001-30033, pp.191-274, 1988.

Broman, D., B. Ganning, C. Lindblad, "Effects of High Pressure, Hot Water Shore Cleaning After Oil Spills on Shore Ecosystems in the Northern Baltic Proper", *Marine Environmental Research*,1, pp.173-187, 1983.

Broome, S., W. Seneca, and W. Woodhouse, Jr., "Long-Term Growth and Development of Transplants of the Saltmarsh Grass, *Spartina alterniflora*", *Estuaries*, 9, pp. 63-74, 1986.

Brownell, R.L., Jr. and B.J. LeBoeuf, "California Sea Lion Mortality: Natural or Artifact?", in *Biological and Oceanographical Survey of the Santa Barbara Channel Oil Spill, 1969,1970, D. Volume I. Biology and Bacteriology*, Straughan (ed.), Allan Hancock Foundation, University of Southern California, CA, pp. 287-306,1971.

Burns, K.A., S.D. Garrity, and S.C. Levings, "How Many Years Until Mangrove Ecosystems Recover from Catastrophic Oil Spills?", *Marine Pollution Bulletin*, 26, pp. 239-248, 1993.

Capuzzo J.M., "Biological Effects of Petroleum Hydrocarbons: Assessments from Experimental Results", in *Long-Term Environmental Effects of Offshore Oil and Gas Development*, D.F. Boesch and N.N. Rabulais (eds.), Elsevier, New York, NY, pp. 343-410, 1987.

Carter, H.R. and G.W. Page, *Central California Oilspill Contingency Plan, Assessment of Numbers and Species Composition of Dead beached Birds*, National Atmospheric and Oceanic Administration, U.S. Department of Commerce, NOAA Technical Memorandum NOSMEMD 25, 1989.

Carter, H.R., V.A. Lee, G.W. Page, M.W. Parker, R.G. Ford, G. Swartzman, S.W. Kress, B.R. Siskin, S.W. Singer, and D.M. Fry, "The 1986 *Apex Houston* Oil Spill in Central California: Seabird Injury Assessments and Litigation Process", *Marine Ornithology*, 31:1, pp. 9-19, 2003.

Chapman, B.R., "Effects of the *Ixtoc I* Oil Spill on Texas Shorebird Populations", in *Proceedings of the 1981 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 461-465, 1981.

Clark, R.B., "Impact of Oil Pollution on Seabirds", *Environmental Pollution* (Series A) 33, pp.1-22, 1984.

Clarke, P.J. and T. Ward, "The Response of Southern Hemisphere Saltmarsh Plants and Gastropods to Experimental Contamination by Petroleum Hydrocarbons", *Journal of Experimental Marine Biology and Ecology*, 175, pp. 43-57, 1994.

Cohen, E.B., M.D. Grosslein, M.P. Sissenwine, F. Steimle, and W. R. Wright, "Energy budget of Georges Bank", in M.C. Mercer (ed.), Multispecies approaches to fisheries management advice, *Canadian Special Publication Fisheries Aquatic Sciences*, 59, pp. 95-107, 1982.

Cowen, R.K, "Oceanographic Influences on Larval Dispersal and Retention and Their Consequences for Population Connectivity" in *Coral Reef Fishes*, Chapter 7, Sale,P. (ed.) Academic Press, San Diego, CA, pp.149-169, 2002.

Croxall, J.P., "The Effects of Oil on Seabirds", *Rapport Procès-Verbal Reunion Conseil International pour L'Exploration de la Mer*, 171, pp. 191-195, 1977.

Cubit, J.D., C.D. Getter, J.B.C. Jackson, S.D. Garrity, H.M. Caffey, R.C. Thompson, E. Weil and M.J. Marshall, "An Oil Spill Affecting Coral Reefs and Mangroves on the Caribbean Coast of Panama", in *Proceedings 1987 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 401-406, 1987.

D'Avanzo, C., J.A. Jusler, and M.E. Kentula, (ed.), "Long Term Evaluation of Wetland Creation Projects" in *Wetland creation and restoration: The status of the science, Vol II: Perspectives*, EPA/600/3 89/038B, 172 p. 1989.

DiToro, D.M., J.A. McGrath, and D.J. Hansen, "Technical Basis for Narcotic Chemicals and Polycyclic Aromatic Hydrocarbon Criteria. I. Water and tissue", *Environmental Toxicology and Chemistry*, 19:1, pp.1951-1970, 2000.

DiToro, D.M. and J.A. McGrath, "Technical Basis for Narcotic Chemicals and Polycyclic Aromatic Hydrocarbon Criteria. II. Mixtures and sediments," *Environmental Toxicology and Chemistry* 19:8, pp. 1971-1982, 2000.

Dunn, W.J. and G.R. Best, "Enhancing Ecological Succession: 5 Seed Bank Survey of Some Florida Marshes and Role of Seed Banks in Marsh Reclamation" in *Proceedings Symposium on Surface Mining Hydrology, Sedimentology and Reclamation*, University of Kentucky, Lexington, KT, pp. 365-370, 1983.

Electric Power Research Institute (EPRI), *Extrapolating Impingement and Entrainment Losses to Equivalent Adult and Production Foregone*. EPRI Report No. 1008471, 2004.

Engelhardt, F.R., "Petroleum Effects on Marine Mammals", *Aquatic Toxicology*, 4, pp. 199-217, 1983.

Engelhardt, F.R. "Assessment of the Vulnerability of Marine Mammals to Oil Pollution", in *The Fate and Effects of Oil in Marine Ecosystems*, J.Kuiper and W. J. van den Brink (eds.), Martinus Nijhoff, Dordrecht, Netherlands, pp. 101-115, 1987.

Evans, P.G.H. and D.N. Nettleship, "Conservation of the Atlantic Alcidae" in *The Atlantic Alcidae*, D.N. Nettleship and T.R. Birkhead (eds.), Academic Press, London, pp. 427-488, 1985.

Faber, P.M., "The Muzzi Marsh, Corte Madera, California Long-term Observations of a Restored Marsh in San Francisco Bay" in *Proceedings of Coastal Zone 1991*, American Society of Civil Engineers, New York, NY. p. 424-438, 1991.

Fenchel, J., "Intrinsic rate of natural increase: the relationship with body size", *Oecologica*, 14, pp. 317-326, 1974.

Ford, R.G., *A Risk Analysis Model for Marine Mammals and Seabirds: A Southern California Bight Scenario*, Final Report to U.S. Department of the Interior, Minerals Management Service MMS 85-0104, Pacific OCS Region, Los Angeles, CA, 236 p., 1985.

Ford, R.G., "Estimating Mortality of Seabirds from Oil Spills", in *Proceedings of 1987 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 547-551, 1987.

Ford, R.G., J.A. Wiens, D. Heinemann and G.L. Hunt, "Modelling the Sensitivity of Colonially Breeding Marine Birds to Oil Spills: Guillemot and Kittiwake Populations on the Pribilof Islands, Bering Sea", *Journal of Applied Ecology*, 19, pp. 1-31, 1982.

Ford, R.G., M.L. Bonnell, D.H. Varoujean, G.W. Page, H.R. Carter, B.E. Sharp, D. Heinemann, and J.L. Casey, "Total Direct Mortality of Seabirds from the *Exxon Valdez* Oil Spill", in *Proceedings of the Exxon Valdez Oil Spill Symposium, American Fisheries Society Symposium 18*, American Fisheries Society, Bethesda, MD, pp. 684-711, 1996.

Foster, M.S., and D.R. Schiel, *The Ecology of Giant Kelp Forests in California: A Community Profile*. U.S. Fish and Wildlife Service Biological Report 85:7.2, 152 p., 1985.

French, D.P. and F.W. French III, "The Biological Component of the CERCLA Type A Damage Assessment Model System", *Oil and Chemical Pollution* 5, pp. 125-163, 1989.

French, D.P., M. Reed, J. Calambokidis and J. Cubbage, "A Simulation Model of Seasonal Migration and Daily Movements of the Northern Fur Seal, *Callorhinus ursinus", Ecological Modelling*, 48, pp. 193-219, 1989.

French, D., M. Reed, K. Jayko, S. Feng, H. Rines, S. Pavignano, T. Isaji, S. Puckett, A. Keller, F.W. French III, D. Gifford, J. McCue, G. Brown, E. MacDonald, J. Quirk, S. Natzke, R. Bishop, M. Welsh, M. Phillips and B.S. Ingram, *Final Report, The CERCLA Type A Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME), Technical Documentation, Vol. I - V.*, Submitted to the Office of Environmental Policy and Compliance, U.S. Department of the Interior, Washington, DC, Contract No. 14-0001-91-C-11, April, 1996.

French, D.P., and H. Rines, "Validation and Use of Spill Impact Modeling for Impact Assessment", in *Proceedings of the 1997 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., API Publ. 4651, pp. 829-834, 1997.

French, D.P., H. Rines and P. Masciangioli, "Validation of an Orimulsion Spill Fates Model Using Observations from Field Test Spills", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 933-961, 1997.

French McCay, D.P., "Development and Application of an Oil Toxicity and Exposure Model, OilToxEx", *Environmental Toxicology and Chemistry*, 21, pp. 2080-2094, 2002.

French McCay, D.P., "Development and Application of Damage Assessment Modeling: Example Assessment for the *North Cape* Oil Spill", *Marine Pollution Bulletin*, 47:9-12, pp. 341-359, 2003.

French McCay, D.P., "Oil Spill Impact Modeling: Development and Validation", *Environmental Toxicology and Chemistry*, 23:10, pp. 2441-2456, 2004.

French McCay, D.P. and J.J. Rowe, "Habitat Restoration as Mitigation for Lost Production at Multiple Trophic Levels", *Marine Ecology Progress Series*, 264, pp. 235-249, 2003.

French McCay, D.P., and J.J. Rowe, "Evaluation of Bird Impacts in Historical Oil Spill Cases Using the SIMAP Oil Spill Model", in *Proceedings of the Twenty-Seventh Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 421-452, 2004.

French McCay, D., N. Whittier, T. Isaji, and W. Saunders, "Assessment of the Potential Impacts of Oil Spills in the James River, Virginia", in *Proceedings of the 26th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, Canada, pp. 857-878, 2003a.

French McCay, D.P., C.H. Peterson, J.T. DeAlteris and J. Catena, "Restoration that Targets Function as Opposed to Structure: Replacing Lost Bivalve Production and Filtration", *Marine Ecology Progress Series*, 264, pp. 197-212, 2003b.

French McCay, D., J. J. Rowe, and N. Whittier, *Final Report, Estimation of Natural Resource Damages for 23 Florida Cases Using Modeling of Physical Fates and*

Biological injuries, (23 volumes). Prepared for Florida Department of Environmental Protection, May 2003c.

French McCay, D., N. Whittier, S. Sankaranarayanan, J. Jennings, and D. S. Etkin, "Estimation of Potential Impacts and Natural Resource Damages of Oil", *Journal of Hazardous Materials*, 107:1-2, pp. 11-25, 2004.

French-McCay, D., J. Rowe, N. Whittier, S. Sankaranarayanan, D.S. Etkin, and L. Pilkey-Jarvis, "Evaluation of the Consequences of Various Response Options Using Modeling of Fate, Effects and NRDA Costs of Oil Spills into Washington Waters", in *Proceedings of the 2005 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 467-473, 2005a.

French-McCay, D.P., N. Whittier, C. Dalton, J.J. Rowe, and S. Sankaranarayanan, "Modeling Fates and Impacts of Hypothetical Oil Spills in Delaware, Florida, Texas, California, and Alaska Waters, Varying Response Options Including Use of Dispersants", in *Proceedings of the International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., Paper 399, 2005b

French McCay, D., N. Whittier, J.J. Rowe, S. Sankaranarayanan and H.-S. Kim, "Use of Probabilistic Trajectory and Impact Modeling to Assess Consequences of Oil Spills with Various Response Strategies", in *Proceedings of the 28th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 253-271, 2005c.

French-McCay, D.P, C. Mueller, K. Jayko, B. Longval, M. Schroeder, J.R. Payne, E. Terrill, M. Carter, M. Otero, S. Y. Kim, W. Nordhausen, M. Lampinen, and C. Ohlmann, "Evaluation of Field-Collected Data Measuring Fluorescein Dye Movements and Dispersion for Dispersed Oil Transport Modeling", in *Proceedings of the 30th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 713-754, 2007.

Fry, D.M., *Seabird Oil Toxicity Study*. Final report to Minerals Management Service, U.S. Department of Interior, Washington, DC, Submitted by Nero and Associates, Inc., Portland, OR, 1987.

Fucik, K.W., T.J. Bight and K.S. Goodman, "Measurements of Damage, Recovery, and Rehabilitation of Coral Reefs Exposed to Oil", in *Restoration of Habitat Impacted by Oil Spills*, J. Cairns Jr. and A.L. Buikema, Jr. (eds.), Butterworth Publishers, Boston, MA, pp. 115-134, 1984.

Galt, J.A., "Uncertainty Analysis Related to Oil Spill Modeling", *Spill Science and Technology Bulletin*, 4:4, pp. 231-238, 1998.

Ganning, B., D.J. Reisch and D. Straughan, "Recovery and Restoration of Rocky Shores, Sandy Beaches, Tidal Flats, and Shallow Subtidal Bottom Impacted by Oil Spills", in *Restoration of Habitats Impacted by Oil Spills*, J. Cairns, Jr. and A.L. Buikema, Jr. (eds.), Butterworth Publishers, Boston, MA, pp. 7-36, 1984.

Garrity, S.D., and S.C. Levings, "Effects of an Oil Spill on Some Organisms Living on Mangrove (*Rhizophora mangle L.*) Roots in Low Wave-energy Habitats in Caribbean Panama", *Marine Environmental Research*, 35, pp. 251-271, 1993.

Geraci, J.R. and D.J. St. Aubin, *Synthesis of Effects of Oil on Marine Mammals*, Report to U.S. Department of the Interior, Minerals Management Service, Atlantic OCS Region, OCS Study, MMS 88 0049, Battelle Memorial Institute, Ventura, CA, 292 p., 1988.

Geraci, J.R. and D.J. St. Aubin (eds.), *Sea Mammals and Oil: Confronting the Risks*, Academic Press, San Diego, CA, 282 p., 1990.

Geraci, J.R. and T.G. Smith, "Direct and Indirect Effects of Oil on Ringed Seals (*Phoca hispida*) of the Beaufort Sea", *Journal of Fisheries Research Board of Canada*, 33, pp.1976-1984, 1976.

Getter, C.G., G. Cintron, B. Dicks, R.R. Lewis III, and E.D. Seneco, "The Recovery and Restoration of Salt Marshes and Mangroves Following an Oil Spill." in *Restoration of Habitats Impacted by Oil Spills*, J. Cairns, Jr. and A.L. Buikema, Jr. (eds), Butterworth Publishers, Boston, MA, pp. 65-113, 1984.

Gilfillan, E.S., D.S. Page, R.P. Gerber, S. Hansen, J. Cooley and J. Hotham, "Fate of the *Zoe Colocotroni* Oil Spill and its Effects on Infaunal Communities Associated with Mangroves", in *Proceedings of the 1981 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 353-360, 1981.

Grabowski J.H., *The Influence of Trophic Interactions, Habitat Complexity, and Landscape Setting on Community Dynamics and Restoration of Oyster Reefs*. PhD thesis, University of North Carolina at Chapel Hill, Chapel Hill, NC, 2002.

Grant, G.C., "Zooneuston: Animals of the Sea Surface", in *Proceedings of the Workshop on the Sea-Surface Microlayer in Relation to Ocean Disposal*, EPA report 556/1-87/005, 45-62. 1986.

Grodzinski, W. and B.A. Wunder, "Ecological Energetics of Small Mammals", in F.B. Golley, K. Petrusewicz and L. Ryszkowski (eds.) *Small mammals: their productivity and population dynamics*. Cambridge University Press, Cambridge, 451p., pp. 173-204, 1975.

Gundlach, E., E.A. Pavia, C. Robinson, and J.C. Gibeaut, "Shoreline Surveys at the *Exxon Valdez* Oil Spill: the State of Alaska Response", in *Proceedings of the 1991 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C. pp. 519- 529, 1991.

Hansen, D.J., "Utility of Toxicity Tests to Measure Effects of Substances on Marine Organisms", in *Concepts in Marine Pollution Measurements*, H.H. White (ed.), Maryland Sea Grant Publication, College Park, MD, pp. 33-56, 1984.

Hargrave, B.T., "Coupling Carbon Flow Through Some Pelagic and Benthic Communities", *Journal of Fisheries Research Board of Canada*, 30, pp.1317-1326, 1973.

Hemmingsen, A.M., "Energy Metabolism as Related to Body Size and Respiratory Surfaces, and its Evolution", *Rpts. Steno. Memor. Hosp., Copenh., Nordisk Insulin Lab*, 9, pp. 1-110, 1960.

Hoffman, D.J., "Embryotoxic Effects of Crude Oil in Mallard Ducks and Chicks", *Toxicology and Applied Pharmacology*, 46, pp.183-190, 1978.

Holmes, W.N., "Petroleum Pollutants in the Marine Environment and Their Effects on Seabirds", in *Reviews in Environmental Toxicology I*, E. Hodgson (ed.), Elsevier Science Publishers, Amsterdam, NL, pp. 251-317, 1984.

Holmes, W.N. and J. Cronshaw, "Biological Effects of Petroleum on Marine Birds", in *Effect of Petroleum on Arctic and Subartic Marine Environments and Organisms. Vol. II. Biological Effects*, D.C. Malins (ed.), Academic Press, New York, pp. 359-398, 1977.

Houghton, J.P., D.C. Lees, W. B. Driskell and A.J. Mearns, "Impacts of the *Exxon Valdez* Spill and Subsequent Cleanup on Intertidal Biota - 1 year later", in *Proceedings of the 1991 Oil Spill Conference,* American Petroleum Institute, Washington, D.C. pp. 467-475, 1991.

Howes, B.L., J.W.H. Dacey, and J.M. Teal JM, "Annual Carbon Mineralization and Belowground Production of *Spartina alterniflora* in a New England Salt Marsh", *Ecology*, 66, pp. 595-605, 1985.

Huang, J.C., "A Review of the State of the Art of Oil Spill Fate/Behavior Models", *Proceedings of the 1983 Oil Spill Conference,* American Petroleum Institute, Washington, D.C., pp. 313-322, 1983.

Jackson, J.B.C., J.D. Cubit, B.D. Keller, V. Batista, K. Burns, H.M. Caffey, R.L. Caldwell, S.D .Garrity., C.D. Getter, C. Gonzalez, H.M. Guzman, K.W. Kaufmann, A.H. Knap, S.C. Levings, M.J. Marshall, R. Steger and R. Thompson, "Ecological Effects of a Major Oil Spill on Panamanian Coastal Marine Communities", *Science*, 243, pp. 37-44, 1989.

Jacobs, R.P.W.M., "Effects of the Amoco Cadiz Oil Spill on the Seagrass Community at Roscoff with Special Reference to the Benthic Infauna" *Marine Ecology Progress Series*, 2, pp. 207-212, 1980.

Jayko K., M. Reed and A. Bowles, "Simulation of Interactions Between Migrating Whales and Potential Oil Spills" *Environmental Pollution*, 63, pp. 97 127, 1990.

Jennings, S., K.J. Warr, S. Mackinson, "Use of Size-based Production and Stable Isotope Analyses to Predict Trophic Transfer Efficiencies and Predator-prey Body Mass Ratios in Food Webs", *Marine Ecology Progress Series*, 240, pp. 11-20, 2002.

Jensen, A.L., R.H. Reider, and W.P. Kovalak, "Estimation of Production Forgone" *North American Journal of Fisheries Management*, 8, pp.191-198, 1988.

Jenssen, B.M., Review article: "Effects of Oil Pollution, Chemically Treated Oil, and Cleaning on the Thermal Balance of Birds", *Environmental Pollution*, 86, pp. 207-215, 1994.

Jenssen, B. M. and M. Ekker, "Dose Dependent Effects of Plumage-Oiling on Thermoregulation of Common Eiders *Somateria mollissima* Residing in Water", *Polar Research*, 10, pp. 579-84, 1991a.

Jenssen, B. M. and M. Ekker, "Effects of Plumage Contamination with Crude Oil Dispersant Mixtures on Thermoregulation in Common Eiders and Mallards", *Archives of Environmental Contamination and Toxicology*, 20, pp. 398-403, 1991b.

Johnson, T.L. and R.A. Pastorak, *Oil Spill Cleanup: Options for Minimizing Adverse Ecological Impacts*, American Petroleum Institute, Washington, DC, API Publication No. 4435, 600 p., December 1985.

Jones, D.A., J. Plaza, I. Watt, and M. AlSanei, "Long-term (1991-1995) Monitoring of the Intertidal Biota of Saudi Arabia after the 1991 Gulf War Oil Spill", *Marine Pollution Bulletin*, 36:6, pp. 472-489, 1998.

Jones, R.K., "A Simplified Pseudo-Component Oil Evaporation Model", in *Proceedings of the 20th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 43-61, 1997.

Judd, F.W., R.I. Lonard, J.H. Everitt, D.E. Escobar and R. Davis, "Resilience of Seacoast Bluestem Barrier Island Communities" in *Coastal Zone '91:*

Proceedings of the Seventh Symposium, American Society of Civil Engineers, New York, NY, pp. 3513-3524, 1991.

Keller, B.D. and J.B.C. Jackson, *Long-term Assessment of the Oil Spill at Bahia Las Minas, Panama, Interim Report, Volume I: Executive Summary*. OCS Study MMS 90-0030. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA. 49 p., 1991.

King and Lefever, "Effects of Oil Transferred from Incubating Gulls to Their Eggs" *Marine Pollution Bulletin*, 10, pp. 319-321, 1979.

King, J.G. and G.A. Sanger, "Oil Vulnerability Index for Marine Oriented Birds", in *Conservation of Marine Birds of Northern North America*, J.C. Bartonek and D.N. Nettleship (eds.), U.S. Fish and Wildlife Service, Wildlife Research Report 11, Washington, DC. pp. 227- 239, 1979.

Kingston, P.F., "Long-term Environmental Impact of Oil Spills", *Spill Science & Technology Bulletin*, 7:1/2, pp. 53–61, 2002.

Kirby, M. F., B.P. Lyons, J. Barry, and R.J. Law, "The Toxicological Impacts of Oil and Chemically Dispersed Oil: UV Mediated Phototoxicity and Implications for Environmental Effects, Statutory Testing and Response Strategies" *Marine Pollution Bulletin*, 54, pp. 464–488, 2007.

Kirstein, B.E., J.R. Clayton, C. Clary, J.R. Payne, D. McNabb, Jr., G.R. Redding, *Fauna and Integration of Suspended Particulate Matter and Oil Transportation Study*. Minerals Management Service, OCS Study MMS87-0083, Anchorage, AK, 216 p. 1987.

Kleiber, M., "Body Size and Metabolic Rate", *Physiological Review*, 27, pp. 511-541, 1947.

LeBoeuf, B.J., "Oil contamination and Elephant Seal Mortality: A "Negative" Finding" in *Biological and Oceanographical Survey of the Santa Barbara Channel Oil Spill 1969 1970. Volume I. Biology and Bacteriology*, D. Straughan (ed.), Allan Hancock Foundation, University of Southern California, CA, p. 277-285, 1971.

Lee, R.F., "Photo-oxidation and Photo-toxicity of Crude and Refined Oils", *Spill Science & Technology Bulletin*, 8:2, pp.157–162, 2003.

Lehr, W.J., J.A. Galt, and R. Overstreet, "Handling Uncertainty in Oil Spill Modeling", in *Proceedings of the 18th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 759-768, 1995.

Lehr, W.J., D. Wesley, D. Simecek-Beatty, R. Jones, G. Kachook and J. Lankford, "Algorithm and Interface Modifications of the NOAA Oil Spill Behavior Model", in *Proceedings of the 23rd Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 525-539, 2000.

Lenihan, H.S., C.H. Peterson, J.E. Byers, J.H. Grabowski, G.W. Thayer, and D. Colby, "Cascading of Habitat Degradation: Oyster Reefs Invaded by Refugee Fishes Escaping Stress", Ecological Applications, 11, pp. 746-782, 2001.

Lewis, R.R., III, "Impact of Oil Spills on Mangrove Forests", in *Tasks for Vegetation Science*, Teas, H.J., (ed.), Dr. W. Junk Publishers, The Hague, NL, pp. 171-181, 1983.

Lin, Q. and I.A. Mendelssohn, "A Comparative Investigation of the Effects of South Louisiana Crude Oil on the Vegetation of Fresh, Brackish and Salt Marshes", *Marine Pollution Bulletin*, 32:2, pp. 202-209, 1996.

Lin, Q., I.A. Mendelssohn, M.T. Suidan, K. Lee and A.D. Venosa, "The Dose-Response Relationship Between No. 2 Fuel Oil and the Growth of the Salt Marsh Grass, *Spartina alterniflora*" *Marine Pollution Bulletin*, 44, pp. 897–902, 2002.

Livingston, R.J., R.L. Howell, X. Niu, F.G. Lewis, G.C. Woodsum, "Recovery of Oyster Reefs (*Crassostrea virginica*) in a Gulf Estuary Following Disturbance by Two Hurricanes", *Bulletin of Marine Science*, 64, pp.465–483, 1999.

Longwell, A.C. 1977. A Genetic Look at Fish Eggs and Oil. Oceanus 20: 45.

Longwell, A.C. and J.B. Hughes, "Cytologic, Cytogenic, and Developmental State of Atlantic Mackerel Eggs from Sea Surface Water of the New York Bight, and Prospects for Biological Effects Monitoring with Ichthyoplankton", *ICES Journal of Marine Science*, 179, pp. 275-291, 1980.

Lorentsen, S-H. and T. Anker-Nilssen, "Behaviour and Oil Vulnerability of Fulmars *Fulmarus glacialis* During an Oil Spill Experiment in the Norwegian Sea", *Marine Pollution Bulletin*, 26:3, pp.144-146, 1993.

Loughlin, T.R., B.E. Ballachey and B.A. Wright. "Overview of Studies to Determine Injury Caused by the *Exxon Valdez* Oil Spill to Marine Mammals", in *Proceedings of the Exxon Valdez Oil Spill Symposium American Fisheries Society Symposium 18*, American Fisheries Society, Bethesda, MD, pp. 798-808, 1996.

Mackay, D, W.Y. Shiu, K. Hossain, W. Stiver, D. McCurdy and S. Peterson, *Development and Calibration of an Oil Spill Behavior Model*, Report No. CG-D-27-83, U.S. Coast Guard, Research and Development Center, Groton, CT, 83 p., 1982.

Mancini, K.M., *Riparian Ecosystem Creation and Restoration: A Literature Summary*, U.S. Fish and Wildlife Service Biological Report 89:20, 59 p., 1989.

McAuliffe, C.D., "Organism Exposure to Volatile/Soluble Hydrocarbons from Crude Oil Spills – a Field and Laboratory Comparison", in *Proceedings of the 1987 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 275-288, 1987.

McEvan, E.H., N. Aitchison and P.E. Whitehead, "Energy Metabolism of Oiled Muskrats", *Canadian Journal of Zoology*, 52, p.1057, 1974.

Malins, D.C. and H.O. Hodgins, "Petroleum and Marine Fishes: A Review of Uptake, Disposition, and Effects", *Environmental Science & Technology*, 15:11, pp. 1272-1280, 1981.

McGuinness, K.A., "Effects of Oil Spills on Macro-invertebrates of Saltmarshes and Mangrove Forests in Botany Bay, New South Wales, Australia", *Journal of Experimental Marine Biology and Ecology*, 142, pp.121-135, 1990.

McNeill, S. and J.H. Lawton, "Annual Production and Respiration in Animal Populations", *Nature* 225, pp. 472-474, 1970.

Milton, S., P. Lutz, and G. Shigenaka, "Oil Toxicity and Impacts on Sea Turtles", In Shigenaka, G. (ed.), *Oil and Sea Turtles: Biology, Planning, and Response*. National Oceanic and Atmospheric Administration, 116 p., 2003.

Moody, A., *A Review of Oil Effects on Marine Plants*, Report to Environmental Canada #91 05066, Environmental Protection, River Road Environmental Technology Centre, Ottawa, CA, 1990, 30 p. 1990.

Munk, P. and T. Kiørboe, "Feeding Behavior and Swimming Activity of Larval Herring (*Clupea harengus*) in Relation to Density of Copepod Nauplii", *Marine Ecology Progress Series* 24, pp. 15-21, 1985.

National Oceanographic and Atmospheric Administration (NOAA), *Habitat Equivalency Analysis: An Overview*, Policy and Technical Paper Series, No 95-1. Damage Assessment and Restoration Program, NOAA, Silver Spring, MD, 24 p., 1997.

National Research Council (NRC), *Oil in the Sea: Inputs, Fates and Effects*, National Academy Press, Washington, D.C., USA, 1985.

National Research Council (NRC). *Oil in the Sea III: Inputs, Fates and Effects,* National Academy Press, Washington, D.C., USA. 2002.

Neff, J.M., J.W. Anderson, B.A. Cox, R.B. Laughlin, Jr., S.S. Rossi, and H.E. Tatem, "Effects of Petroleum on Survival Respiration, and Growth of Marine Animals", in *Sources, Effects and Sinks of Hydrocarbons in the Aquatic Environment*. American Institute of Biological Sciences, Washington, D.C., pp. 515-539, 1976.

Neff, J.M. and J.W. Anderson, *Response of Marine Animals to Petroleum and Specific Petroleum Hydrocarbons,* Applied Science Publishers Ltd., London and Halsted Press Division, John Wiley & Sons, NY, 177p., 1981.

Newell S.Y., and D. Porter, "Microbial Secondary Production from Salt Marsh-Grass Shoots, and its Known and Potential Fates", in M.P. Weinstein and D.A. Kreeger (eds), *Concepts and Controversies in Tidal Marsh Ecology*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 159-185, 2000.

Odum, E.P., *Fundamentals of Ecology,* W.B. Saunders Co., Philadelphia, PA, 574 p., 1971.

Odum E, and A. de la Cruz, "Particulate Organic Detritus in a Georgia Salt Marsh-Estuarine Ecosystem", in Lauff, G. (ed) *Estuaries*. American Association Advancement Science Publication 83, Washington, DC, pp. 383-388, 1967.

Ohlendorf, H.M., R.W. Risebrough and K. Vermeer, *Exposure of Marine Birds to Environmental Pollutants*, U.S. Fish and Wildlife Service Wildlife Research Report 9, 40 p., 1978.

Owens, E.H. and G.A Sergy, *Field Guide to the Documentation and Description of Oiled Shorelines*, Environmental Technology Centre, Environment Canada, 66 p., 1994.

Pacific Estuarine Research Laboratory (PERL), *A Manual for Assessing Restored and Natural Coastal Wetlands with Examples from Southern California,* California Sea Grant Report No. T-CSGCP-021, La Jolla, CA, 105 p., 1990.

Page, G.W. and H.R. Carter, *Impacts of the 1986 San Joaquin Valley Crude Oil Spill on Marine Birds in Central California,* Special Science Report, Point Reyes Bird Observatory, Stinson Beach, CA, 53 p. 1986.

Page, G.W., H.R. Carter, and R.G. Ford, "Numbers of Seabirds Killed or Debilitated in the 1986 *Apex Houston* Oil Spill in Central California", *Studies in Avian Biology*, 14, pp. 164-174, 1990.

Pauly D., and V. Christensen, "Primary Production Required to Sustain Global Fisheries", *Nature*, 374, pp. 255-257, 1995.

Payne, J.R., B.E. Kirstein, G.D. McNabb, Jr., J.L. Lambach, R. Redding R.E. Jordan, W. Hom, C. deOliveria, G.S. Smith, D.M. Baxter, and R. Gaegel, *Multivariate Analysis of Petroleum Weathering in the Marine Environment – sub Arctic,*

Environmental Assessment of the Alaskan Continental Shelf, OCEAP, Final Report of Principal investigators, Vol. 21 and 22, 690 p., 1984.

Payne, J.R., B.E. Kirstein, J.R. Clayton, Jr., C. Clary, R. Redding, G.D. McNabb, Jr., and G. Farmer, *Integration of Suspended Particulate Matter and Oil Transportation Study*. Final Report, Minerals Management Service, Environmental Studies Branch, Anchorage, AK. Contract No. 14-12-0001-30146, 216 p. 1987.

Peakall, D.B., P.G. Wells and D. Mackay, "A Hazard Assessment of Chemically Dispersed Oil Spills and Seabirds - A Novel Approach", in *Proceedings of the 8th Technical Semi Annual Arctic Marine Oil Spill Program*, Environmental Canada, Edmonton, AB, pp. 78- 90, 1985.

Peterson, C.H., J. Grabowski and S. Powers, "Estimated Enhancement of Fish Production Resulting from Restoring Oyster Reef Habitat: Quantitative Valuation", *Marine Ecology Progress Series*, 264, pp. 249-264, 2003.

Piatt, J.F., C.J. Lensick, W. Butler, M. Kendziorek, and D.R. Nysewander, "Immediate Impact of the *Exxon Valdez* Oil Spill on Marine Birds", *The Auk*, 107, pp. 387-397, 1990.

Pimm, S.L., *Food Webs*. Chapman and Hall, London and NY, 219 p., 1982.

Point Reyes Bird Observatory, *The Impacts of the T/V Puerto Rican Oil Spill on Marine Bird and Mammal Populations in the Gulf of Farallones, 6 19 November 1984*, Special Science Report, Point Reyes Bird Observatory, 70 p. 1985.

Rago, P.J., "Production Foregone: An Alternative Method for Assessing the Consequences of Fish Entrainment and Impingement at Power Plants and Water Intakes", *Ecological Modelling*, 24, pp.79-111, 1984.

Reed, M., D.P. French, J. Calambokidis and J. Cubbage, "Simulation Modelling of the Effects of Oil Spills on Population Dynamics of Northern Fur Seals", *Ecological Modelling*, 49, pp.49-71, 1989.

Reed, M., O. Johansen, P.J. Brandvik, P. Daling, A. Lewis, R. Fiocco, D. Mackay, and R. Prentki, "Oil Spill Modeling Towards the Close of the 20th Century: Overview of the State-of-the-Art", *Spill Science and Technology Bulletin*, 5 :1, pp. 3-16, 1999.

Reed, M., P.S. Daling, O.G. Brakstd, I. Singsaas, L.-G. Faksness, B. Hetland, and N. Efrol, "OSCAR 2000: A Multi-Component 3-Dimensional Oil Spill Contingency and Response Model", in *Proceedings of the 23rd Arctic Marine Oil Spill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, ON, pp. 663-952, 2000.

Research Planning, Inc. (RPI), *Environmental Assessment and Restoration Recommendations for a Mangrove Forest Affected by Jet Fuel, Report to Roosevelt Roads Naval Station, Puerto Rico*, by RPI, Columbia, SC, 1987.

Rice, S.D., J.W. Short and J.F. Karinen, "Comparative Oil Toxicity and Comparative Animal Sensitivity" in *Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms*, D.A. Wolfe (ed.), Pergamon Press, NY, pp. 78-94. 1977.

Rice, S.D., R.B. Spies, D.A. Wolfe and B.A. Wright (eds.) *Proceedings of the Exxon Valdez Oil Spill Symposium, American Fisheries Society Symposium 18*, American Fisheries Society, Bethesda, MD, 931 p., 1996.

Ricker, W.E., "Computation and Interpretation of Biological Statistics of Fish Populations", *Bulletin of Fisheries Research Board of Canada*, 191, p. 382, 1975.

Rolan, R.G. and R. Gallagher, "Recovery of Intertidal Biotic Communities at Sullom Voe Following the *Esso Bernicia* Oil Spill of 1978" in *Proceedings of the 1991 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C API Publ. 4529, pp. 461-465, 1991.

Samuels, W.B. and A. Ladino, "Calculations of Seabird Populations Recovery from Potential Oil Spills in the Mid Atlantic Region of the United States", *Ecological Modelling*, 21, pp.63-84, 1984.

Samuels, W.B. and K.J. Lanfear, "Simulations of Seabird Damage and Recovery from Oil Spills in the Northern Gulf of Alaska", *Journal of Environmental Management*, 15, pp.169-182, 1982.

Santos, A.M.P., RE Pedro, P., A. Dos Santos, and A.Peliz, "Vertical Distribution of the European Sardine (*Sardina pilchardus*) Larvae and Its Implications for Their Survival", *Journal of Plankton Research*, 28, pp. 523-532, 2006.

Seip, K.L., E. Sandersen, F. Mehlum and J. Ryssdel, "Damages to Seabirds from Oil Spills: Comparing Simulation Results and Vulnerability Indexes". *Ecological Modelling*, 53, pp. 39-59, 1991.

Sell, D., L. Conway, T. Clark, G.B. Picken, J.M. Baker, G.M. Dunnet, A.D. Mcintyre, and R.B. Clark, "Scientific Criteria to Optimize Oil Spill Clean Up", in *Proceedings of the 1995 Oil Spill Conference*, American Petroleum Institute, Washington, DC, pp. 595-611, 1995.

Shigenaka, G., *Toxicity of Oil to Reef-Building Corals: A Spill Response Perspective*, NOAA Technical Memorandum, NOAA OR&R 8., National Oceanic and Atmospheric Administration, Office of Response and Restoration (OR&R), Hazardous Materials Response Division, Seattle, Washington, 95 p., 2001.

Shigenaka, G., "Chapter 2. Oil Toxicity", in *Oil Spills in Mangroves: Planning and Response Considerations*, R. Hoff (ed.), National Oceanic and Atmospheric Administration, Office of Response and Restoration (OR&R), 70 p., 2002.

Shigenaka, G. (ed.), *Oil and Sea Turtles: Biology, Planning, and Response*, National Oceanic and Atmospheric Administration, Office of Response and Restoration (OR&R), 116 p., 2003.

Simpson, J.G. and W.G. Gilmartin, "An Investigation of Elephant Seal and Sea Lion Mortality on San Miguel Island", *BioScience*, 20, p. 289, 1970.

Sloan, N.A., *Oil Impacts on Cold-water Marine Resources: A Review Relevant to Parks Canada's Evolving Marine Mandate*, Occasional Paper No. 11, Parks Canada, National Parks, 67 p., 1999.

Slobodkin, L.B., "Ecological Energy Relationships at the Population Level", *American Naturalist*, 95, pp. 213-236, 1960.

Spaulding, M.L., "A State-of-the-Art Review of Oil Spill Trajectory and Fate Modeling", *Oil and Chemical Pollution*, 4, pp. 39-55, 1988.

Spaulding, M.L., S.B. Saila, E. Lorda, H.A. Walker, E.L. Anderson and J.C. Swanson, "Oil Spill Fishery Interaction Modelling: Application to Selected Georges Bank Fish Species", *Estuarine, Coastal and Shelf Science*, 16, pp. 511-541, 1983.

Speich, S.M., D.A. Manuwal and T.R. Wahl, “The Bird/Habitat Oil Index: A Habitat Vulnerability Index Based on Avian Utilization”, *Wildlife Society Bulletin*, 19, pp. 216-221, 1991.

Spies, R.B., S.D. Rice, D.A. Wolfe and B.A. Wright, “The Effects of the *Exxon Valdez* Oil Spill on the Alaskan Coastal Environment”, in *Proceedings of the Exxon Valdez Oil Spill Symposium 18*, American Fisheries Society, Bethesda, MD, pp. 1-16, 1996.

Sprague, J.B., “Measurement of pollutant toxicity to fish. I. Bioassay Methods for Acute Toxicity”, *Water Research*, 3, pp. 793-821, 1969.

Steele, J.H., , *The Structure of Marine Ecosystems*, Harvard Univ. Press, Cambridge, Mass., 128 p., 1974.

Stirling, H.P., “Effects of a Spill of Marine Diesel on the Rocky Shore Fauna of Lamma Island, Hong Kong” *Environmental Pollution*, 12, pp. 93-117, 1977.

Southward, A.J. and E.C. Southward, “Recolonization of Rocky Shores in Cornwall after Use of Toxic Dispersants to Clean Up the Torrey Canyon Spill”, *Journal of the Fisheries Research Board of Canada*, 35, pp. 682-706, 1978.

Swartz, R.C., D.W. Schults, R.J. Ozretich, J.O. Lamberson, F.A. Cole, T.H. DeWitt, M.S. Redmond, and S.P. Ferraro, “ΣPAH: A Model to Predict the Toxicity of Polynuclear Aromatic Hydrocarbon Mixtures in Field-Collected Sediments”, *Environmental Toxicology and Chemistry*, 14(11), pp. 1977-1987, 1995.

Teal, J.M., “Energy Flow in the Salt Marsh Ecosystem of Georgia”, *Ecology*, 43, pp. 614-624, 1962.

Teal, J.M. and R.W. Howarth, “Oil Spill Studies: A Review of Ecological Effects” *Environmental Management*, 8, pp. 27-44, 1984.

Teruhisa, T., M. Nakaoka, Kawai, H., T. Yamamoto, Marine Life Research Group of Takeno, K. Ohwada, “Impacts by Heavy Oil Spill from *Nakhodka* on Inter-tidal Ecosystem in the Sea of Japan: An Approach to Impact Evaluation with Geographical Information System”, *Marine Pollution Bulletin*, 47, pp. 99-104, 2003.

Thayer, G.W., W.J. Kenworthy and M.S. Fonseca, “The Ecology of Eelgrass Meadows of the Atlantic coast: a Community Profile”, *US Fish and Wildlife Service*, FWS/OBS-84/02, 1984.

Thomas, M.L.H., “Comparison of Oiled and Unoiled Intertidal Communities in Chedubucto Bay, Nova Scotia”, *Journal of the Fisheries Research Board of Canada*, 35, pp. 707-716, 1978.

U.S.A., *Summary of Effects of the Exxon Valdez Oil Spill on Natural Resources and Archaeological Resources, March 1991*, Notice of Lodging of United States' Summary, United States District Court, District of Alaska, Civil Action No. A91 082, 19 p., Filed April 8, 1991.

U.S. Environmental Protection Agency (USEPA), *Final Rule, Clean Water Act §316(b), National Pollutant Discharge Elimination System, Final Regulations to Establish Requirements for Cooling Water Intake Structures at Phase II Existing Facilities*, U.S. Environmental Protection Agency, July 2004.

Vargo, S., P. Lutz, D. Odell, E. Van Vleep and G. Bossart. *Final Report: Study of Effects of Oil on Marine Turtles*, Technical Report OCS study MMS 86-0070. Vol. 2, 181 p., 1986.

Varoujean, D.H., D.M. Baltz, B. Allen, D. Power, D.A. Schroeder, and K.M. Kempner, *Seabird-Oil Spill Behavior Study, Vol 1: Executive Summary, Volume 2: Technical Report, Volume 3: Appendices.* Final Report to U.S. Dept. of the Interior, Minerals Management Service, Reston, VA, by Nero and Associates, Inc., Portland, OR, MMS-QN-TE-83-007, NTIS #PB84- 17930, 365 p., 1983.

Whittaker, R.H., *Communities and Ecosystems*. 2nd edition, MacMillan Publishing Co., NY, 385 p., 1975.

Wilhelm, S.I., G. J. Robertson, P. C. Ryan, and D. C. Schneider, "Comparing an Estimate of Seabirds at Risk to a Mortality Estimate from the November 2004 Terra Nova FPSO Oil Spill", *Marine Pollution Bulletin*, 54, pp. 537–544. 2007.

Wolfe, J.L. and R.J. Esher, "Effects of Crude Oil on Swimming Behavior and Survival in the Rice Rat", *Environmental Research*, 26, pp. 486-489, 1981.

Wragg, L.E., "The Effects of DDT and Oil on Muskrats", *Canadian Field Naturalist*, 68, p.11, 1954.

Yamamoto, T., M. Nakaoka, T. Komatsu, H. Kawai, Marine Life Research Group of Takeno, and K. Ohwada, "Impacts by Heavy-Oil Spill from the Russian Tanker *Nakhodka* on Intertidal Ecosystems: Recovery of Animal Community", *Marine Pollution Bulletin*, 47, pp. 91–98, 2003.

Yender, R.A. and A.J. Mearns, "Case studies of spills that threaten sea turtles", In Shigenaka, G. (ed.), *Oil and Sea Turtles: Biology, Planning, and Response*. National Oceanic and Atmospheric Administration, 116 p., 2003.

Zeuthen, E., "Oxygen Uptake as Related to Body Size in Organisms", *Quarterly Review of Biology*, 28, pp. 1-12, 1953.

Zieman, J.C. and R.T. Zieman, *The Ecology of the Seagrass Meadows of the West Coast of Florida: A Community Profile*, U.S. Fish and Wildlife Service Biological Report 85:7.25, 155 p., 1989.

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Attachment B: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Sensitivity Analysis for Trajectory

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ROUGE RIVER 2002 MYSTERY OIL SPILL
SIMAP INJURY REPORT
Appendix B: Sensitivity Analysis for Trajectory
Draft for Trustee Review

Submitted To:
Stephanie Millsap, Contaminants Specialist
U.S. Fish and Wildlife Service
USEPA LLRS
9311 Groh Rd.
Grosse Ile, MI 48138

Submitted By:
Jonathan R. Grant and Timothy J. Reilly
Lighthouse Technical Consultants, Inc.
Deborah French McCay, Jill Rowe, and Eileen Graham
Applied Science Associates, Inc. (ASA)

Pursuant to Requisition/Purchase Number: 314107015A

May 9, 2011

Several variables were assessed to determine which set provided the best trajectory to match the observations of the Rouge River mystery spill. This sensitivity analysis tested the speed of the currents, the advective horizontal dispersion coefficient, and a slow release of a percentage of the total spill (Table B-1). Preliminary runs varying these parameters were used to narrow down to the input assumptions that best fit the observations. Then a final set of simulations were performed for assumptions closest to best fit, to determine the best case and sensitivity to the input assumptions. The currents scaling factor affected the distribution of oil in the rivers at 12 noon on 10 April 2002 when the first overflights were recorded. This component was varied between 1.0 and 1.2. The horizontal dispersion coefficient controls the random horizontal component of the oil's movement and was varied between 1 and 5 m^2/s. Results from runs with horizontal dispersion coefficients of 1 m^2/s to 3 m^2/s are shown below. Runs with higher horizontal coefficients did not distribute the oil sufficiently in the upper part of the Detroit River. The slow release was added to model oil that remained in the Rouge River on 10 April to match observations. For this variable, percentages of 0, 1, and 3 were tested.

From these runs, a base case was chosen that best matched the overflight observations. This required that the run show surface oil throughout the Detroit River with large patched between the top of Grosse Isle and Fighting Island, around the Livingstone Channel and just north of Point Mouille at the mouth of the Detroit River. Additionally, shore oil needed to impact much of the western bank of the Detroit, around Grassy Island as well as much of the Canadian shoreline. This appendix contains the mass balance of oil in the system at 12 noon on 10 April 2002 (Table B-2) and figures of the maximum amount of surface oil (g/m^2) passing through each model grid cell also at 12 noon on 10 April 2002 (Figures B-1 – B-5).

Table B-1. List of scenarios used for sensitivity analysis.

Scenario name	Current scaling factor	Horizontal dispersion coefficient (m^2/sec)	Percent slow release (%)
RR-2PH-FV11-2HA-1PCT	**1.1**	**2**	**1**
Test: Scaling Factor			
RR-2PH-FV10-2HA-1PCT	**1.0**	2	1
RR-2PH-FV12-2HA-1PCT	**1.2**	2	1
Test: Horizontal Coefficient			
RR-2PH-FV11-1HA-1PCT	1.1	**1**	1
RR-2PH-FV11-3HA-1PCT	1.1	**3**	1
Test: Percent Slow Release			
RR-2PH-FV11-2HA-0PCT	1.1	2	**0**
RR-2PH-FV11-2HA-3PCT	1.1	2	**3**

Table B-2. Mass of oil (metric tonnes) on the surface, in the water column, on shore, evaporated, decayed, in the sediment and cleaned (removed) from the system at noon on 10 April 2002.

Scenario	Surface	Water Column	Ashore	Evaporated	Decayed	Sediment
RR-2PH-FV11-2HA-1PCT	**65.91**	**2.57**	**10.95**	**19.42**	**1.00**	**0.14**
Test: Scaling Factor						
RR-2PH-FV10-2HA-1PCT	64.97	2.52	12.13	19.25	1.00	0.12
RR-2PH-FV12-2HA-1PCT	66.76	3.95	9.43	18.70	1.01	0.15
Test: Horizontal Coefficient						
RR-2PH-FV11-1HA-1PCT	67.15	5.16	3.71	22.92	0.96	0.09
RR-2PH-FV11-3HA-1PCT	57.18	0.62	15.39	25.69	0.94	0.18
Test: Percent Slow Release						
RR-2PH-FV11-2HA-0PCT	63.96	2.70	11.37	20.83	0.99	0.15
RR-2PH-FV11-2HA-3PCT	64.41	2.85	11.83	19.76	0.99	0.15

Base Case:

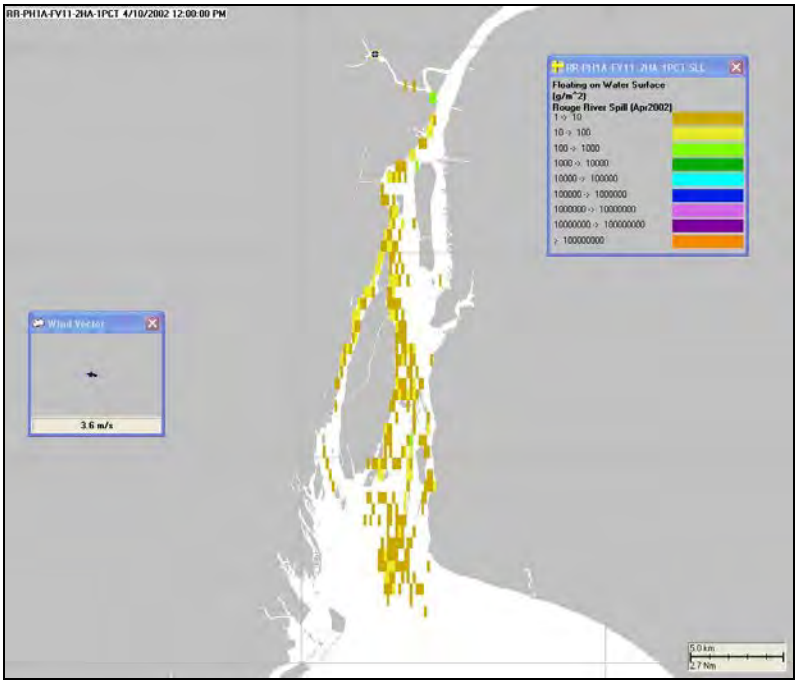

Figure B-1. RR-2PH-FV11-2HA-1PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

Testing the Current Scaling Factor:

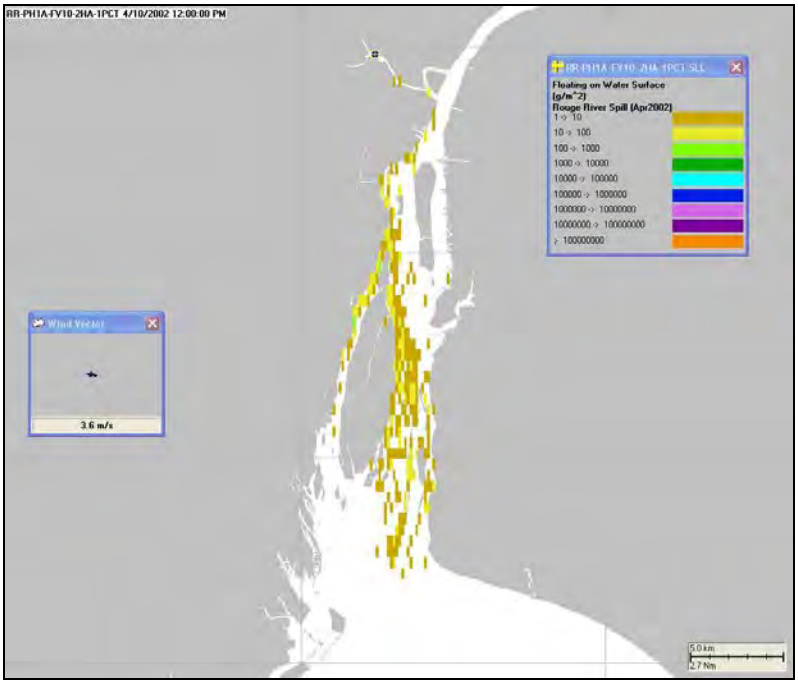

Figure B-2. RR-2PH-FV10-2HA-1PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

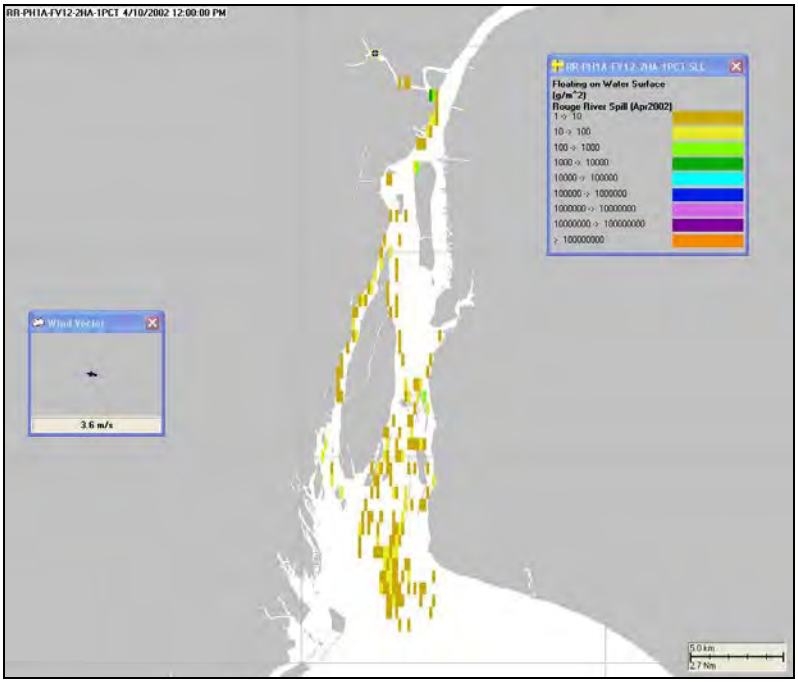

Figure B-3. RR-2PH-FV12-2HA-1PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

Testing the Advective Horizontal Dispersion Coefficient:

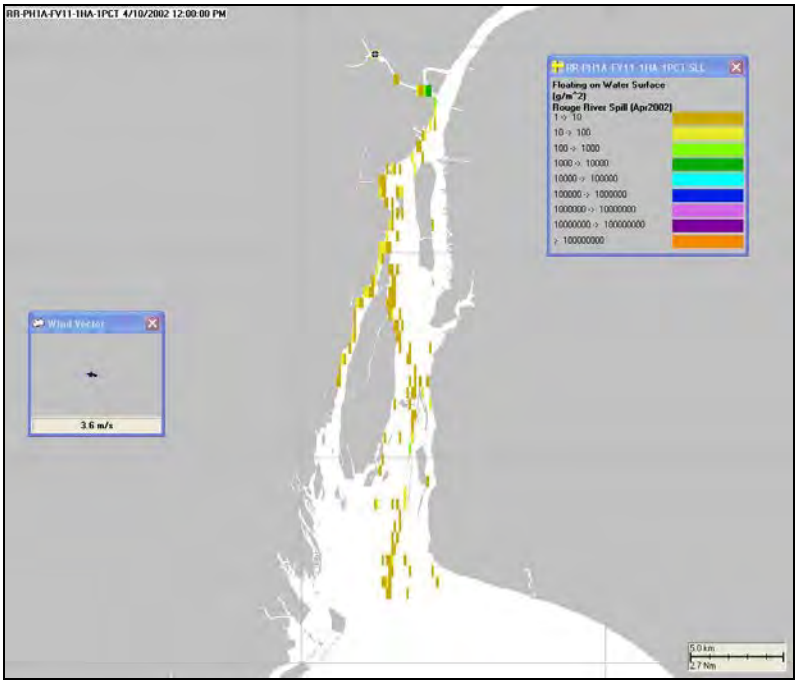

Figure B-4. RR-2PH-FV11-1HA-1PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

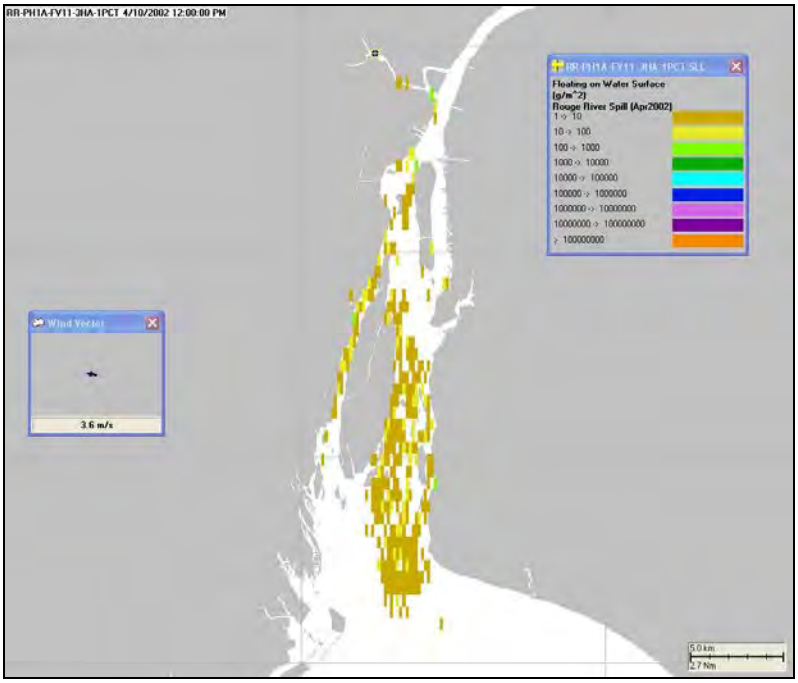

Figure B-5. RR-2PH-FV11-3HA-1PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

Testing the Percent Slow Release:

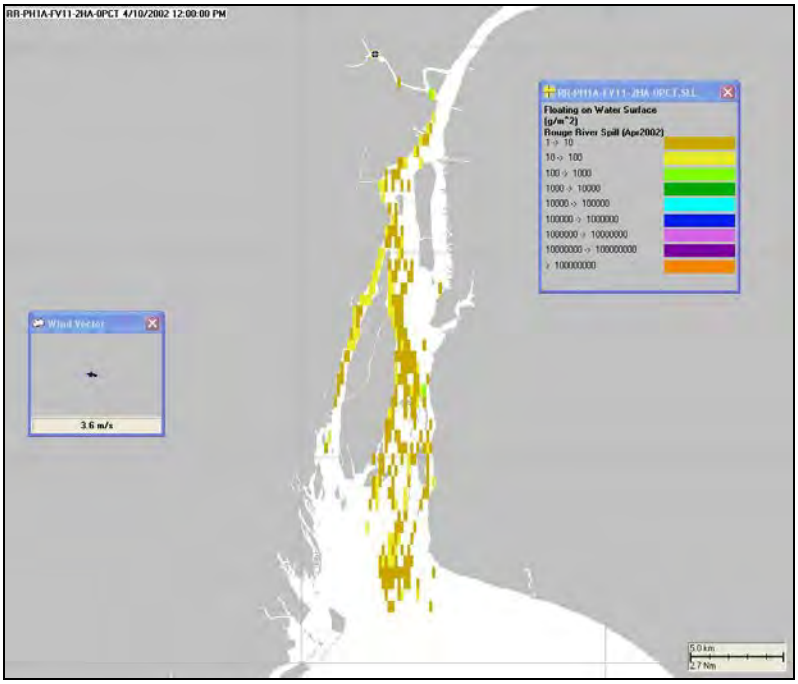

Figure B-6. RR-2PH-FV11-2HA-0PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

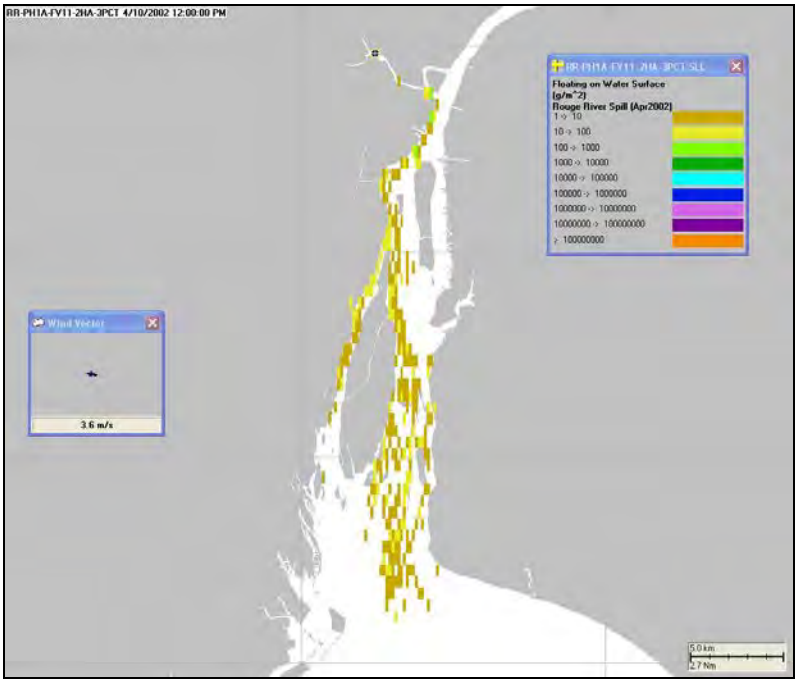

Figure B-7. RR-2PH-FV11-2HA-3PCT: the maximum amount of surface oil (g/m^2) passing through each model grid cell also at noon on 10 April 2002.

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Attachment C: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Fates Model Results

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ROUGE RIVER 2002 MYSTERY OIL SPILL
SIMAP INJURY REPORT
Appendix C: Fates Model Results
Draft for Trustee Review

Submitted To:
Stephanie Millsap, Contaminants Specialist
U.S. Fish and Wildlife Service
USEPA LLRS
9311 Groh Rd.
Grosse Ile, MI 48138

Submitted By:
Jonathan R. Grant and Timothy J. Reilly
Lighthouse Technical Consultants, Inc.
Deborah French McCay, Jill Rowe, and Eileen Graham
Applied Science Associates, Inc. (ASA)

Pursuant to Requisition/Purchase Number: 314107015A

December 20, 2013

C.1 Description of Fate and Mass Balance

This section of Appendix C provides the fates model results for the best simulation of the spill, scenario name "RR-2PH-FV11-2HA-1PCT-1MGrid".

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

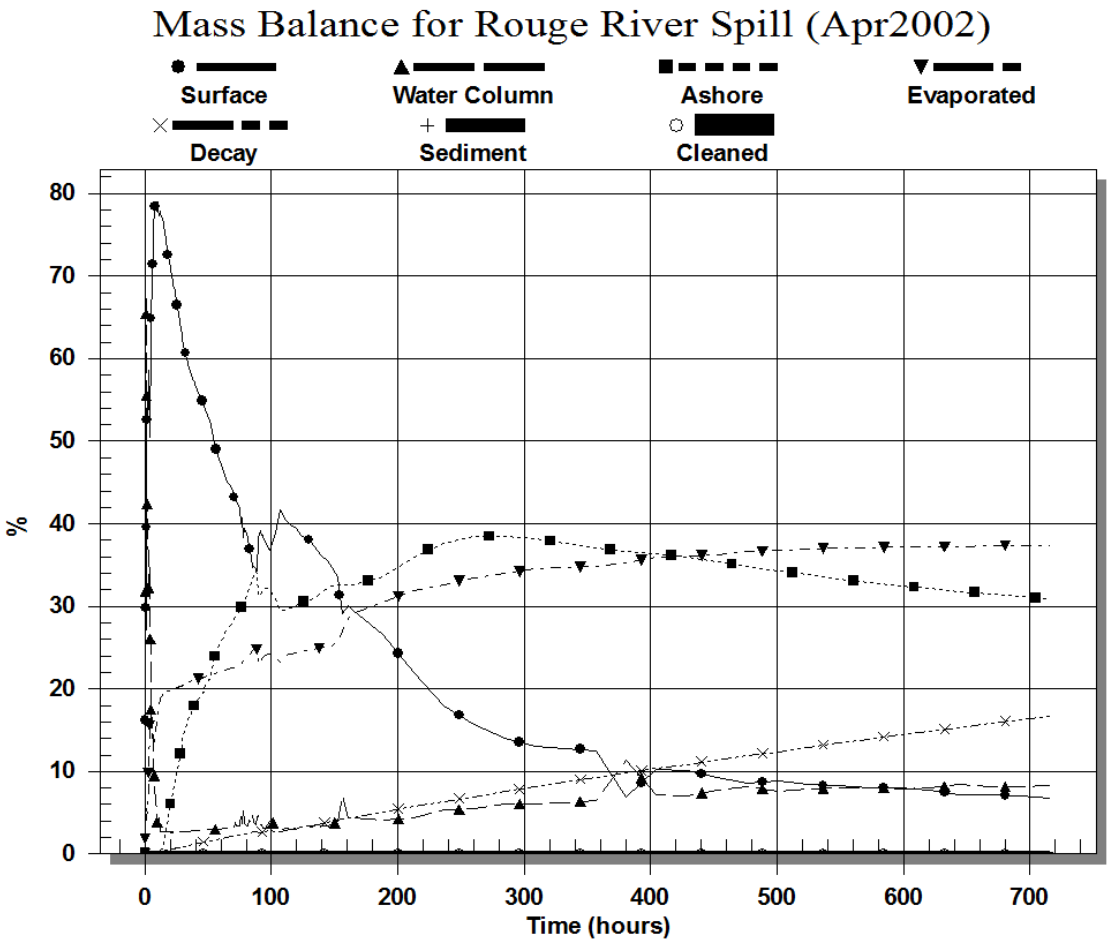

Figure C-1. Over all mass balance of oil versus time after the spill for the base case simulation (RR-2PH-FV11-2HA-1PCT-1MGrid).

Table C-1 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
0.08	0	0	99.9965	0	0	0.0035	1
0.17	74.9914	0.0001	25.0015	0	0	0.0069	1
0.25	34.8367	1.2828	63.6185	0	0.2551	0.0069	1
0.33	48.3782	1.894	49.4837	0	0.2353	0.0089	2
0.42	57.3504	3.4967	38.8896	0	0.251	0.0123	2
0.5	32.3182	3.813	63.6308	0	0.2258	0.0121	2
0.58	37.713	4.2664	57.794	0	0.2126	0.0139	3
0.67	40.6108	5.5733	53.5636	0	0.235	0.0172	3
0.75	38.5554	5.4995	55.7342	0	0.1939	0.017	3
0.83	40.4881	5.9894	53.3205	0	0.1832	0.0188	4
0.92	41.5119	7.1729	51.0921	0	0.2012	0.022	4
1	27.2089	5.4408	67.1889	0	0.1438	0.0175	6
2	53.3292	5.608	40.9617	0	0.072	0.0292	25
3	56.9489	11.3314	31.5783	0	0.0885	0.0531	35
4	50.4675	16.6195	32.7375	0	0.0994	0.0762	43
5	66.7106	17.4371	15.6336	0	0.1186	0.1003	49
6	71.0043	14.4893	14.2943	0	0.1056	0.1066	64
7	75.2067	12.9292	11.6427	0	0.1014	0.1201	79
8	78.1482	14.3683	7.1728	0	0.155	0.1559	79
9	77.8909	15.8123	5.7966	0	0.3093	0.1911	79
10	78.9407	16.9144	3.5883	0	0.331	0.2258	79
11	77.2563	17.7907	4.3443	0	0.3487	0.2601	79
12	77.8099	18.6152	2.8485	0	0.4326	0.2939	79
13	77.2969	19.0394	2.7369	0	0.5994	0.3275	79
14	76.84	19.286	2.715	0	0.7981	0.3609	79
15	76.0725	19.4584	2.7271	0	1.3478	0.3942	79
16	75.2207	19.6026	2.7164	0	2.0329	0.4274	79
17	74.1573	19.705	2.6934	0	2.9838	0.4606	79
18	72.8206	19.7576	2.6726	0	4.2556	0.4936	79
19	71.8944	19.8092	2.6558	0	5.1139	0.5267	79
20	71.0138	19.8518	2.6783	0	5.8967	0.5594	79
21	70.2537	19.8993	2.6673	0	6.5873	0.5924	79
22	69.2831	19.9812	2.6613	0	7.4492	0.6252	79
23	68.5937	20.029	2.6557	0	8.0636	0.658	79
24	67.698	20.0834	2.65	0	8.8778	0.6908	79
25	66.6687	20.1262	2.7198	0	9.7618	0.7235	79
26	65.9983	20.191	2.7149	0	10.3397	0.7562	79
27	65.1573	20.2573	2.7115	0	11.0852	0.7888	79
28	64.3609	20.3312	2.7088	0	11.7775	0.8215	79
29	62.9319	20.3719	2.7019	0	13.1402	0.854	79
30	61.8164	20.408	2.6957	0	14.1934	0.8865	79

Time (hr)	% on Water Surface	% in Atmos-phere	% in Water Column	% in Sediment	% Ashore	% Decayed	% Spilled
31	61.2108	20.4849	2.6874	0	14.698	0.9189	79
32	60.8134	20.556	2.6849	0.0001	14.994	0.9516	79
33	60.0493	20.6402	2.6866	0	15.6398	0.984	79
34	59.2695	20.7261	2.6493	0	16.3385	1.0167	79
35	58.7471	20.8142	2.6508	0	16.7387	1.0493	79
36	58.4127	20.8932	2.6474	0	16.965	1.0818	79
37	57.9879	20.9825	2.8293	0	17.086	1.1143	79
38	57.493	21.0583	2.8225	0	17.4795	1.1468	79
39	57.1234	21.1089	2.8168	0	17.7715	1.1794	79
40	56.5744	21.1472	2.8095	0.0001	18.2565	1.2122	79
41	56.3157	21.1835	2.8049	0	18.451	1.2449	79
42	56.0017	21.2191	2.8021	0.0003	18.6991	1.2776	79
43	55.7012	21.2541	2.7997	0	18.9346	1.3103	79
44	55.3452	21.2891	2.7976	0	19.2254	1.3426	79
45	55.1176	21.3308	2.7956	0	19.3812	1.3749	79
46	54.8054	21.3858	2.7934	0	19.6079	1.4076	79
47	54.3179	21.4362	2.7914	0	20.0147	1.4398	79
48	53.8621	21.4905	2.7898	0	20.3857	1.4719	79
49	53.2231	21.5395	2.9812	0	20.7522	1.5041	79
50	52.799	21.5866	2.9794	0	21.0987	1.5362	79
51	52.6184	21.633	2.9777	0	21.2026	1.5683	79
52	51.9337	21.6845	2.976	0	21.8055	1.6003	79
53	51.1816	21.7362	2.9742	0	22.4756	1.6325	79
54	50.5078	21.7867	2.9727	0	23.0685	1.6644	79
55	49.7687	21.8364	2.9709	0	23.7277	1.6963	79
56	49.2079	21.8849	2.9693	0	24.2096	1.7282	79
57	48.8086	21.947	2.9677	0	24.5166	1.7601	79
58	48.4014	22.0104	2.9656	0	24.8306	1.792	79
59	47.7421	22.0723	2.9544	0	25.4074	1.8238	79
60	47.2305	22.1377	2.9528	0	25.8233	1.8556	79
61	46.7778	22.1981	3.1566	0	25.9802	1.8873	79
62	46.4117	22.2563	3.155	0	26.258	1.919	79
63	45.9205	22.3006	3.1533	0	26.6749	1.9506	79
64	45.4052	22.3328	3.1516	0	27.1281	1.9822	79
65	45.1469	22.3675	3.1499	0	27.3218	2.0139	79
66	44.9761	22.407	3.1479	0	27.4235	2.0455	79
67	44.7803	22.4426	3.1463	0	27.5538	2.077	79
68	44.6021	22.4812	3.1447	0	27.6635	2.1085	79
69	44.3581	22.5244	3.1432	0	27.8344	2.1399	79
70	43.7343	22.5677	3.1415	0	28.3852	2.1713	79
71	42.7274	22.6291	3.7999	0	28.6406	2.203	79
72	42.8395	22.7027	3.3393	0.0084	28.8749	2.2351	79
73	42.5183	22.7732	3.4714	0.0072	28.9623	2.2676	79
74	42.1856	22.817	3.4588	0.006	29.2325	2.3001	79

Time (hr)	% on Water Surface	% in Atmos-phere	% in Water Column	% in Sediment	% Ashore	% Decayed	% Spilled
75	41.9761	22.8602	3.4486	0.0055	29.3771	2.3325	79
76	40.022	22.9725	4.8983	0.0061	29.7361	2.365	79
77	40.6645	23.1815	3.6823	0.0146	30.0598	2.3973	79
78	38.2944	23.42	5.5581	0.0133	30.2846	2.4296	79
79	39.4965	23.6841	3.6688	0.0201	30.668	2.4617	79
80	38.878	23.8147	3.4744	0.0187	31.3195	2.4938	79
81	38.3592	23.9191	3.4331	0.0173	31.7445	2.5258	79
82	37.1018	24.0286	4.1081	0.0159	32.1868	2.5578	79
83	36.7354	24.2254	4.0238	0.0145	32.4102	2.5898	79
84	35.9166	24.4271	4.1728	0.0131	32.8478	2.6216	79
85	34.6726	24.6141	4.741	0.0116	33.3064	2.6534	79
86	34.8173	24.7622	3.9724	0.0101	33.7521	2.6852	79
87	34.6702	24.8509	3.641	0.0086	34.1116	2.7168	79
88	34.5128	24.8983	3.6113	0.0071	34.2223	2.7474	80
89	34.298	24.6798	4.3539	0.0055	33.9165	2.7454	80
90	38.3891	22.9839	4.6678	0.0037	31.3934	2.5613	87
91	39.1093	23.2983	3.585	0.0023	31.4214	2.5831	88
92	38.5675	23.5324	3.5399	0.0009	31.7432	2.6153	88
93	38.557	23.7381	3.1763	0	31.8809	2.6469	88
94	38.112	23.9153	3.164	0	32.1303	2.6775	88
95	37.8546	24.0836	3.1557	0	32.1964	2.7089	88
96	37.4905	24.2611	3.2004	0	32.3078	2.7394	88
97	36.9647	24.4262	3.5913	0	32.2472	2.7698	88
98	36.6448	24.5221	3.544	0	32.4914	2.7969	88
99	36.826	24.343	3.8572	0	32.1884	2.7846	89
100	38.4044	23.8025	3.8742	0	31.197	2.7212	92
101	38.9979	23.9006	3.2921	0	31.0727	2.7359	93
102	38.7141	24.0347	3.2832	0	31.2022	2.765	93
103	38.8167	23.9353	3.3976	0	31.0754	2.7742	94
104	39.6879	23.5103	3.5942	0	30.4683	2.7385	96
105	41.3863	22.9335	3.5187	0	29.4876	2.6732	99
106	41.7701	23.034	3.0896	0	29.4204	2.6853	100
107	41.6787	23.2499	2.8798	0	29.4748	2.7162	100
108	41.3903	23.504	2.8618	0	29.4962	2.747	100
109	41.0347	23.6938	3.0477	0	29.4456	2.7777	100
110	40.7911	23.8303	3.0456	0	29.524	2.8082	100
111	40.5393	23.9952	3.0592	0	29.5668	2.8388	100
112	40.3577	24.0844	3.0485	0	29.6396	2.8692	100
113	40.2347	24.15	3.0437	0	29.6701	2.9007	100
114	40.095	24.2055	3.0409	0	29.7268	2.9311	100
115	39.923	24.2577	3.0395	0	29.8178	2.9614	100
116	39.7876	24.3062	3.0378	0	29.8759	2.9917	100
117	39.6802	24.336	3.033	0	29.9281	3.022	100
118	39.589	24.3708	3.0315	0	29.9558	3.0522	100

Time (hr)	% on Water Surface	% in Atmos-phere	% in Water Column	% in Sediment	% Ashore	% Decayed	% Spilled
119	39.4655	24.3964	3.0278	0	30.0271	3.0824	100
120	39.3859	24.4194	3.0249	0	30.0564	3.1126	100
121	39.2363	24.4431	3.2073	0	29.9698	3.1428	100
122	38.9663	24.4686	3.2049	0	30.1866	3.173	100
123	38.7126	24.4858	3.2023	0	30.3955	3.2031	100
124	38.6148	24.5057	3.2	0	30.4456	3.2332	100
125	38.4963	24.5299	3.1987	0	30.5111	3.2633	100
126	38.3433	24.5516	3.1964	0	30.6146	3.2933	100
127	38.2465	24.5732	3.1945	0	30.6618	3.3234	100
128	38.1921	24.5884	3.191	0.0006	30.673	3.3543	100
129	38.1424	24.6025	3.1886	0	30.6809	3.385	100
130	38.0803	24.6167	3.1862	0	30.7012	3.4149	100
131	37.9123	24.6512	3.19	0	30.8009	3.4449	100
132	37.8135	24.6867	3.1909	0	30.8332	3.4749	100
133	37.5569	24.7312	3.4632	0	30.7432	3.5048	100
134	37.4743	24.7768	3.4032	0	30.8104	3.5347	100
135	37.0914	24.8241	3.4943	0	31.025	3.5645	100
136	36.7863	24.8701	3.544	0	31.2045	3.5943	100
137	36.5474	24.9158	3.5843	0	31.3276	3.6241	100
138	36.5114	24.9518	3.4612	0	31.4211	3.6539	100
139	36.2831	24.9852	3.4289	0	31.6186	3.6836	100
140	36.0895	25.0173	3.4099	0.0028	31.7661	3.7138	100
141	35.9139	25.0445	3.4027	0.0014	31.8919	3.7449	100
142	35.7924	25.07	3.3973	0	31.9635	3.776	100
143	35.6649	25.101	3.3989	0	32.0289	3.8056	100
144	35.4847	25.1296	3.3945	0	32.1553	3.8352	100
145	35.2076	25.157	3.5583	0	32.2115	3.8649	100
146	35.0374	25.1844	3.5556	0	32.3272	3.8946	100
147	34.8638	25.2184	3.5652	0	32.4278	3.9242	100
148	34.7121	25.2548	3.5714	0	32.5074	3.9537	100
149	32.977	25.3085	5.1318	0	32.5989	3.9831	100
150	33.3165	25.412	4.6467	0	32.6116	4.0126	100
151	33.12	25.5579	4.6428	0	32.6366	4.042	100
152	33.5219	25.7118	4.0486	0	32.6457	4.0713	100
153	32.1983	25.8998	5.1238	0	32.6768	4.1005	100
154	31.6209	26.2087	5.358	0	32.6819	4.1298	100
155	32.2894	26.5316	4.3416	0	32.6776	4.159	100
156	29.3829	26.8646	6.8938	0	32.6703	4.1878	100
157	27.8687	27.3311	7.8899	0	32.6933	4.2164	100
158	27.543	27.7674	7.8865	0	32.5576	4.2448	100
159	29.192	28.1663	5.7781	0	32.59	4.273	100
160	30.2406	28.4397	4.4149	0.0024	32.5995	4.3021	100
161	29.8698	28.6348	4.5491	0.0009	32.6132	4.3316	100
162	29.6688	28.8101	4.5465	0	32.6135	4.3604	100

Time (hr)	% on Water Surface	% in Atmos-phere	% in Water Column	% in Sediment	% Ashore	% Decayed	% Spilled
163	29.8231	28.9445	4.2092	0	32.6344	4.3882	100
164	29.3814	29.054	4.4972	0	32.6509	4.4159	100
165	29.5496	29.1544	4.1772	0.0004	32.6727	4.445	100
166	29.5178	29.2202	4.0905	0	32.6977	4.473	100
167	29.4915	29.2627	4.02	0	32.7245	4.5007	100
168	29.445	29.2915	3.977	0	32.7575	4.5282	100
174	27.5661	29.5278	5.3824	0	32.8273	4.6957	100
180	27.4794	30.3234	4.069	0	33.2683	4.8593	100
186	26.8676	30.5063	4.1169	0	33.4855	5.023	100
192	25.4197	30.6642	4.8248	0	33.901	5.1896	100
198	22.7883	31.1716	6.3951	0	34.2921	5.3523	100
204	22.0235	31.6676	5.6944	0	35.0982	5.5155	100
210	22.0376	31.8929	4.5	0	35.8972	5.6716	100
216	21.6272	31.9354	4.3622	0	36.2443	5.8302	100
222	21.1482	31.9889	4.5319	0	36.3454	5.9849	100
228	17.3639	32.2935	7.1585	0	37.0448	6.1386	100
234	18.1924	32.6225	5.3852	0	37.5083	6.2909	100
240	15.7144	32.9021	7.0788	0	37.8617	6.4422	100
246	16.3555	33.1124	6.0848	0	37.854	6.5927	100
252	16.7954	33.3118	5.0557	0	38.0945	6.7419	100
258	15.8218	33.4394	5.5544	0	38.2932	6.8906	100
264	13.7025	33.5502	7.0766	0	38.6305	7.0395	100
270	14.9833	33.6618	5.6359	0	38.5316	7.1866	100
276	14.4242	33.7869	5.8064	0	38.6487	7.3331	100
282	12.6884	33.9313	7.4192	0	38.4815	7.4789	100
288	12.8869	34.0534	7.0007	0	38.4342	7.6242	100
294	13.2562	34.1436	6.6292	0	38.2018	7.7686	100
300	13.2139	34.2983	6.3293	0	38.2474	7.9104	100
306	12.3503	34.4515	6.9779	0	38.1661	8.0535	100
312	13.2439	34.5225	5.8709	0	38.1661	8.1958	100
318	13.1226	34.5637	5.989	0	37.9846	8.3394	100
324	12.6844	34.6133	6.287	0	37.9337	8.4808	100
330	12.7948	34.6619	6.2261	0	37.694	8.6225	100
336	12.8011	34.686	6.1437	0	37.6054	8.7631	100
360	12.4679	34.8101	6.4267	0	36.973	9.3216	100
384	10.1517	35.341	7.8721	0	36.7628	9.8717	100
408	10.2872	35.9765	6.9584	0	36.3652	10.412	100
432	10.0477	36.0878	7.0669	0	35.8565	10.9404	100
456	9.6032	36.3071	7.3337	0	35.2932	11.462	100
480	8.903	36.638	7.7165	0	34.7662	11.9757	100
504	8.8439	36.7574	7.6669	0	34.2491	12.4819	100
528	8.5353	36.9393	7.7558	0	33.7875	12.9815	100
552	8.2857	37.0214	7.9308	0	33.2865	13.4749	100
576	7.7017	37.1336	8.3363	0	32.8652	13.9624	100
600	7.9703	37.1757	7.934	0	32.475	14.4443	100

Time (hr)	% on Water Surface	% in Atmos-phere	% in Water Column	% in Sediment	% Ashore	% Decayed	% Spilled
624	7.7572	37.2192	7.9966	0	32.1038	14.9226	100
648	7.3735	37.2812	8.1296	0	31.8212	15.3938	100
672	7.1648	37.3213	8.1225	0	31.531	15.8597	100
696	6.8708	37.3634	8.3148	0	31.1298	16.3206	100
720	6.7813	37.4051	8.207	0	30.8295	16.7764	100

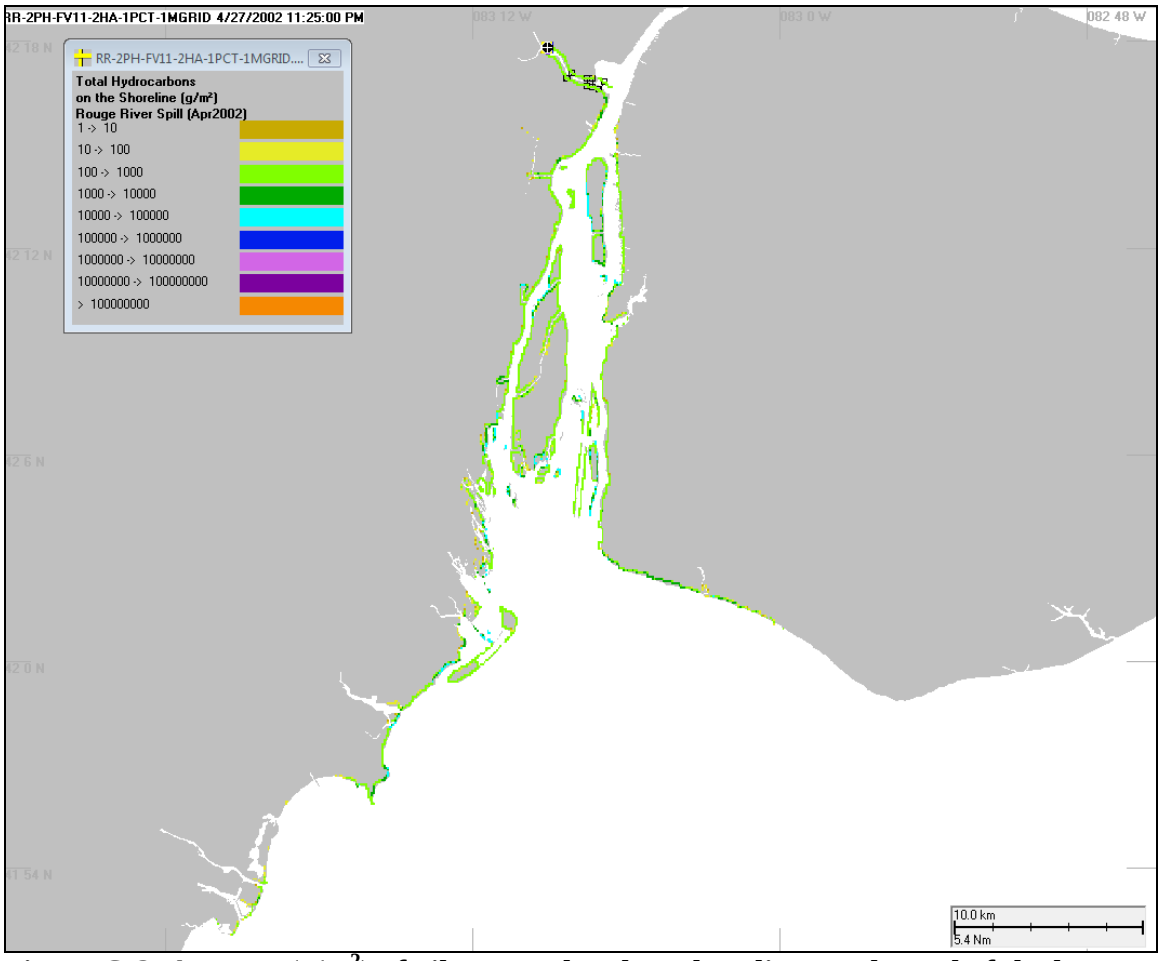

Figure C-2. Amount (g/m^2) of oil accumulated on shorelines at the end of the base case simulation (RR-2PH-FV11-2HA-1PCT-1MGrid), as mass of total hydrocarbons per unit area (averaged in each habitat grid cell).

C.2 Shoreline Oiling

Tables C-3 to C-8 provide the shoreline oiling results for the base case (RR-2PH-FV11-2HA-1PCT) and the other scenarios run as a sensitivity analysis (Table C-2). The width of oiling all of the shore types is assumed to be 1 meter; therefore, in each of these cases, the length (m) of shore oiled is equal to the area (m^2) of shore oiled.

Table C-2. List of scenarios used for sensitivity analysis of shoreline oiling.

Scenario name	Description
RR-2PH-FV11-2HA-1PCT-1MGrid	**Base case**
RR-2PH-FV11-2HA-0PCT-1MGrid	Base case with 0% slow release
RR-2PH-FV11-2HA-3PCT-1MGrid	Base case with 3% slow release
RR-2PH-FV11-2HA-1PCT-10MO-1MGrid	Base case with 10% water in oil when fully emulsified as mousse
RR-2PH-FV11-2HA-1PCT-60MO-1MGrid	Base case with 60% water in oil when fully emulsified as mousse

Table C-3. Base scenario : RR-2PH-FV11-2HA-1PCT-1MGrid - Area (m^2) of shoreline oiled by shore type with average thickness of oil greater than thresholds specific to impacts on animals (0.1 mm) and vegetation (1mm).

Shore Type	Area (m^2) > threshold for animals (0.1 mm)	Area (m^2) > threshold for vegetation (1 mm)
Rocky shoreline	6,132	3,066
Gravel beach	8,775	1,692
Sand beach	12,476	3,912
Mud shore	40,386	26,959
Fringing marsh	10,150	5,498
Artificial shoreline	0	0
Total shoreline	**77,919**	**41,127**

Table C-3. Base scenario : RR-2PH-FV11-2HA-1PCT-1MGrid - Total area (m^2) oiled at any time using a thickness threshold greater than 0.01 mm.

Shore Type	Area (m^2) > threshold of 0.01 mm
Marsh/wetland	2,276,577
Mud flats	134,171
Total	**2,410,748**

Table C-4. Scenario : RR-2PH-FV11-2HA-0PCT-1MGrid - Area (m^2) of shoreline oiled by shore type with average thickness of oil greater than thresholds specific to impacts on animals (0.1 mm) and vegetation (1mm).

Shore Type	Area (m^2) > threshold for animals (0.1 mm)	Area (m^2) > threshold for vegetation (1 mm)
Rocky shoreline	6,026	3,383
Gravel beach	9,727	2,220
Sand beach	11,207	4,335
Mud shore	9,198	5,075
Fringing marsh	40,915	28,757
Artificial shoreline	-	-
Total shoreline	**77,073**	**43,770**

Table C-5. Scenario : RR-2PH-FV11-2HA-0PCT-1MGrid - Total area (m^2) oiled at any time using a thickness threshold greater than 0.01 mm.

Shore Type	Area (m^2) > threshold of 0.01 mm
Marsh/wetland	2,247,025
Mud flats	153,597
Total	**2,400,622**

Table C-6. Scenario : RR-2PH-FV11-2HA-3PCT-1MGrid - Area (m^2) of shoreline oiled by shore type with average thickness of oil greater than thresholds specific to impacts on animals (0.1 mm) and vegetation (1mm).

Shore Type	Area (m^2) > threshold for animals (0.1 mm)	Area (m^2) > threshold for vegetation (1 mm)
Rocky shoreline	5,921	3,172
Gravel beach	10,784	2,115
Sand beach	12,687	3,912
Mud shore	9,410	4,969
Fringing marsh	41,338	28,228
Artificial shoreline	-	-
Total shoreline	**80,140**	**42,396**

Table C-7. Scenario : RR-2PH-FV11-2HA-3PCT-1MGrid - Total area (m^2) oiled at any time using a thickness threshold greater than 0.01 mm.

Shore Type	Area (m^2) > threshold of 0.01 mm
Marsh/wetland	2,296,514
Mud flats	148,581
Total	**2,445,095**

Table C-8. Scenario : RR-2PH-FV11-2HA-1PCT-10MO-1MGrid - Area (m^2) of shoreline oiled by shore type with average thickness of oil greater than thresholds specific to impacts on animals (0.1 mm) and vegetation (1mm).

Shore Type	Area (m^2) > threshold for animals (0.1 mm)	Area (m^2) > threshold for vegetation (1 mm)
Rocky shoreline	5,180	2,960
Gravel beach	5,392	1,692
Sand beach	9,304	2,643
Mud shore	8,987	5,075
Fringing marsh	37,214	25,902
Artificial shoreline	-	-
Total shoreline	**66,077**	**38,272**

Table C-9. Scenario : RR-2PH-FV11-2HA-1PCT-10MO-1MGrid - Total area (m^2) oiled at any time using a thickness threshold of greater than 0.01 mm.

Shore Type	Area (m^2) > threshold of 0.01 mm
Marsh/wetland	2,031,155
Mud flats	101,255
Total	**2,132,410**

Table C-10. Scenario : RR-2PH-FV11-2HA-1PCT-60MO -1MGrid - Area (m^2) of shoreline oiled by shore type with average thickness of oil greater than thresholds specific to impacts on animals (0.1 mm) and vegetation (1mm).

Shore Type	Area (m^2) > threshold for animals (0.1 mm)	Area (m^2) > threshold for vegetation (1 mm)
Rocky shoreline	7,506	2,855
Gravel beach	11,841	1,798
Sand beach	14,484	2,960
Mud shore	13,110	6,026
Fringing marsh	48,633	29,814
Artificial shoreline	-	-
Total shoreline	**95,574**	**43,453**

Table C-11. Scenario : RR-2PH-FV11-2HA-1PCT-60MO-1MGrid - Total area (m^2) oiled at any time using a thickness threshold of greater than 0.01 mm.

Shore Type	Area (m^2) > threshold of 0.01 mm
Marsh/wetland	2,545,406
Mud flats	300,596
Total	**2,846,002**

C.3 Model Output Description

The following text describes the model output that can be viewed in the *.avi files provided on CD.

The “Rouge_trajectory.avi” file shows 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 (Section 3.1 of main report) defines the actual shoreline to the model

The “Rouge_THC-max.avi” shows the concentrations of total hydrocarbons (oil) in the water column over time. The animated movie shows the vertical maximum concentration on any given time step.

The “Rouge_float-oil.avi” file shows the maximum amount of surface oil (g/m^2) passing through each model grid cell.

The “Rouge_diss-arom.avi” file shows the maximum concentration (ppb) of dissolved aromatics passing through each model grid cell.

Attachment D: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Biological Data

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ROUGE RIVER 2002 MYSTERY OIL SPILL
SIMAP INJURY REPORT
Appendix D: Biological Data
Draft for Trustee Review

Submitted To:
Stephanie Millsap, Contaminants Specialist
U.S. Fish and Wildlife Service
USEPA LLRS
9311 Groh Rd.
Grosse Ile, MI 48138

Submitted By:
Jonathan R. Grant and Timothy J. Reilly
Lighthouse Technical Consultants, Inc.
Deborah French McCay, Jill Rowe, and Eileen Graham
Applied Science Associates, Inc. (ASA)

Pursuant to Requisition/Purchase Number: 314107015A

May 9, 2011

D.1 Wildlife Abundance

Spring bird densities were based on Pointe Mouillee spring shorebird survey data. This survey counts all birds found within the Pointe Mouillee Wildlife Refuge and State Game Area on at least a bimonthly schedule (Robison, 2009). Additional bird density data from the Ohio Division of Wildlife (ODW) Aerial Waterfowl Survey provided a means to estimate the ratio of bird densities in open waters, as opposed to the protected waters of Pointe Mouillee (Figure D-1). For the ODW survey, one transect was in western Lake Erie, from the mouth of the Maumee River to West Sister Island. This survey, which is only conducted through March, counts all birds observed over approximately 8.7 square miles (22.5 km^2) of open water (Witt, 2009). March open water abundances were averaged over years 2000-2006. The Pointe Mouillee Shorebird Survey data were used in the modeling for waterfowl and grebes; however, the data were corrected using the ratio of Pointe Mouillee Survey data averaged for the month of April from 2002-2008 to the March data of the ODW Aerial Waterfowl Survey. Three species were found in both datasets and had the following ratios: American black duck = 15.17, canvasback = 100.91 and mallard = 327.04. The average ratio derived from these species was 148, and the Pointe Mouillee density estimates were divided by 148 and applied to all waters < 1m deep in the model grid (i.e., covering the Rouge River, Detroit River and Lake Erie).

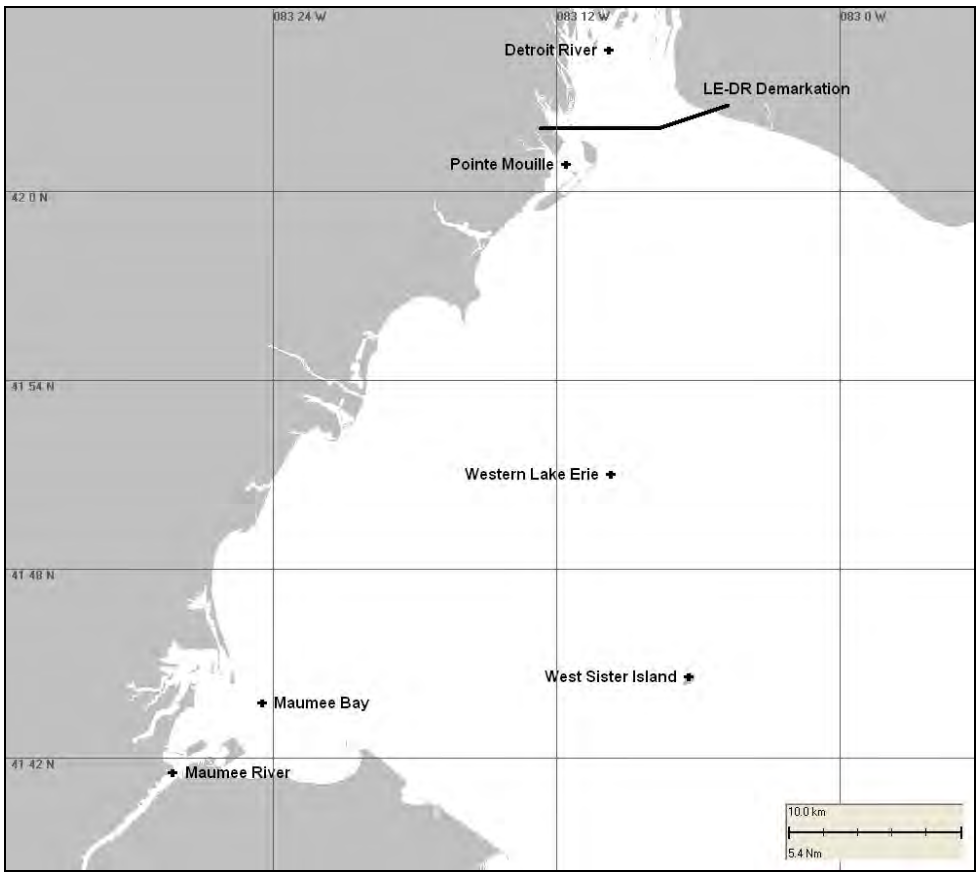

Figure D-1. Bird survey locations in Western Lake Erie. The solid black line marks the delineation between the Detroit River and Lake Erie.

When comparing the Pt. Mouillee Shorebird Survey to the open water western Lake Erie survey, mergansers and scaups were found in approximately equal densities in both open water near shore and marshes. Therefore, the observed densities from the Pt. Mouillee Survey were used, uncorrected, for mergansers in <1m deep waters of Detroit River and Lake Erie and for scaups in 1-3 deep waters of Lake Erie.

Abundance data from Stapanian and Waite (2003) were used for cormorants, Bonaparte's gulls, herring gulls and ring-billed gulls. This survey counted birds along 31 established transects in four habitats in western Lake Erie, including offshore of waterbird refuges, offshore of beaches with human development, on reefs and shoals, and in open water. Mean abundances for the open water and developed shorelines were used for these species in the modeling. For terns and the other gull species not included in Stapanian and Waite (2003), the Pointe Mouillee Shorebird Survey data were used and corrected using a ratio of counted gull and cormorant species based on the Pointe Mouillee Shorebird Survey to the Stapanian and Waite (2003) survey for open water and developed shorelines. The four species found in both data sets that were used to create the ratio for gulls and cormorants were Bonaparte's gull, herring gull, ring-billed gull, and double-crested cormorant. The ratio derived from the data for these species was 29.

The Pointe Mouillee Shorebird Survey data were used for wading birds and shorebirds, which use wetlands and shorelines only. No correction factor was used on the data for these species.

Herpetological data was contracted from the Detroit River Herpetological Survey (Mifsud, pers. comm.). These data had previously been summarized in a report to the U.S. Fish and Wildlife Service (Mifsud, 2006). Data from the 15 sites surveyed south of the Rouge River were averaged and input for spring months. These data are only an estimate as surveys were performed throughout the spring and summer months, these species are notoriously shy, and their activity, and thus ability to be detected, is greatly affected by the weather conditions (Mifsud, 2009). These data were applied to the wetlands portions of the habitat grid.

Muskrat densities included in the model were from the NRDAM/GLE and input for spring months (Tori, 1989). These data was applied to the wetlands portions of the habitat grid.

Table D-1 provides the wildlife density data that were used in the model, based on the assumptions outlined above.

Table D-1. Wildlife density data (#/km^2) used in the model for the Rouge River, Detroit River and Lake Erie using an average of 2002-2008 April data from the Pointe Mouillee Survey.

Species Name:	Abundances (#/km^2) in Detroit River and Lake Erie	Abundances (#/km^2) in Rouge River
American black duck	0.01	0
American coot	1.11	1.11
American widgeon	0.08	0.08
Blue-winged teal	0.04	0.04
Bufflehead	0.04	0.04

Species Name:	Abundances (#/km^2) in Detroit River and Lake Erie	Abundances (#/km^2) in Rouge River
Canada goose	0.12	0.12
Canvasback	0.05	0.05
Common goldeneye	0.002	0.002
Common loon	0.001	0
Eurasian Wigeon	0.0004	0.0004
Gadwall	0.33	0.33
Green-winged teal	0.42	0.42
Horned grebe	0.002	0.002
Long-tailed duck	0.0001	0
Mallard	0.06	0.06
Red-breasted merganser	1.41	0
Common merganser	1.74	0
Hooded merganser	0.28	0
Northern pintail	0.10	0.10
Northern shoveler	0.07	0.07
Pied-billed grebe	0.02	0.02
Redhead	0.13	0.13
Ring-necked duck	0.06	0.06
Ruddy duck	0.17	0.17
Surf scoter	0.0001	0
Scaup, greater*	45.4	0
Scaup, lesser*	55.6	0
Scaup spp. (unidentified)*	3.16	0
Mute swan	0.07	0.07
Tundra swan	0.0002	0.0002
Wood duck	0.0002	0
Bonapartes gull	0.43	0.43
Caspian tern	0.06	0.06
Doublecrested cormorant	0.60	0.60
Forsters tern	0.05	0.05
Glaucous gull	0.001	0.001
Great black-back gull	0.004	0.004
Herring gull	0.47	0.47
Lesser black-back gull	0.001	0.001
Ring-billed gull	0.21	0.21
American bittern	0.01	0
Black-crowned heron	0.29	0
Common moorhen	0.09	0
Great blue heron	1.73	0
Great egret	1.19	0
Green heron	0.01	0
Sandhill crane	0.03	0
Sora	0.19	0
Virginia rail	0.05	0
American avocet	0.21	0
Black-necked stilt	0.01	0

Species Name:	Abundances (#/km^2) in Detroit River and Lake Erie	Abundances (#/km^2) in Rouge River
Common snipe	1.32	0
Dunlin	10.6	0
Greater yellowlegs	1.21	0
Killdeer	1.25	0
Least sandpiper	0.03	0
Lesser yellowlegs	2.28	0
Long-bill dowitcher	0.05	0
Pectoral sandpiper	3.00	0
Semipalmated plover	0.01	0
Short-bill dowitcher	0.02	0
Solitary sandpiper	0.01	0
Spotted sandpiper	0.07	0
Willet	0.23	0
Wilsons snipe	0.21	0
Muskrat	108.00	0
Black rat snake	0.03	0
Blandings turtle	0.54	0
Butlers garter snake	1.88	0
Eastern fox snake	1.48	0
Eastern garter snake	4.56	0
Eastern spiny softshell	0.40	0
Map turtle	18.15	0
Midland paint turtle	15.50	0
Northern brown snake	0.84	0
Northern water snake	1.74	0
Red-ear slider turtle	0.40	0
Snapping turtle	3.09	0
American toad	4.73	0
Bullfrog	4.33	0
Gray tree frog	0.10	0
Green frog	2.82	0
Leopard frog	14.96	0
Western chorus frog	0.13	0
Wood frog	0.07	0
Total scaups	104.2	0
Total waterfowl (other than scaups)	6.3	2.9
Total seabirds	1.8	1.8
Total waders and shorebirds	20.5	0
Total mammals	108.0	0
Total reptiles	48.61	0
Total amphibians	27.14	0

D.2 Wildlife Behaviors

The various wildlife behavior groups were applied to specific sections of the littoral/limnetic habitat grid, as shown in Figure 3-1 of the main SIMAP Injury report. All waterfowl (dabblers, coots, diving ducks, and grebes) were applied to littoral waters and structured/wetland habitats. Aerial seabirds, such as cormorants, gulls and terns, were applied to all waters. Waders (herons, etc.), shorebirds (yellowlegs, sandpipers, etc.), reptiles and amphibians, were applied to all structured/wetland habitats. The lack of structured/wetland habitats in the Rouge River due to grid resolution precluded waders, shorebirds, reptiles and amphibians from injury within this region. The probabilities of oiling were based on analyses built into the SIMAP model, as described in the SIMAP Injury report and French McCay (2009).

After applying species based on behavior group, further assumptions were made taking shoreline development into account. A correction was made for species that were assumed to not occur within the Rouge River due to its heavily developed shoreline. Species removed from the Rouge River, and therefore applied to only appropriate habitat types in the Detroit River and Lake Erie, were the American black duck, mergansers, scoters, loons, long-tailed duck and wood duck. Another correction was made for two species of scaup, which were assumed to only be found within Lake Erie and not in either the Rouge or Detroit Rivers.

D.3 Wildlife Life History

Table D-2 provides the wildlife life history data that were used in the model. Data for bird species and muskrat are from the NRDAM/GLE database. Frog and toad data are based on life history values for the American bullfrog and Northern leopard frog (Hine et al. 1981; Duellman and Trueb, 1994; Smith and Keinath 2007; Myers et al. 2008). Turtle life history is based on the Common map turtle and the Painted turtle in Michigan (Ernst et al., 1994). Snake life history is based on Eastern garter snake and Northern water snake life histories (Harding, 1997; Brown and Weatherhead 1999; Myers et al. 2008)

Table D-2. Wildlife life history parameters used in the model.
(M = natural mortality, H = hunting mortality, YrRepr = age of reproduction, Life = max.age (yrs), MoHat = mo. hatched, MoFlg = age (mo.) fledged, F-Hat = #hatched/adult, F-Flg = #fledged/adult, AveKg = ave. wt in kg)

Species Name	M-1yr	M>1yr	H-1yr	H>1yr	YrRepr	Life	MoHat	MoFlg	F-Hat	F-Flg	AveKg
American black duck	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
American coot	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
American widgeon	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Blue-winged teal	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Bufflehead	0.73	0.62	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Canada goose	0.55	0.35	0.47	0.16	3	20	6	2	1.7	1.4	5
Canvasback	0.73	0.62	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Common goldeneye	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1

Species Name	M-1yr	M>1yr	H-1yr	H>1yr	YrRepr	Life	MoHat	MoFlg	F-Hat	F-Flg	AveKg
Common merganser	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Dabblers	0	0	0	0	1	1	5	5	0	0	0
Diving ducks	0	0	0	0	1	1	5	5	0	0	0
Gadwall	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Greater scaup	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Green-winged teal	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Hooded merganser	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Horned grebe	0.24	0.11	0	0	2	24	6	2	1.3	1	0.4
Lesser scaup	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Mallard	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Mute swan	0.15	0.15	0	0	3	25	6	2	0.6	0.5	6.7
Northern pintail	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Northern shoveler	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Pied-billed grebe	0.24	0.11	0	0	2	24	6	2	1.3	1	0.4
Red-breast merganser	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Redhead	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Ring-necked duck	0.73	0.62	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Ruddy duck	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Scaup	0.73	0.42	0.36	0.22	2	15	6	2	1.5	1.3	1.1
Wood duck	0.65	0.4	0.33	0.2	1	10	6	2	2.1	1.2	0.8
Bonapartes gull	0.33	0.1	0	0	4	15	6	1	1.17	0.75	1.1
Caspian tern	0.52	0.14	0	0	3	25	6	1	0.89	0.37	0.16
Doublecrested cormorant	0.24	0.16	0	0	3	23	6	2	1.37	0.79	2
Forsters tern	0.52	0.14	0	0	3	25	6	1	0.89	0.37	0.16
Great black-back gull	0.33	0.1	0	0	4	15	6	1	1.17	0.75	1.1
Herring gull	0.33	0.1	0	0	4	15	6	1	1.17	0.75	1.1
Ring-billed gull	0.33	0.1	0	0	4	15	6	1	1.17	0.75	1.1
Black-crowned heron	0.68	0.34	0	0	2	17	5	2	1.59	0.84	1.3
Great blue heron	0.68	0.34	0	0	2	17	5	2	1.59	0.84	1.3
Great egret	0.68	0.34	0	0	2	17	5	2	1.59	0.84	1.3
Sora	0.68	0.34	0	0	2	17	5	2	4.5	2.3	1.3
American avocet	0.38	0.09	0	0	3	15	5	1	1.75	0.9	0.1
Common snipe	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Dunlin	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Greater yellowlegs	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Killdeer	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Lesser yellowlegs	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03

Species Name	M-1yr	M>1yr	H-1yr	H>1yr	YrRepr	Life	MoHat	MoFlg	F-Hat	F-Flg	AveKg
Pectoral sandpiper	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Willet	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Wilsons snipe	0.53	0.2	0	0	1	8	5	1	1.8	0.87	0.03
Muskrat	0.71	0.75	0.63	0.48	1	10	6	1	7.5	4.9	1.2
Black rat snake	0.6	0.5	0	0	2	8	8	0	20	0	0.15
Blandings turtle	0.81	0.24	0	0	8	20	8	0	20	0	0.35
Butlers garter snake	0.6	0.5	0	0	2	8	8	0	20	0	0.15
Eastern fox snake	0.6	0.5	0	0	2	8	8	0	20	0	0.15
Eastern garter snake	0.6	0.5	0	0	2	8	8	0	20	0	0.15
Eastern spiny softshell	0.81	0.24	0	0	8	20	8	0	20	0	0.35
Map turtle	0.81	0.24	0	0	14	20	8	0	24	0	0.35
Midland paint turtle	0.81	0.24	0	0	8	20	8	0	20	0	0.35
N brown snake	0.6	0.5	0	0	2	8	8	0	20	0	0.15
N water snake	0.6	0.5	0	0	2	8	8	0	20	0	0.15
Red-ear slider turtle	0.81	0.24	0	0	8	20	8	0	20	0	0.35
Snapping turtle	0.81	0.24	0	0	8	20	8	0	20	0	0.35
American toad	0.95	0.75	0	0	1	4	5	0	3,000	0	0.023
Bullfrog	0.95	0.75	0	0	1	4	5	0	20,000	0	0.15
Gray tree frog	0.95	0.75	0	0	1	4	5	0	3,000	0	0.023
Green frog	0.95	0.75	0	0	1	4	5	0	3,000	0	0.023
Leopard frog	0.95	0.75	0	0	1	4	5	0	3,000	0	0.023
W chorus frog	0.95	0.75	0	0	1	4	5	0	3,000	0	0.023
Wood frog	0.95	0.75	0	0	1	4	5	0	3,000	0	0.023

D.4 Fish Biomass

Three sources were used to generate the fish database to evaluate impacts from the Rouge River spill. In 2006, the USGS and the Lake Erie Biological Station (LEBS) conducted a survey for forage fish in the western basin of Lake Erie (Kocovsky et al., 2007). The sampling stations were located between Point Pelee and the western edge of the lake in Ontario and Michigan waters. Samples were collected in June and contained individuals of all size classes. The second study was also conducted in 2006 by Michigan Department of Natural Resources (MIDNR). This survey sampled nearshore fish populations of the Detroit River in July. Electrofishing was used to sample all class ranges (Francis, 2009b). The third source was an estimate of the walleye population travelling through the Detroit River. MIDNR estimated 1.7 million age 2 and older walleye were in the Detroit River between March and May 2002 (Francis, 2009a). Walleye densities were calculated by estimating the area of the Detroit River and scaling for higher migration rates in April using catch-per-unit-effort data from a MIDNR creel survey (Francis, 2005).

To use the data collected, densities (#/area) had to be converted to biomass (kg/area). In order to do this, life history on all species was collected. Biomass (kg/km^2) for each species was estimated by calculating the weight of fish in the population by age class using the number sampled per unit area from the abundance data as a basis and assuming a stable age distribution defined by annual mortality rates (see French McCay, 2009). Individual weight by age class was derived from the von Bertalanffy length at age, and the standard weight verses length, relationships (Ricker, 1975). Life history parameters including L_∞, K, alpha(a) and beta(b) were used to derive these relationships (see Table D-4 for values used). The population was modeled over time using the standard exponential growth equation:

$$N(t) = N_o e^{-zt}$$

Where N(t) represents the population at a given time t, N_o represents the population at time 0, z represents total mortality or the intrinsic rate of natural decrease, and t is time. The mortality rates (natural (M) and fishing (F)) and age recruited to fishery used for each species are listed in Table D-4.

Due to availability of life history information, species were grouped into larger categories and characteristics of a representative species life history were used for the conversions. Species listed individually were bowfins, longnose gar, northern pike, rainbow trout, silversides, rock bass, largemouth bass, smallmouth bass, yellow perch, walleye, white perch, and freshwater drum. The following species groups were comprised of the individual species listed:

- Herrings: combined alewife and gizzard shad
- Bullhead catfishes (brown, black, yellow)
- Sunfishes: sunfish (orangespotted, green, longear), bluegill, pumpkinseed
- Large forage fish: common carp and buffalos (bigmouth and black)
- Medium forage fish: quillback, redhorses (golden, silver, shorthead), suckers (spotted, white, northern hog), and goldfish
- Small forage fish: shiners (spotfin, spottail, emerald, mimic, sand, common, striped, golden), bluntnose minnows, chubs (hornyhead, river), brook silversides, banded killifish

If a species was only found in the Lake Erie study, the density number given in the report was used. If a species was found in both the Lake Erie and Detroit River surveys, the densities were averaged. Numerical densities were then converted using compiled life history information and the model described above. All species except rainbow trout were applied to all habitats. Rainbow trout, because they were only found in the western basin of Lake Erie, were only applied to open water habitat of the Detroit River and Lake Erie.

Table D-3 provides the fish biomass data that were used in the model, based on the assumptions outlined above.

Table D-3. Fish biomass data (kg/km^2) used in the model for the Rouge River, Detroit River and Lake Erie.

Species Name	Biomass (kg/km^2) in Detroit River and Lake Erie	Biomass (kg/km^2) in Rouge River
Herrings	233	233
Sunfishes	233	233
Rainbow smelt	2.6	0
Freshwater drum	54	54
White perch	219	219
Bowfin	202	202
Bullhead catfish	77	77
Marsh forage fish	3,400	3,400
Large forage fish	1,027	1,027
Medium forage fish	639	639
Small forage fish	79	79
Rainbow trout	16	16
Northern pike	49	49
White bass	64	64
Rock bass	411	411
Smallmouth bass	504	504
Largemouth bass	1,050	1,050
Longnose gar	514	514
Walleye	188	188
Yellow perch	86	86

D.5 Fish Life History

Table D-4 provides the fish life history data that were used in the model. All data were compiled from the FishBase database, unless otherwise noted. Parameters collected from FishBase were from the data source in closest proximity or similar habitat to the Detroit River and Lake Erie system.

Mortality data were collected from a variety of sources for each species, generally from primary literature. Bowfin (*Amia calva*) and rainbow trout (*Oncorhynchus mykiss*) were compiled from FishBase, the remaining data were collected from the following sources:

- Freshwater drum (*Aplodinotus grunniens*) was based on Bur (1984) for Lake Erie
- Yellow perch (*Perca flavescens*) was based on Henderson and Nepszy (1990) for Lake Erie and Lake St. Clair and GLFC (1987; 1988, Lake Erie).
- Bullheads and catfish were based on values for the channel catfish (*Ictalurus punctatus*) from Haak (1987) for Michigan.
- Herrings were based on values for the gizzard shad (*Dorosoma cepedianum*) from Michaletz (1998) for several Missouri lakes and reservoirs.
- Northern pike (*Esox lucius*) was based on LeCren (1987) from Canada.

- Large forage fish were based on values for the common carp (*Cyprinus carpio*); fishing mortality was based on McLenmore et al. (1991) Kentucky and natural mortality was based on Reed et al. (1992) and references therein.
- Sunfishes were based on values for the bluegill (*Lepomis macrochirus*); fishing mortality was based on McLenmore et al (1991) for Kentucky water bodies and natural mortality was based on Goedde and Coble (1981) from Wisconsin.
- Rock bass (*Ambloplites rupestris*) was collected from Covington et al. (1983) for Missouri streams.
- White perch (*Morone americana*) was based on Great Lakes Fishery Commission (GLFC) (1987; 1988).
- White bass (*Morone chrysops*) was based on Colvin (2002) from Missouri water bodies.
- Longnose gar (*Lepisosteus osseus*) was based on Hoffmeister et al. (2007) from Indiana.
- Medium forage fish were based on values for the white sucker (*Catostomus commersoni*) from Wakefield and Beckman (2005) for a Missouri lake and tributaries; fishing mortality was assumed to be zero.
- Largemouth bass (*Micropterus salmoides*) was based on Allen et al. (2008), and references therein, from Iowa.
- Walleye (*Sander vitreus*) was based on the GLFC Lake Erie Coordinated Percid Management Study (2004).
- Smallmouth bass (*Micropterus dolomieu*) was from Calhoun (1966).

Table D-4. Fish life history parameters used in the model.
(M = natural mortality, F = fishing mortality, YrRecr = age of recruitment, Life = max.age (yrs) Lmax, K, to = vonBertalanffy parameters, a,b = wt(g)-L(cm) parameters, Kg-max = max wt in kg)

Species group	Age	M	F	Yr Recr	Life	Lmax (cm)	K	to	a	b	kg-max
Herrings	7	1.11	0	2	7	43.7	0.480	0	1	3.071	109.1
Marsh forage fish	All	0.20	0	1	11	9.0	0.580	-0.4	0.011	3	0.01
Rainbow smelt	All	1.10	1	2	6	22.5	0.723	0	0.005	3.034	0.1
White bass	All	0.40	0.94	2	9	35.7	0.454	0	0.016	3.132	1.2
White perch	All	0.40	0.2	2	6	52.0	0.073	-1.52	0.012	3.02	1.8
Bowfin	19	0.37	0	1	19	73.5	0.328	0	0.009	3	3.6
Bullhead catfish	All	0.19	0.26	2	10	38.8	0.229	-0.13	1	2.924	44.1
Freshwater drum	All	0.30	0.36	2	16	128.9	0.063	-0.707	0.005	3	10.7
Large forage fish	All	0.50	0.06	2	12	74.8	0.157	0	1	3.025	466.2
Largemouth bass	All	0.43	0.39	2	13	55.4	0.200	0	0.024	2.993	4.0
Longnose gar	8	0.30	0.65	2	8	140.0	0.080	-5.8	1	3.12	4,965
Medium forage fish	All	0.55	0	2	12	55.6	0.150	0.08	1	3.04	201.8
Northern pike	All	0.30	0.65	2	24	142.0	0.140	0	1	2.779	957.7
Rainbow trout	All	1.40	0	2	8	74.4	0.383	0.62	0.014	2.911	3.9
Rock bass	All	0.17	0.78	4	9	19.2	0.340	0	0.047	2.969	0.3
Small forage fish	All	0.86	0	2	12	12.0	0.530	0	0.001	3.2	0.003
Smallmouth bass	All	0.45	0.25	5	14	49.3	0.230	0	0.018	3.052	2.6
Sunfishes	All	0.36	0.36	2	12	19.2	0.340	0	0.022	3.11	0.2
Walleye	All	0.32	0.15	5	20	54.4	0.237	0	0.008	3.097	1.9
Yellow perch	5	0.35	1.04	3	5	49.3	0.165	0	0.017	3.015	2.2

D.6 Primary and Invertebrate Production

A phytoplankton production value of 0.061 g C/m^2/d for the Detroit River was used for the spring months (NRDAM/GLE: Edwards et al., 1987; Edsall et al., 1988). This number was applied to all open water.

A zooplankton production value of 0.0093 g C/m^2/d and macrozoobenthos biomass value of 0.0060 g C/m^2/d was used for the Detroit River during the spring months (NRDAM/GLE: Edwards et al., 1987; Edsall et al., 1988). These numbers were applied to all open water.

The macrophyte production for the Detroit River was converted from a yearly value into a daily value (NRDAM/GLE: Edwards et al., 1987; Edsall et al., 1988). Daily values were then multiplied by two because growth is limited in autumn and winter seasons. Submerged macrophyte production of 0.3836 g C/m^2/d was used for spring months in aquatic bed habitats. An emergent macrophyte production rate of 1.0247 g C/m^2/d was used for spring months in emergent wetland habitats. Benthic microflora production for the Detroit River was also multiplied by two to account for little growth during the cold seasons, and a production rate of 0.086 g C/m^2/d was used for spring months in all nearshore and wetland habitats.

Table D-5 provides the primary and secondary productivity rates by habitat type within the Detroit River area for the spring months. The primary productivity rates indicate the production of phytoplankton, macrophytes and benthic microflora in the area, while the secondary productivity rates represents the production of zooplankton and benthic invertebrates.

Table D-5. Primary and secondary productivity rates during the spring in the area of the Detroit River.

	Primary Productivity Rates (g C/m^2/d)			**Secondary Productivity Rates (g C/m^2/d)**		
Habitat Type	**Phytoplankton**	**Macrophytes**	**Benthic Microflora**	**Zooplankton**	**Macro-zoobenthos**	**Benthic Invertebrates**
Rocky shoreline	0.72					
Gravel beach	0.72					
Sand beach	2.0					
Marsh/wetland	2.0	0.19	0.043	0.0093	0.006	0.025
Mud flats	2.0					

D.7 References

Allen, M.S., C.J. Walters, and R. Myers. 2008. Temporal trends in largemouth bass mortality, with fishery implications. *North American Journal of Fisheries Management* 28: 419-427.

Brown, G.P. and P.J. Weatherhead. 1999. Demography and sexual size dimorphism in northern water snakes, *Nerodia sipedon*. *Canadian Journal of Zoology* 77: 1358-1366.

Bur, M.T. 1984. Growth, reproduction, mortality, distribution, and biomass of freshwater drum in Lake Erie. *Journal of Great Lakes Research* 10: 48-58.

Calhoun, A.J. 1966. *Inland Fisheries Management*. State of California: The Resources Agency, Department of Fish and Game.

Colvin, M.A. 2002. Population and fishery characteristics of white bass in four large Missouri reservoirs. *North American Journal of Fisheries Management* 22: 677-689.

Covington. W.G., R.E. Marteney and C.F. Rabeni. 1983. Population characteristics of sympatric smallmouth bass and rock bass in the Jacks Fork and Current Rivers, Missouri. *Transactions of Missouri Academy of Science* 17: 27-35.

Duellman, W.E. and L. Trueb. 1994. *Biology of Amphibians*. Johns Hopkins University Press, Baltimore, MD.

Edsall, T.A., B.A. Manny, and C.N. Raphael. 1988. The St. Clair River and Lake St. Clair, Michigan: an ecological profile. *US Fish and Wildlife Service Biological Report* 85(7.3) 130pp.

Edwards, C., R. Haas, P.L. Hudson, C. Liston, B.A. Manny, C. McNabb, and S. Nepsey. 1987. Great Lakes Connecting Channels. Large Rivers Symposium. *Canada Technical Report of Fisheries and Aquatic Science* No. 1307

Ernst, C.H., J.E. Lovich, and R.W. Barbour. 1994. Turtles of the United States and Canada. Smithsonian Institution Press, Washington, D.C.

Francis, J.T. 2009a. Detroit River walleye population estimate. Michigan Department of Natural Resources. Personal communication, 5 February 2009.

Francis, J.T. 2009b. Detroit River nearshore fish survey. Michigan Department of Natural Resources. Personal communication, 5 February 2009.

Francis, J.T. 2005. The walleye fishery of the Detroit River, Spring 2000. *Michigan Department of Natural Resources, Fisheries Technical Report* 2005-1, Ann Arbor.

Goedde, L.E. and D.W. Coble. 1981. Effects of angling on a previously fished and an unfished warm water fish community in two Wisconsin lakes. *Transactions of the American Fisheries Society* 110: 594-603.

Great Lakes Fishery Commission, Lake Erie Committee. 2004. Lake Erie Coordinated Percid Management Strategy. December, 2004.

Great Lakes Fishery Commission (GLFC), Lake Erie Committee. 1987. Minutes of the 1987 annual meeting, Hotel Sofitel Toledo, Toledo, Ohio, March 24-25, 1987. 293 p.

Great Lakes Fishery Commission (GLFC), Lake Erie Committee. 1988. Minutes of the 1988 annual meeting, Holiday Inn, Grand Island, NY, March 22-23, 1988. 315 p.

Haak, R.J. 1987. Mortality, growth and yield of channel catfish in Saginaw Bay Lake Huron. Michigan Department of Natural Resources Fisheries Division, Fisheries Research Report 1947.

Harding, J.H. 1997. Amphibians and Reptiles of the Great Lakes Region. University of Michigan Press.

Henderson, B.A. and S.J. Nepszy. 1990. Yield of yellow perch in Lakes Erie and St. Clair: Community associations. *Transactions of the American Fisheries Society* 119: 741-756.

Hine, Ruth L.; Les, Betty L.; Hellmich, Bruce F.. Hine, Ruth L., Editor *Leopard frog populations and mortality in Wisconsin* (Technical bulletin. (Wisconsin Dept. of Natural Resources), No. 122) Madison, Wisconsin: Wisconsin Department of Natural Resources, 1981. 39 pgs. http://digital.library.wisc.edu/1711.dl/EcoNatRes.DNRBull122

Hoffmeister, J.L., T.M. Sutton, and R.A. Zeiber. 2007. Age and growth of longnose and shortnose gar on the Wabash River. Purdue University: http://www.ag.purdue.edu/oap/Documents/Abstracts2007.pdf

Kocovsky, P.M., M.T. Bur, M.A. Stapanian, and W. H. Edwards. 2007. Comparison of Spring and Autumn bottom trawl sampling in the western basin of Lake Erie. Report to Great Lakes Fisheries Commission, Lake Erie Committee Meeting, 22-23 March 2007, Ypsilanti, Michigan.

LeCren, E.D. 1987. Perch (*Perca fluviatilis)* and pike (*Esox lucius*) in Windermere from 1940 to 1985. *Canadian Journal of Fisheries Aquatic Sciences* 44(Supl. 2): 217-228.
McLemore W.N., D.E. Bell and B.D. Laflin. 1991. Annual performance report district fisheries management project part I of III subsection I: Lakes and tail waters research and management. Department of Fish and Wildlife Resources Kentucky.

Michaletz, P.H. 1998. Population characteristics of gizzard shad in Missouri reservoirs and their relation to reservoir productivity, mean depth, and sport fish growth. *North American Journal of Fisheries Management* 18: 114-123.

Mifsud, D.A. 2006. Detroit River International Wildlife Refuge Herpetological Survey Report 2006. Prepared for U.S. Fish and Wildlife Service, Large Lakes Research Station, Grosse Ile, MI.

Mifsud, D.A. 2009. Detroit River Herpetological Survey. Herpetological Resource and Management, LLC. Personal communication, 16 March 2009.

Myers, P., R. Espinosa, C. S. Parr, T. Jones, G. S. Hammond, and T. A. Dewey. 2008. The Animal Diversity Web (online). Accessed at http://animaldiversity.org.

Reed, M., D.P. French, S. Feng, F.W. French III, E. Howlett, K. Jayko, W. Knauss, J. McCure, S. Pavignano, S. Puckett, and H. Rines, R. Bishop, M. Welsh, J. Press. 1992. The CERCLA type A natural resource damage assessment model for the Great Lakes Environments (NRDAM/GLE). Contract No. 14-01-0001-88-C-27. Report for Office of Environmental Affairs, U.S. Department of the Interior, Washington, DC.

Robison, J. 2009. Pointe Mouillee spring shorebird survey. Pointe Mouillee State Game Area. Personal communication, 18 February 2009.

Smith, B.E. and D.A. Keniath, 2007. Northern leopard frog (Rana pipiens): a technical conservation assessment. USDA Forest Service, Rocky Mountain Region, 66 pp.

Stapanian, M.A. and T.A. Waite. 2003. Species density of waterbirds in offshore habitats in western Lake Erie. *Journal of Field Ornithology* 74(4): 381-393.

Tori, G.M. 1989. Crane Creek Wildlife Experiment Station, Ohio Dept. of Natural Resources, Oak Harbor, Ohio. Personal communication, Apr. 7, 1989.

Wakefield, C.K. and D.W. Beckman. 2005. Life history attributes of White sucker (*Catostomus commersoni*) in Lake Taneycomo and associated tributaries in southwestern Missouri. The Southwestern Naturalist 50(4): 423-434.

Witt, M. 2009. Ohio Division of Wildlife (ODW) Aerial Waterfowl Survey. Personal communication, 5 August 2009.

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Attachment E: Rouge River 2002 Mystery Oil Spill SIMAP Injury Report: Biological Model Results

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ROUGE RIVER 2002 MYSTERY OIL SPILL
SIMAP INJURY REPORT
Appendix E: Biological Model Results
Draft for Trustee Review

Submitted To:
Stephanie Millsap, Contaminants Specialist
U.S. Fish and Wildlife Service
USEPA LLRS
9311 Groh Rd.
Grosse Ile, MI 48138

Submitted By:
Jonathan R. Grant and Timothy J. Reilly
Lighthouse Technical Consultants, Inc.
Deborah French McCay, Jill Rowe, and Eileen Graham
Applied Science Associates, Inc. (ASA)

Pursuant to Requisition/Purchase Number: 314107015A

May 9, 2011

E.1 Biological Model Results

The biological model was run on the base case (RR-2PH-FV11-2HA-1PCT, as described in Appendix B, Sensitivity Analysis), the two sensitivity cases for the percent slow release (0% and 3% slow release; Table E-1) as these inputs were the most uncertain ones for the fates model, and two sensitivity cases varying the oil property of percent water when fully emulsified as mousse (10% and 60%: Table E-1). For the fish and invertebrate injury, each of the three scenarios were then modeled using three $LC50_{\infty}$ values to estimate injuries for sensitive, average and insensitive species. Table E-1 provides the matrix of biological scenarios modeled.

Table E-1. List of scenarios used for sensitivity analysis for biological modeling.

Scenario name	$LC50_{\infty}$ for sensitive species	$LC50_{\infty}$ for average species	$LC50_{\infty}$ for insensitive species
RR-2PH-FV11-2HA-1PCT (base case)	**5**	**44**	**370**
RR-2PH-FV11-2HA-0PCT	5	44	370
RR-2PH-FV11-2HA-3PCT	5	44	370
RR-2PH-FV11-2HA-1PCT-10MO	5	44	370
RR-2PH-FV11-2HA-1PCT-60MO	5	44	370

For the wildlife injury estimates, the results were divided into those for the Rouge River only, and those for the Detroit River and Lake Erie, combined, because of different assumed densities of animals in each area. Tables E-2 to E-25 provide the wildlife injury results for the five fates scenarios modeled. The results indicate that the wildlife injuries computed by the model are insensitive to the assumed percentage of the oil released slowly and after the majority of the first oil release had moved out of the Rouge River.

It should be noted that it is uncertain what the pre-spill densities of birds and other wildlife were before the spill. The density data used for the modeling, which was best available information, was from other locations and times (see Appendix D.1). However, the model results are directly proportional to the density data assumed. Therefore, if the densities assumed were a factor 2 lower, the injury results would also be a factor 2 lower. The counts of animals observed oiled or dead in the field totaled 110 birds and 3 turtles. Thus, these model results suggest that one in 49 birds oiled were actually observed; whereas the rule of thumb for past spills has been about 1 in 10 might be observed. Yet, these ratios are highly uncertain, and dependant on the degree of search effort, losses to scavengers, and other factors. Estimates for the likelihood of observing oiled turtles are not available, but 1 in 100 is not unreasonable in this situation.

Due to the fact that the scaup injury accounted for the majority of the wildlife injury, those injuries are presented in separate tables. These injuries are high due to the assumed pre-spill density of 104 individuals/km^2 in Lake Erie waters from 1-3 meters in depth (Figure 3-5 of main SIMAP Injury Report). While this abundance seems high, these numbers (the mean observed in Pointe Mouillee area in April 2002-2008) were corroborated by two species counts: one from close to shore in the Pointe Mouillee marsh area (on 13 April 2002, 109 individuals/km2 were

counted there) and the other from an open water survey between Maumee Bay and West Sister Island (101 individuals/km^2, sampling location shown in Figure D-1). Additionally, the model estimate of the area oiled for waters between 1 and 3 meters deep in Lake Erie was 39.4 km^2, a reasonable estimate; and scaup are known to spend most of their time on the water surface (and so are very vulnerable to oiling). Therefore, the calculations indicating that there should be close to 5,000 scaups oiled is realistic.

The area of habitat between 1 and 3 meters deep in western Lake Erie was 212 km^2; therefore, applying an average abundance of 104 scaup/km^2 results in a total population estimate of approximately 22,000 scaup in Western Lake Erie in April. For the entire Upper Mississippi River and Great Lakes Joint Venture Region, the spring migration estimate for scaup is approximately 1.5 million birds, and the winter population is approximately 200,000 birds (Souillere et al. 2007). The model simulation killed 18.6% of the population, or 4,106 individuals. Even though these numbers seem large based on reported observations after the spill, there are several reasons this should be a reliable injury estimate. First, scaup are not often found close to shore; therefore, they are unlikely to take refuge in the areas that were easily surveyed after the spill. Secondly, scaup are dark in color (brown, non-breeding plumage being prevalent in April for both species), which would make identifying an oiled bird from shore nearly impossible. Third, the scale of impact is due to the fact that much of the oil impacted the area surrounding Pointe Mouillee, where high abundances of scaup have been documented in April, and that nearly 40 km^2 of habitat 1-3 meters in depth (Figures E-1 and E-2) were estimated as oiled 11 April through 14 April 2002.

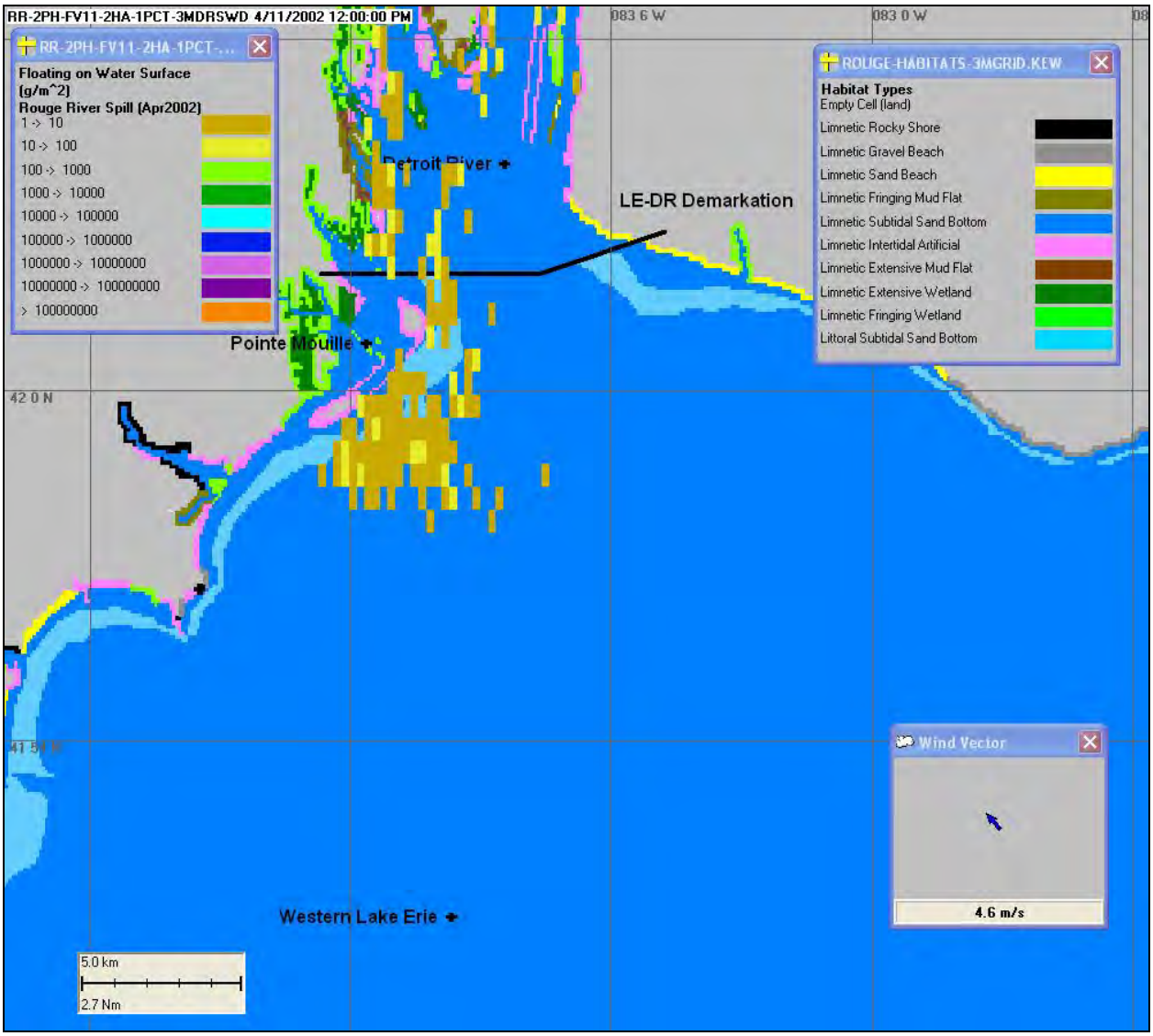

Figure E-1. Concentration of oil on the surface of the water at noon on 11 April 2002 over the habitat grid developed for scaup, which were applied to 1-3 meter deep water in Lake Erie. The solid black line marks the delineation between the Detroit River and Lake Erie.

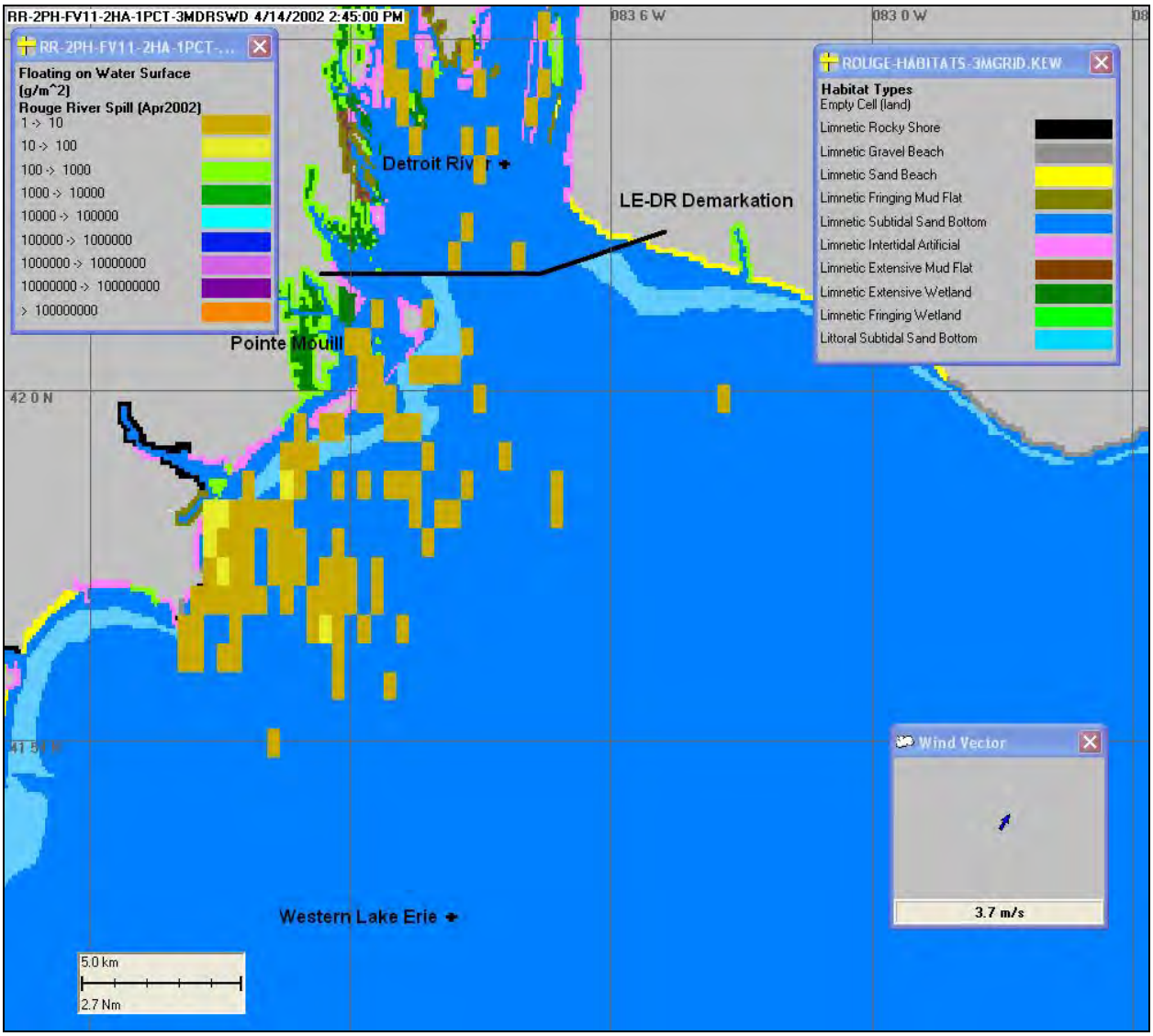

Figure E-2. Concentration of oil on the surface of the water at 2:45 pm on 14 April 2002 over the habitat grid developed for scaup which were applied to 1-3 meter deep water in Lake Erie. The solid black line marks the delineation between the Detroit River and Lake Erie.

Table E-2. RR-2PH-FV11-2HA-1PCT: Estimated injuries to avifauna (other than scaups) for the Detroit River, Lake Erie and Rouge River using a 1 percent slow release of the oil. Note that the number oiled is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region, whereas zeros indicate the injury estimate is less than 0.1 individual.

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
American black duck	0.5	-	0.5
American coot	72.5	9.9	82.4
American widgeon	4.9	0.7	5.6
Blue-winged teal	2.6	0.4	2.9
Bufflehead	2.4	0.3	2.7
Canada goose	8.0	1.1	9.0
Canvasback	3.1	0.4	3.5
Common goldeneye	0.1	0.0	0.1
Common loon	0.0	-	0.0
Eurasian Wigeon	0.0	0.0	0.0
Gadwall	21.5	2.9	24.4
Green-winged teal	27.4	3.7	31.1
Horned grebe	0.1	0.0	0.2
Long-tailed duck	0.0	-	0.0
Mallard	4.0	0.5	4.6
Red-breasted merganser	91.7	-	91.7
Common merganser	114	-	114
Hooded merganser	18.1	-	18.1
Northern pintail	6.3	0.9	7.2
Northern shoveler	4.4	0.6	5.0
Pied-billed grebe	1.0	0.1	1.2
Redhead	8.7	1.2	9.8
Ring-necked duck	3.8	0.5	4.3
Ruddy duck	10.8	1.5	12.2
Surf scoter	0.0	-	0.0
Mute swan	4.8	0.7	5.4
Tundra swan	0.0	0.0	0.0
Wood duck	0.1	-	0.1
Bonapartes gull	173	0.2	173
Caspian tern	23.5	0.0	23.6
Doublecrested cormorant	242	0.3	242
Forsters tern	22.1	0.0	22.1
Glaucous gull	0.2	0.0	0.2

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Great black-back gull	1.7	0.0	1.7
Herring gull	191	0.3	191
Lesser black-back gull	0.2	0.0	0.2
Ring-billed gull	83.4	0.1	83.5
American bittern	0.0	-	0.0
Black-crowned heron	0.8	-	0.8
Common moorhen	0.3	-	0.3
Great blue heron	4.9	-	4.9
Great egret	3.4	-	3.4
Green heron	0.0	-	0.0
Sandhill crane	0.1	-	0.1
Sora	0.5	-	0.5
Virginia rail	0.2	-	0.2
American avocet	0.6	-	0.6
Black-necked stilt	0.0	-	0.0
Common snipe	3.8	-	3.8
Dunlin	30.1	-	30.1
Greater yellowlegs	3.4	-	3.4
Killdeer	3.6	-	3.6
Least sandpiper	0.1	-	0.1
Lesser yellowlegs	6.5	-	6.5
Long-bill dowitcher	0.1	-	0.1
Pectoral sandpiper	8.6	-	8.6
Semipalmated plover	0.0	-	0.0
Short-bill dowitcher	0.1	-	0.1
Solitary sandpiper	0.0	-	0.0
Spotted sandpiper	0.2	-	0.2
Willet	0.7	-	0.7
Wilsons snipe	0.6	-	0.6
Total Waterfowl	410	25	436
Total Seabirds	737	1	738
Total Wading birds	10	-	10
Total Shorebirds	58	-	58
Total All Avian Species	1,215	26	1,241

Table E-3. RR-2PH-FV11-2HA-1PCT: Estimated injuries to scaups for the base case model scenario using a 1 percent slow release of the oil. "-" indicates species was not present in region.

Scaup Species	Number Killed in Lake Erie	Number Killed in Rouge and Detroit River*	Total Number Killed
Scaup spp.	125	-	125
Greater scaup	1,789	-	1,789
Lesser scaup	2,192	-	2,192
Total All Scaup Species			4,106

***Scaup species assumed to only occur in Lake Erie waters from 1-3m deep.**

Table E-4. RR-2PH-FV11-2HA-1PCT: Estimated injuries to mammals for the base case model scenario using a 1 percent slow release of the oil. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Mammal Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Muskrat	308	-	308
Total All Mammal Species			308

Table E-5. RR-2PH-FV11-2HA-1PCT: Estimated injuries to herpetofauna for the base case model scenario using a 1 percent slow release of the oil. Note that the number oiled is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Herptile Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Black rat snake	0.0	-	0.0
Blandings turtle	1.5	-	1.5
Butlers garter snake	0.0	-	0.0
Eastern fox snake	0.0	-	0.0
Eastern garter snake	0.1	-	0.1
Eastern spiny softshell	1.2	-	1.2
Map turtle	51.8	-	51.8
Midland painted turtle	44.2	-	44.2
Northern brown snake	0.0	-	0.0
Northern water snake	5.0	-	5.0
Red-ear slider turtle	1.2	-	1.2
Snapping turtle	8.8	-	8.8
American toad	13.5	-	13.5
Bullfrog	12.4	-	12.4
Gray tree frog	0.3	-	0.3

Herptile Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Green frog	8.0	-	8.0
Leopard frog	42.7	-	42.7
Western chorus frog	0.4	-	0.4
Wood frog	0.2	-	0.2
Total Reptiles			114
Total Amphibians			77.5
Total All Herptile Species			191.3

Table E-6. RR-2PH-FV11-2HA-1PCT: Estimated equivalent losses of bird fledglings (other than scaups) for the base case model scenario using a 1 percent slow release of the oil. Note that the number lost is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region.

	Equivalent Fledgling Losses		
Avian Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
American black duck	1.5	-	1.5
American coot	240	32.7	273
American widgeon	16.3	2.2	18.5
Blue-winged teal	8.5	1.2	9.7
Bufflehead	8.4	1.1	9.5
Canada goose	24.4	3.3	27.7
Canvasback	10.8	1.5	12.3
Common goldeneye	0.4	0.1	0.5
Common loon	0.3	-	0.3
Eurasian Wigeon	0.1	0.0	0.1
Gadwall	71.2	9.7	80.9
Green-winged teal	90.8	12.3	103
Horned grebe	0.5	0.1	0.6
Long-tailed duck	0.0	-	0.0
Mallard	13.3	1.8	15.1
Red-breasted merganser	320	-	320
Common merganser	396	-	396
Hooded merganser	63.0	-	63.0
Northern pintail	20.9	2.8	23.8
Northern shoveler	14.6	2.0	16.6
Pied-billed grebe	4.0	0.6	4.6
Redhead	30.2	4.1	34.3
Ring-necked duck	13.2	1.8	15.0
Ruddy duck	37.5	5.1	42.6

	Equivalent Fledgling Losses		
Avian Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Surf scoter	0.0	-	0.0
Mute swan	13.6	1.8	15.4
Tundra swan	0.0	0.0	0.0
Wood duck	0.5	-	0.5
Bonapartes gull	635	0.8	636
Caspian tern	83.7	0.1	83.8
Doublecrested cormorant	940	1.2	941
Forsters tern	78.5	0.1	78.6
Glaucous gull	0.8	0.0	0.8
Great black-back gull	6.3	0.0	6.3
Herring gull	702	0.9	703
Lesser black-back gull	0.8	0.0	0.8
Ring-billed gull	306	0.4	307
American bittern	0.1	-	0.1
Black-crowned heron	2.8	-	2.8
Common moorhen	0.9	-	0.9
Great blue heron	16.4	-	16.4
Great egret	11.3	-	11.3
Green heron	0.1	-	0.1
Sandhill crane	0.3	-	0.3
Sora	1.8	-	1.8
Virginia rail	0.5	-	0.5
American avocet	2.1	-	2.1
Black-necked stilt	0.1	-	0.1
Common snipe	13.3	-	13.3
Dunlin	106	-	106
Greater yellowlegs	12.2	-	12.2
Killdeer	12.6	-	12.6
Least sandpiper	0.3	-	0.3
Lesser yellowlegs	17.2	-	17.2
Long-bill dowitcher	0.5	-	0.5
Pectoral sandpiper	30.2	-	30.2
Semipalmated plover	0.1	-	0.1
Short-bill dowitcher	0.2	-	0.2
Solitary sandpiper	0.1	-	0.1
Spotted sandpiper	0.7	-	0.7
Willet	2.3	-	2.3
Wilsons snipe	2.2	-	2.2
Total Waterfowl			1,485

	Equivalent Fledgling Losses		
Avian Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Total Seabirds			2,757
Total Wading birds			34.2
Total Shorebirds			200
Total All Avian Species			4,476

Table E-7. RR-2PH-FV11-2HA-1PCT: Estimated equivalent losses of scaup fledglings for the base case model scenario using a 1 percent slow release of the oil. "-" indicates species was not present in region.

	Fledglings Lost		
Scaup Species	**Lake Erie**	**Rouge and Detroit River**	**Total**
Scaup spp.	435	-	435
Greater scaup	6,245	-	6,245
Lesser scaup	7,652	-	7,652
Total All Scaup Species			14,332

Table E-8. RR-2PH-FV11-2HA-1PCT: Estimated equivalent losses of age-zero (newly-weaned) mammals for the base case model scenario using a 1 percent slow release of the oil. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

	Equivalent Newly-Weaned Individuals Lost		
Mammal Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Muskrat	940	-	940
Total All Mammal Species			940

Table E-9. RR-2PH-FV11-2HA-1PCT: Estimated equivalent losses of herpetofauna hatchlings for the base case model scenario using a 1 percent slow release of the oil. Note that the number lost is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

	Equivalent Hatchling Losses			
Herptile Species	**Number Hatched per Adult**	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Black rat snake	20	0.0	-	0.0
Blandings turtle	20	33.0	-	33.0
Butlers garter snake	20	0.3	-	0.3

	Equivalent Hatchling Losses			
Herptile Species	**Number Hatched per Adult**	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Eastern fox snake	20	0.2	-	0.2
Eastern garter snake	20	0.7	-	0.7
Eastern spiny softshell	20	24.7	-	24.7
Map turtle	24	4067	-	407
Midland painted turtle	20	952	-	952
Northern brown snake	20	0.1	-	0.1
Northern water snake	20	74.2	-	74.2
Red-ear slider turtle	20	24.7	-	24.7
Snapping turtle	20	190	-	190
American toad	3,000	13,180	-	13,180
Bullfrog	20,000	80,030	-	80,030
Gray tree frog	3,000	280	-	280
Green frog	3,000	7,850	-	7,850
Leopard frog	3,000	41,690	-	41,690
Western chorus frog	3,000	374	-	374
Wood frog	3,000	187.0	-	187.0
Total Reptiles				1,700
Total Amphibians				143,600
Total All Herptile Species				145,300

Table E-10. RR-2PH-FV11-2HA-1PCT: Estimated injuries (interim loss) for avian species (excluding scaups) as individual bird-years (all age classes combined) for the base case model scenario using a 1 percent slow release of the oil. Note that the number lost is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region.

	Individual-years Lost (all ages)		
Avian Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
American black duck	1.3	-	1.3
American coot	201	27.3	228
American widgeon	13.6	1.84	15.4
Blue-winged teal	7.1	0.97	8.1
Bufflehead	5.2	0.7	5.9
Canada goose	29.8	4.05	33.8
Canvasback	6.7	0.91	7.6

	Individual-years Lost (all ages)		
Avian Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Common goldeneye	0.3	0.03	0.3
Common loon	0.6	-	0.6
Eurasian Wigeon	0.1	0.01	0.1
Gadwall	59.4	8.08	67.5
Green-winged teal	75.8	10.3	86.1
Horned grebe	2.2	0.29	2.5
Long-tailed duck	0.0	-	0.0
Mallard	11.1	1.51	12.6
Red-breasted merganser	198	-	198
Common merganser	245	-	245
Hooded merganser	38.9	-	38.9
Northern pintail	17.5	2.37	19.8
Northern shoveler	12.2	1.65	13.8
Pied-billed grebe	16.4	2.23	18.7
Redhead	18.6	2.53	21.2
Ring-necked duck	8.1	1.11	9.3
Ruddy duck	23.2	3.15	26.4
Surf scoter	0.0	-	0.0
Mute swan	65.5	8.9	74.4
Tundra swan	0.2	0.02	0.2
Wood duck	0.3	-	0.3
Bonapartes gull	2,990	3.86	2,994
Caspian tern	188	0.24	188
Doublecrested cormorant	3,836	4.95	3,840
Forsters tern	176	0.23	176
Glaucous gull	3.5	0	3.5
Great black-back gull	29.6	0.04	29.6
Herring gull	3,307	4.27	3,311
Lesser black-back gull	3.5	0	3.5
Ring-billed gull	1,443	1.86	1,444
American bittern	0.1	-	0.1
Black-crowned heron	2.5	-	2.5
Common moorhen	0.8	-	0.8
Great blue heron	14.6	-	14.6
Great egret	10.1	-	10.1
Green heron	0.1	-	0.1
Sandhill crane	0.2	-	0.2
Sora	1.6	-	1.6
Virginia rail	0.4	-	0.4

	Individual-years Lost (all ages)		
Avian Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
American avocet	3.9	-	3.9
Black-necked stilt	0.3	-	0.3
Common snipe	24.3	-	24.3
Dunlin	194	-	194
Greater yellowlegs	22.2	-	22.2
Killdeer	23.0	-	23.0
Least sandpiper	0.5	-	0.5
Lesser yellowlegs	16.3	-	16.3
Long-bill dowitcher	0.8	-	0.8
Pectoral sandpiper	55.2	-	55.2
Semipalmated plover	0.2	-	0.2
Short-bill dowitcher	0.3	-	0.3
Solitary sandpiper	0.2	-	0.2
Spotted sandpiper	1.2	-	1.2
Willet	4.3	-	4.3
Wilsons snipe	3.9	-	3.9
Total Waterfowl			1,135
Total Seabirds			11,992
Total Wading birds			30.5
Total Shorebirds			351
Total All Avian Species			13,510

Table E-11. RR-2PH-FV11-2HA-1PCT: Estimated injuries (interim loss) as individual scaup-years for the base case model scenario using a 1 percent slow release of the oil. "-" indicates species was not present in region.

	Individual-years Lost		
Scaup Species	**Lake Erie**	**Rouge and Detroit River**	**Total**
Scaup spp.	269	-	269
Greater scaup	3,859	-	3,859
Lesser scaup	4,728	-	4,728
Total All Scaup Species			8,855

Table E-12. RR-2PH-FV11-2HA-1PCT: Estimated injuries (interim loss) as individual mammal-years (all age classes combined) for the base case model scenario using a 1 percent slow release of the oil. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

	Individual-years Lost (all ages)		
Mammal Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Muskrat	398	-	398
Total All Mammal Species			398

Table E-13. RR-2PH-FV11-2HA-1PCT: Estimated injuries (interim loss) as individual herptile-years (all age classes combined) for the base case model scenario using a 1 percent slow release of the oil. Note that the number lost is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

	Individual-years Lost (all ages)		
Herptile Species	**Detroit River and Lake Erie**	**Rouge River**	**Total**
Black rat snake	0.0	-	0.0
Blandings turtle	23.9	-	23.9
Butlers garter snake	0.2	-	0.2
Eastern fox snake	0.2	-	0.2
Eastern garter snake	0.6	-	0.6
Eastern spiny softshell	17.9	-	17.9
Map turtle	294	-	294
Midland painted turtle	689	-	689
Northern brown snake	0.1	-	0.1
Northern water snake	57.5	-	57.5
Red-ear slider turtle	17.9	-	17.9
Snapping turtle	137	-	137
American toad	867	-	867
Bullfrog	5,270	-	5,270
Gray tree frog	18.4	-	18.4
Green frog	517	-	517
Leopard frog	2,743	-	2,743
Western chorus frog	24.6	-	24.6
Wood frog	12.3	-	12.3
Total Reptiles			1,238
Total Amphibians			9,448
Total All Herptile Species			10,690

Table E-14. RR-2PH-FV11-2HA-0PCT: Estimated injuries to avifauna (other than scaups) for the Detroit River, Lake Erie, and Rouge River using a 0 percent slow release of the oil.

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
American black duck	0.5	0.0	0.5
American coot	71.2	9.6	80.9
American widgeon	4.8	0.7	5.5
Blue-winged teal	2.5	0.3	2.9
Bufflehead	2.4	0.3	2.7
Canada goose	7.8	1.1	8.9
Canvasback	3.0	0.4	3.4
Common goldeneye	0.1	0.0	0.1
Common loon	0.0	0.0	0.0
Eurasian Wigeon	0.0	0.0	0.0
Gadwall	21.1	2.9	24.0
Green-winged teal	26.9	3.6	30.6
Horned grebe	0.1	0.0	0.2
Long-tailed duck	0.0	0.0	0.0
Mallard	3.9	0.5	4.5
Merganser red-breast	90.0	0.0	90.0
Merganser, common	111.5	0.0	111.5
Merganser, hooded	17.7	0.0	17.7
Northern pintail	6.2	0.8	7.0
Northern shoveler	4.3	0.6	4.9
Pied-billed grebe	1.0	0.1	1.2
Redhead	8.5	1.2	9.6
Ring-necked duck	3.7	0.5	4.2
Ruddy duck	10.6	1.4	12.0
Scoter, surf	0.0	0.0	0.0
Swan, mute	4.7	0.6	5.3
Swan, tundra	0.0	0.0	0.0
Wood duck	0.1	0.0	0.1
Bonapartes gull	170.0	0.2	170.2
Caspian tern	23.2	0.0	23.2
Doublecrested cormorant	237.9	0.3	238.2
Forsters tern	21.7	0.0	21.7
Glaucous gull	0.2	0.0	0.2
Great black-backed gull	1.7	0.0	1.7
Herring gull	187.9	0.2	188.2
Lesser black-backed gull	0.2	0.0	0.2
Ring-billed gull	82.0	0.1	82.1
American bittern	0.1	-	0.1
Black-crowned heron	1.0	-	1.0
Common moorhen	0.3	-	0.3
Great blue heron	5.6	-	5.6
Great egret	3.8	-	3.8
Green heron	0.1	-	0.1

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Sandhill crane	0.1	-	0.1
Sora	0.6	-	0.6
Virginia rail	0.2	-	0.2
American avocet	0.7	-	0.7
Black-necked stilt	0.1	-	0.1
Common snipe	4.3	-	4.3
Dunlin	34.1	-	34.1
Greater yellowlegs	3.9	-	3.9
Killdeer	4.0	-	4.0
Least sandpiper	0.1	-	0.1
Lesser yellowlegs	7.4	-	7.4
Long-bill dowitcher	0.2	-	0.2
Pectoral sandpiper	9.7	-	9.7
Semipalmated plover	0.0	-	0.0
Short-bill dowitcher	0.1	-	0.1
Solitary sandpiper	0.0	-	0.0
Spotted sandpiper	0.2	-	0.2
Willet	0.8	-	0.8
Wilsons snipe	0.7	-	0.7
Total Waterfowl			427.7
Total Seabirds			725.7
Total Wading birds			11.8
Total Shorebirds			66.3
Total All Avian Species			1,231.5

Table E-15. RR-2PH-FV11-2HA-0PCT: Estimated injuries to mammals for the Detroit River, Lake Erie, and Rouge River using a 0 percent slow release of the oil. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Mammal Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Muskrat	348.7	-	348.7
Total All Mammal Species			348.7

Table E-16. RR-2PH-FV11-2HA-0PCT: Estimated injuries to herpetofauna for the Detroit River, Lake Erie, and Rouge River using a 0 percent slow release of the oil. Note that the number oiled is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Herptile Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Black rat snake	0.0	-	0.0
Blandings turtle	1.7	-	1.7
Butlers garter snake	0.0	-	0.0
Eastern fox snake	0.0	-	0.0
Eastern garter snake	0.1	-	0.1
Eastern spiny softshell	1.3	-	1.3
Map turtle	58.6	-	58.6
Midland painted turtle	50.0	-	50.0
Northern brown snake	0.0	-	0.0
Northern water snake	5.6	-	5.6
Red-ear slider turtle	1.3	-	1.3
Snapping turtle	10.0	-	10.0
American toad	15.3	-	15.3
Bullfrog	14.0	-	14.0
Gray tree frog	0.3	-	0.3
Green frog	9.1	-	9.1
Leopard frog	48.3	-	48.3
Western chorus frog	0.4	-	0.4
Wood frog	0.2	-	0.2
Total Reptiles			128.7
Total Amphibians			87.6
Total All Herptile Species			216.3

Table E-17. RR-2PH-FV11-2HA-3PCT: Estimated injuries to avifauna (other than scaups) for the Detroit River, Lake Erie and Rouge River using a 3 percent slow release of the oil.

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
American black duck	0.5	0.0	0.5
American coot	71.8	9.7	81.5
American widgeon	4.9	0.7	5.5
Blue-winged teal	2.6	0.3	2.9
Bufflehead	2.4	0.3	2.7
Canada goose	7.9	1.1	8.9
Canvasback	3.1	0.4	3.5
Common goldeneye	0.1	0.0	0.1
Common loon	0.0	0.0	0.0
Eurasian Wigeon	0.0	0.0	0.0
Gadwall	21.3	2.9	24.1
Green-winged teal	27.1	3.7	30.8
Horned grebe	0.1	0.0	0.2
Long-tailed duck	0.0	0.0	0.0
Mallard	4.0	0.5	4.5
Merganser red-breast	90.7	0.0	90.7
Merganser, common	112.3	0.0	112.3
Merganser, hooded	17.9	0.0	17.9
Northern pintail	6.2	0.9	7.1
Northern shoveler	4.4	0.6	4.9
Pied-billed grebe	1.0	0.1	1.2
Redhead	8.6	1.2	9.7
Ring-necked duck	3.7	0.5	4.2
Ruddy duck	10.6	1.4	12.1
Scoter, surf	0.0	0.0	0.0
Swan, mute	4.7	0.6	5.3
Swan, tundra	0.0	0.0	0.0
Wood duck	0.1	0.0	0.1
Bonapartes gull	158.7	0.2	158.9
Caspian tern	21.6	0.0	21.7
Doublecrested cormorant	222.1	0.3	222.4
Forsters tern	20.3	0.0	20.3
Glaucous gull	0.2	0.0	0.2
Great black-backed gull	1.6	0.0	1.6
Herring gull	175.5	0.2	175.7
Lesser black-backed gull	0.2	0.0	0.2
Ring-billed gull	76.5	0.1	76.6
American bittern	0.0	-	0.0
Black-crowned heron	0.9	-	0.9
Common moorhen	0.3	-	0.3
Great blue heron	5.2	-	5.2
Great egret	3.6	-	3.6
Green heron	0.0	-	0.0

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Sandhill crane	0.1	-	0.1
Sora	0.6	-	0.6
Virginia rail	0.2	-	0.2
American avocet	0.6	-	0.6
Black-necked stilt	0.0	-	0.0
Common snipe	4.0	-	4.0
Dunlin	31.6	-	31.6
Greater yellowlegs	3.6	-	3.6
Killdeer	3.7	-	3.7
Least sandpiper	0.1	-	0.1
Lesser yellowlegs	6.8	-	6.8
Long-bill dowitcher	0.1	-	0.1
Pectoral sandpiper	9.0	-	9.0
Semipalmated plover	0.0	-	0.0
Short-bill dowitcher	0.1	-	0.1
Solitary sandpiper	0.0	-	0.0
Spotted sandpiper	0.2	-	0.2
Willet	0.7	-	0.7
Wilsons snipe	0.6	-	0.6
Total Waterfowl			431
Total Seabirds			678
Total Wading birds			11
Total Shorebirds			61
Total All Avian Species			1,180

Table E-18. RR-2PH-FV11-2HA-3PCT: Estimated injuries to mammals for the Detroit River, Lake Erie, and Rouge River using a 3 percent slow release of the oil. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Mammal Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Muskrat	323.3	-	323.3
Total All Mammal Species			323

Table E-19. RR-2PH-FV11-2HA-3PCT: Estimated injuries to herpetofauna for the Detroit River, Lake Erie, and Rouge River using a 3 percent slow release of the oil. Note that the number oiled is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Herptile Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Black rat snake	0.0	-	0.0
Blandings turtle	1.6	-	1.6
Butlers garter snake	0.0	-	0.0
Eastern fox snake	0.0	-	0.0
Eastern garter snake	0.1	-	0.1
Eastern spiny softshell	1.2	-	1.2
Map turtle	54.3	-	54.3
Midland painted turtle	46.4	-	46.4
Northern brown snake	0.0	-	0.0
Northern water snake	5.2	-	5.2
Red-ear slider turtle	1.2	-	1.2
Snapping turtle	9.2	-	9.2
American toad	14.2	-	14.2
Bullfrog	13.0	-	13.0
Gray tree frog	0.3	-	0.3
Green frog	8.4	-	8.4
Leopard frog	44.8	-	44.8
Western chorus frog	0.4	-	0.4
Wood frog	0.2	-	0.2
Total Reptiles			119
Total Amphibians			81
Total All Herptile Species			200

Table E-20. RR-2PH-FV11-2HA-1PCT-10MO: Estimated injuries to avifauna (other than scaups) for the Detroit River, Lake Erie and Rouge River using a 1 percent slow release of the oil and an oil mixture with 10 percent water when fully emulsified as mousse.

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
American black duck	0.4	0.0	0.4
American coot	64.4	9.1	73.4
American widgeon	4.4	0.6	5.0
Blue-winged teal	2.3	0.3	2.6
Bufflehead	2.1	0.3	2.4
Canada goose	7.1	1.0	8.1
Canvasback	2.7	0.4	3.1
Common goldeneye	0.1	0.0	0.1
Common loon	0.0	0.0	0.0
Eurasian Wigeon	0.0	0.0	0.0
Gadwall	19.1	2.7	21.8
Green-winged teal	24.3	3.4	27.7
Horned grebe	0.1	0.0	0.1
Long-tailed duck	0.0	0.0	0.0
Mallard	3.6	0.5	4.1
Merganser red-breast	81.3	0.0	81.3
Merganser, common	100.7	0.0	100.7
Merganser, hooded	16.0	0.0	16.0
Northern pintail	5.6	0.8	6.4
Northern shoveler	3.9	0.6	4.5
Pied-billed grebe	0.9	0.1	1.1
Redhead	7.7	1.1	8.8
Ring-necked duck	3.4	0.5	3.8
Ruddy duck	9.5	1.4	10.9
Scoter, surf	0.0	0.0	0.0
Swan, mute	4.2	0.6	4.8
Swan, tundra	0.0	0.0	0.0
Wood duck	0.1	0.0	0.1
Bonapartes gull	120.8	0.2	121.0
Caspian tern	16.5	0.0	16.5
Doublecrested cormorant	169.2	0.3	169.5
Forsters tern	15.4	0.0	15.5
Glaucous gull	0.1	0.0	0.1
Great black-backed gull	1.2	0.0	1.2
Herring gull	133.6	0.2	133.9
Lesser black-backed gull	0.1	0.0	0.1
Ring-billed gull	58.3	0.1	58.4
American bittern	0.0	-	0.0
Black-crowned heron	0.6	-	0.6
Common moorhen	0.2	-	0.2
Great blue heron	3.8	-	3.8
Great egret	2.6	-	2.6

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Green heron	0.0	-	0.0
Sandhill crane	0.1	-	0.1
Sora	0.4	-	0.4
Virginia rail	0.1	-	0.1
American avocet	0.5	-	0.5
Black-necked stilt	0.0	-	0.0
Common snipe	2.9	-	2.9
Dunlin	23.0	-	23.0
Greater yellowlegs	2.6	-	2.6
Killdeer	2.7	-	2.7
Least sandpiper	0.1	-	0.1
Lesser yellowlegs	5.0	-	5.0
Long-bill dowitcher	0.1	-	0.1
Pectoral sandpiper	6.5	-	6.5
Semipalmated plover	0.0	-	0.0
Short-bill dowitcher	0.0	-	0.0
Solitary sandpiper	0.0	-	0.0
Spotted sandpiper	0.1	-	0.1
Willet	0.5	-	0.5
Wilsons snipe	0.5	-	0.5
Total Waterfowl			387
Total Seabirds			516
Total Wading birds			8
Total Shorebirds			44
Total All Avian Species			956

Table E-21. RR-2PH-FV11-2HA-1PCT-10MO: Estimated injuries to mammals for the base case model scenario using a 1 percent slow release of the oil and an oil mixture with 10 percent water when fully emulsified as mousse. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Mammal Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Muskrat	235.5	-	235.5
Total All Mammal Species			235.5

Table E-22. RR-2PH-FV11-2HA-1PCT-10MO: Estimated injuries to herpetofauna for the base case model scenario using a 1 percent slow release of the oil and an oil mixture with 10 percent water when fully emulsified as mousse. Note that the number oiled is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Herptile Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Black rat snake	0.0	-	0.0
Blandings turtle	1.2	-	1.2
Butlers garter snake	0.0	-	0.0
Eastern fox snake	0.0	-	0.0
Eastern garter snake	0.0	-	0.0
Eastern spiny softshell	0.9	-	0.9
Map turtle	39.6	-	39.6
Midland painted turtle	33.8	-	33.8
Northern brown snake	0.0	-	0.0
Northern water snake	3.8	-	3.8
Red-ear slider turtle	0.9	-	0.9
Snapping turtle	6.7	-	6.7
American toad	10.3	-	10.3
Bullfrog	9.4	-	9.4
Gray tree frog	0.2	-	0.2
Green frog	6.1	-	6.1
Leopard frog	32.6	-	32.6
Western chorus frog	0.3	-	0.3
Wood frog	0.2	-	0.2
Total Reptiles			87
Total Amphibians			59
Total All Herptile Species			146

Table E-23. RR-2PH-FV11-2HA-1PCT-60MO: Estimated injuries to avifauna (other than scaups) for the Detroit River, Lake Erie and Rouge River using a 1 percent slow release of the oil and an oil mixture with 60 percent water when fully emulsified as mousse.

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
American black duck	0.6	0.0	0.6
American coot	85.6	10.2	95.7
American widgeon	5.8	0.7	6.5
Blue-winged teal	3.0	0.4	3.4
Bufflehead	2.8	0.3	3.2
Canada goose	9.4	1.1	10.5
Canvasback	3.7	0.4	4.1
Common goldeneye	0.1	0.0	0.2
Common loon	0.0	0.0	0.0
Eurasian Wigeon	0.0	0.0	0.0
Gadwall	25.4	3.0	28.4
Green-winged teal	32.3	3.8	36.2
Horned grebe	0.2	0.0	0.2
Long-tailed duck	0.0	0.0	0.0
Mallard	4.7	0.6	5.3
Merganser red-breast	108.1	0.0	108.1
Merganser, common	134.0	0.0	134.0
Merganser, hooded	21.3	0.0	21.3
Northern pintail	7.5	0.9	8.3
Northern shoveler	5.2	0.6	5.8
Pied-billed grebe	1.2	0.2	1.4
Redhead	10.2	1.2	11.4
Ring-necked duck	4.5	0.5	5.0
Ruddy duck	12.7	1.5	14.2
Scoter, surf	0.0	0.0	0.0
Swan, mute	5.6	0.7	6.3
Swan, tundra	0.0	0.0	0.0
Wood duck	0.2	0.0	0.2
Bonapartes gull	199.8	0.3	200.1
Caspian tern	27.2	0.0	27.3
Doublecrested cormorant	279.7	0.4	280.1
Forsters tern	25.5	0.0	25.6
Glaucous gull	0.2	0.0	0.2
Great black-backed gull	2.0	0.0	2.0
Herring gull	221.0	0.3	221.3
Lesser black-backed gull	0.2	0.0	0.2
Ring-billed gull	96.4	0.1	96.5
American bittern	0.1	-	0.1
Black-crowned heron	1.0	-	1.0
Common moorhen	0.3	-	0.3
Great blue heron	5.7	-	5.7
Great egret	3.9	-	3.9

Avian Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Green heron	0.1	-	0.1
Sandhill crane	0.1	-	0.1
Sora	0.6	-	0.6
Virginia rail	0.2	-	0.2
American avocet	0.7	-	0.7
Black-necked stilt	0.1	-	0.1
Common snipe	4.4	-	4.4
Dunlin	34.9	-	34.9
Greater yellowlegs	4.0	-	4.0
Killdeer	4.1	-	4.1
Least sandpiper	0.1	-	0.1
Lesser yellowlegs	7.5	-	7.5
Long-bill dowitcher	0.2	-	0.2
Pectoral sandpiper	9.9	-	9.9
Semipalmated plover	0.0	-	0.0
Short-bill dowitcher	0.1	-	0.1
Solitary sandpiper	0.0	-	0.0
Spotted sandpiper	0.2	-	0.2
Willet	0.8	-	0.8
Wilsons snipe	0.7	-	0.7
Total Waterfowl			510
Total Seabirds			853
Total Wading birds			12
Total Shorebirds			68
Total All Avian Species			1,443

Table E-24. RR-2PH-FV11-2HA-1PCT-60MO: Estimated injuries to mammals for the base case model scenario using a 1 percent slow release of the oil and an oil mixture with 60 percent water when fully emulsified as mousse. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Mammal Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Muskrat	356.8	-	356.8
Total All Mammal Species			356.8

Table E-25. RR-2PH-FV11-2HA-1PCT-60MO: Estimated injuries to herpetofauna for the base case model scenario using a 1 percent slow release of the oil and an oil mixture with 60 percent water when fully emulsified as mousse. Note that the number oiled is based on a probability, and so mathematically can be < 1 animal. "-" indicates species was not present in region (due to lack of sufficient habitat to be resolved in the model grid).

Herptile Species	Number Killed in Detroit River and Lake Erie	Number Killed in Rouge River	Total Number Killed
Black rat snake	0.0	-	0.0
Blandings turtle	1.8	-	1.8
Butlers garter snake	0.0	-	0.0
Eastern fox snake	0.0	-	0.0
Eastern garter snake	0.1	-	0.1
Eastern spiny softshell	1.3	-	1.3
Map turtle	60.0	-	60.0
Midland painted turtle	51.2	-	51.2
Northern brown snake	0.0	-	0.0
Northern water snake	5.8	-	5.8
Red-ear slider turtle	1.3	-	1.3
Snapping turtle	10.2	-	10.2
American toad	15.6	-	15.6
Bullfrog	14.3	-	14.3
Gray tree frog	0.3	-	0.3
Green frog	9.3	-	9.3
Leopard frog	49.4	-	49.4
Western chorus frog	0.4	-	0.4
Wood frog	0.2	-	0.2
Total Reptiles			132
Total Amphibians			90
Total All Herptile Species			221

Tables E-26 to E-30 provide the estimated injuries to fish from the oil spill based on a $LC50_{\infty}$ value of 44ppb for species with average sensitivity to the Rouge River diesel and lubricating oil mixture. Scenarios were also run for $LC50_{\infty}$ values of 5ppb (for sensitive species) and 370ppb (for insensitive species) to bound these estimates, with the total range representing 95% of sensitivities to oil hydrocarbons based on species to date. The results indicate that the fish injuries computed by the model vary somewhat depending on the assumed percentage of the oil released slowly and after the majority of the first oil release had moved out of the Rouge River. The total injuries to fish for the 0 percent, 1 percent and 3 percent slow release scenarios, using an $LC50_{\infty}$ value of 44ppb for species of average sensitivity, are 153 kg, 228 kg and 258 kg, respectively. The total injuries to fish for the base case (1 percent slow release) scenario with oil containing 10 percent and 60 percent water when fully emulsified in mousse, using an $LC50_{\infty}$ value of 44ppb for species of average sensitivity, are 214 kg and 155 kg, respectively. Variation in species sensitivity to oil hydrocarbons induces a factor of 20 change in injuries. Thus, the fish injuries are not very sensitive to variation in the fates model inputs assumed, but are sensitive to the toxicity parameter range tested. Note, however, that most species would be close to average in sensitivity to oil hydrocarbons. In this system, it is unlikely that any of the species present would be highly sensitive to oil hydrocarbons (PAHs), given the historical and present levels of background contamination.

Table E-26. RR-2PH-FV11-2HA-1PCT: Estimated injuries to fish in the Rouge River, Detroit River, and Lake Erie using a 1 percent slow release of the oil and an LC50□value of 44ppb for species with average sensitivity to the Rouge River diesel and lubricating oil mix.

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Herrings	1.5	2.2	0.0	2.2
Marsh forage fish	0.0	0.0	0.0	0.0
Rainbow smelt	0.0	0.0	0.0	0.0
White bass	11.3	2.0	1.4	3.4
White perch	227	6.5	5.8	12.3
Bowfin	0.9	3.6	0.0	3.6
Bullhead catfish	24.4	1.4	1.4	2.8
Freshwater drum	8.5	1.0	1.3	2.3
Large forage fish	70.2	18.7	23.0	41.8
Largemouth bass	98.8	19.8	21.2	41.0
Longnose gar	6.5	9.1	0.0	9.1
Medium forage fish	131	9.8	12.7	22.5
Northern pike	1.2	0.8	0.9	1.6
Rainbow trout	2.0	0.3	0.3	0.5
Rock bass	174	12.2	11.3	23.4
Small forage fish	2,940	1.7	1.1	2.8
Smallmouth bass	64.0	18.6	20.1	38.7

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Sunfishes	139	4.4	3.9	8.3
Walleye	17.2	5.2	5.4	10.5
Yellow perch	3.8	1.5	0.0	1.5
Total small pelagic fish	1.5	2.2	0.0	2.2
Total large pelagic fish	238.0	8.4	7.2	15.6
Total demersal fish	3,680	108	102	211
Total demersal invertebrates	0.0	0.0	0.0	0.0
Total mollusks	0.0	0.0	0.0	0.0
Total	3,920	119	110	228

Table E-27. RR-2PH-FV11-2HA-0PCT: Summary of estimated injuries to fish in the Rouge River, Detroit River, and Lake Erie using a 0 percent slow release of the oil and an LC50∞ value of 44ppb for species with average sensitivity to the Rouge River diesel and lubricating oil mix.

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Herrings	1.0	1.4	0.0	1.4
Marsh forage fish	0.0	0.0	0.0	0.0
Rainbow smelt	0.0	0.0	0.0	0.0
White bass	12.3	2.1	1.5	3.7
White perch	246.9	7.1	6.3	13.4
Bowfin	0.6	2.3	0.0	2.3
Bullhead catfish	15.5	0.9	0.9	1.8
Freshwater drum	5.4	0.6	0.8	1.4
Large forage fish	44.5	11.9	14.6	26.5
Largemouth bass	62.7	12.5	13.5	26.0
Longnose gar	4.1	5.8	0.0	5.8
Medium forage fish	90.9	6.8	8.8	15.6
Northern pike	0.9	0.6	0.6	1.1
Rainbow trout	1.4	0.2	0.2	0.4
Rock bass	110.6	7.7	7.1	14.9
Small forage fish	1,863.6	1.1	0.7	1.8
Smallmouth bass	40.6	11.8	12.8	24.6
Sunfishes	88.4	2.8	2.5	5.3
Walleye	10.9	3.3	3.4	6.7
Yellow perch	2.4	1.0	0.0	1.0
Total small pelagic fish	1.0	1.4	0.0	1.4
Total large pelagic fish	259	9.2	7.8	17.0
Total demersal fish	2,342.4	69.2	65.8	135.0

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Total demersal invertebrates	0.0	0.0	0.0	0.0
Total mollusks	0.0	0.0	0.0	0.0
Total	2,602.5	79.8	73.6	153.4

Table E-28. RR-2PH-FV11-2HA-3PCT: Estimated injuries to fish in the Rouge River, Detroit River, and Lake Erie using a 3 percent slow release of the oil and an $LC50_{\infty}$ value of 44ppb for species with average sensitivity to the Rouge River diesel and lubricating oil mix.

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Herrings	1.4	2.0	0.0	2.0
Marsh forage fish	0.0	0.0	0.0	0.0
Rainbow smelt	0.0	0.0	0.0	0.0
White bass	15.1	2.6	1.9	4.5
White perch	304.1	8.7	7.8	16.5
Bowfin	1.0	4.0	0.0	4.0
Bullhead catfish	27.3	1.6	1.6	3.1
Freshwater drum	9.5	1.1	1.4	2.5
Large forage fish	78.6	21.0	25.8	46.7
Largemouth bass	110.6	22.1	23.8	45.9
Longnose gar	7.2	10.2	0.0	10.2
Medium forage fish	141.7	10.6	13.7	24.4
Northern pike	1.3	0.9	0.9	1.8
Rainbow trout	2.2	0.3	0.3	0.6
Rock bass	195.0	13.6	12.6	26.2
Small forage fish	3,287.9	1.9	1.2	3.1
Smallmouth bass	71.6	20.8	22.5	43.3
Sunfishes	156.0	4.9	4.4	9.3
Walleye	19.2	5.8	6.0	11.8
Yellow perch	4.3	1.7	0.0	1.7
Total small pelagic fish	1.4	2.0	0.0	2.0
Total large pelagic fish	319.2	11.3	9.7	21.0
Total demersal fish	4,113.4	120.5	114.1	234.6
Total demersal invertebrates	0.0	0.0	0.0	0.0
Total mollusks	0.0	0.0	0.0	0.0
Total	4,434.0	133.9	123.8	257.6

Table E-29. RR-2PH-FV11-2HA-1PCT-10MO: Estimated injuries to fish in the Rouge River, Detroit River, and Lake Erie using a 1 percent slow release of the oil and an $LC50_{\infty}$ value of 44ppb for species with average sensitivity to the Rouge River diesel and lubricating oil mix with oil containing 10 percent water when fully emulsified as mousse (i.e., assuming a low percentage of lubricating oil in the oil mixture).

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Herrings	1.0	1.5	0.0	1.5
Marsh forage fish	0.0	0.0	0.0	0.0
Rainbow smelt	0.0	0.0	0.0	0.0
White bass	13.3	2.3	1.7	4.0
White perch	267.0	7.6	6.8	14.4
Bowfin	0.8	3.3	0.0	3.3
Bullhead catfish	22.5	1.3	1.3	2.6
Freshwater drum	7.8	0.9	1.2	2.1
Large forage fish	64.7	17.3	21.2	38.5
Largemouth bass	91.1	18.2	19.6	37.8
Longnose gar	6.0	8.4	0.0	8.4
Medium forage fish	119.3	9.0	11.5	20.5
Northern pike	1.1	0.7	0.8	1.5
Rainbow trout	1.8	0.2	0.3	0.5
Rock bass	160.6	11.2	10.4	21.6
Small forage fish	2,707.9	1.6	1.0	2.6
Smallmouth bass	58.9	17.1	18.6	35.7
Sunfishes	128.5	4.1	3.6	7.7
Walleye	15.8	4.8	4.9	9.7
Yellow perch	3.5	1.4	0.0	1.4
Total small pelagic fish	1.0	1.5	0.0	1.5
Total large pelagic fish	280.3	9.9	8.5	18.4
Total demersal fish	3,390.4	99.5	94.3	193.7
Total demersal invertebrates	0.0	0.0	0.0	0.0
Total mollusks	0.0	0.0	0.0	0.0
Total	3,671.7	110.9	102.7	213.6

Table E-30. RR-2PH-FV11-2HA-1PCT-60MO: Estimated injuries to fish in the Rouge River, Detroit River, and Lake Erie using a 1 percent slow release of the oil and an $LC50_{\infty}$ value of 44ppb for species with average sensitivity to the Rouge River diesel and lubricating oil mix with oil containing 60 percent water when fully emulsified as mousse (i.e., assuming a high percentage of lubricating oil in the oil mixture).

Fish species:	Kill (#)	Kill (kg)	Production Forgone (kg)	Total Injury (kg)
Herrings	1.4	2.1	0.0	2.1
Marsh forage fish	0.0	0.0	0.0	0.0
Rainbow smelt	0.0	0.0	0.0	0.0
White bass	12.0	2.1	1.5	3.6
White perch	240.8	6.9	6.1	13.0
Bowfin	0.6	2.3	0.0	2.3
Bullhead catfish	15.7	0.9	0.9	1.8
Freshwater drum	5.5	0.7	0.8	1.5
Large forage fish	45.3	12.1	14.9	27.0
Largemouth bass	63.8	12.8	13.7	26.5
Longnose gar	4.2	5.9	0.0	5.9
Medium forage fish	88.7	6.7	8.6	15.2
Northern pike	0.8	0.5	0.6	1.1
Rainbow trout	1.4	0.2	0.2	0.4
Rock bass	112.5	7.9	7.3	15.1
Small forage fish	1,896.8	1.1	0.7	1.8
Smallmouth bass	41.3	12.0	13.0	25.0
Sunfishes	90.0	2.9	2.5	5.4
Walleye	11.1	3.4	3.5	6.8
Yellow perch	2.5	1.0	0.0	1.0
Total small pelagic fish	1.4	2.1	0.0	2.1
Total large pelagic fish	252.8	9.0	7.6	16.6
Total demersal fish	2,380.2	70.1	66.6	136.7
Total demersal invertebrates	0.0	0.0	0.0	0.0
Total mollusks	0.0	0.0	0.0	0.0
Total	2,634.3	81.1	74.2	155.3

E.2 Biological Model Results - Spatial

Figures E-3 to E-5 show the percent losses (the direct kill due to exposure to dissolved aromatics) for three behavior classes of fish: demersal, small pelagic and large pelagic. The injury represents a small percentage of the fish present in the Rouge River. Concentrations were diluted sufficiently by the time they reached the Detroit River such that the injury was not significant there. The fish were assumed in the model to remain within the Rouge River for the duration of the spill simulation, and so were exposed long enough for an injury to result.

Pelagic young-of-year represent planktonic stages of fish. The plankton are transported out of the Rouge River with the currents, and so their exposure was likely brief and did not cause much injury. Figure E-6 shows the ultimate locations of injured individuals at the end of the simulation.

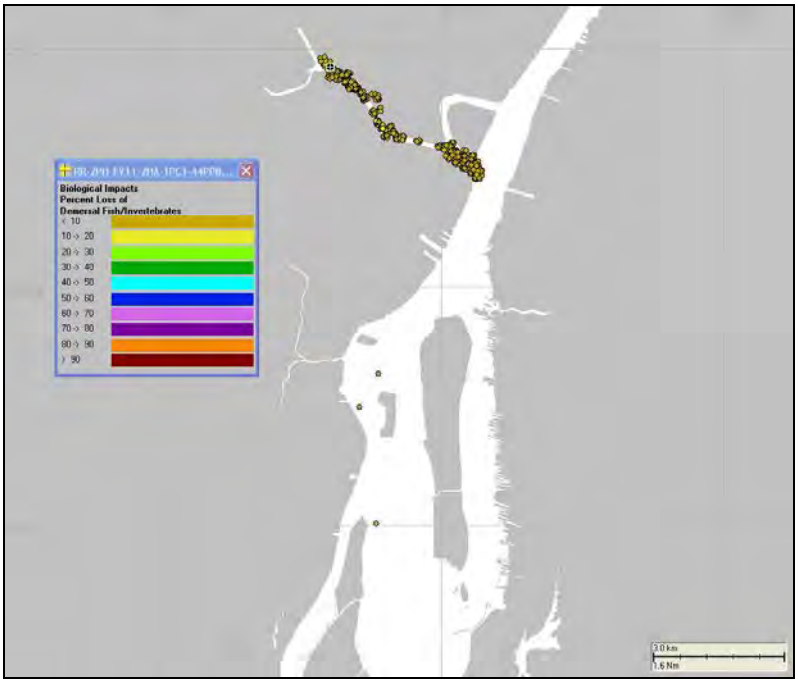

Figure E-3 Percent loss of demersal fish and invertebrates at the end of the base case simulation.

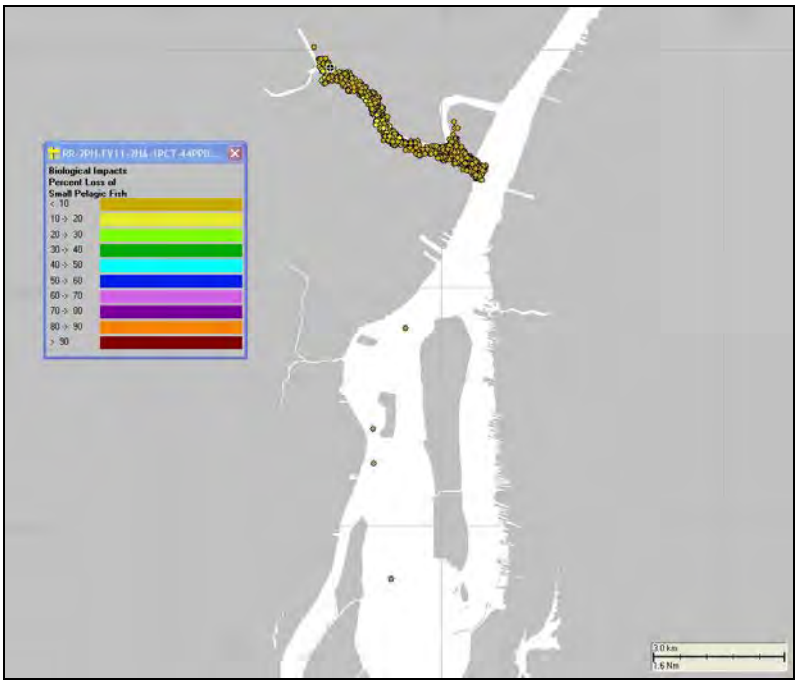

Figure E-4 Percent loss of small pelagic fish at the end of the base case simulation.

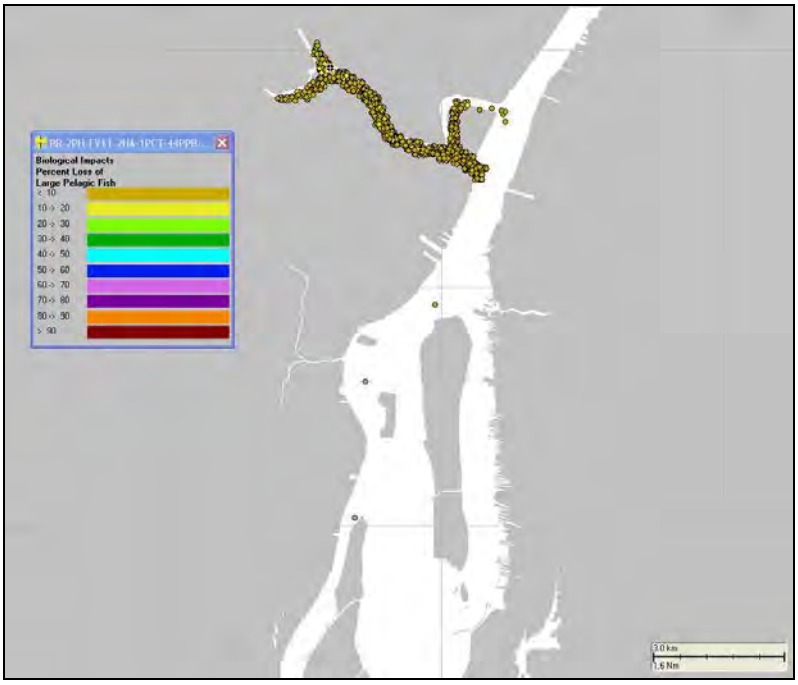

Figure E-5 Percent loss of large pelagic fish at the end of the base case simulation.

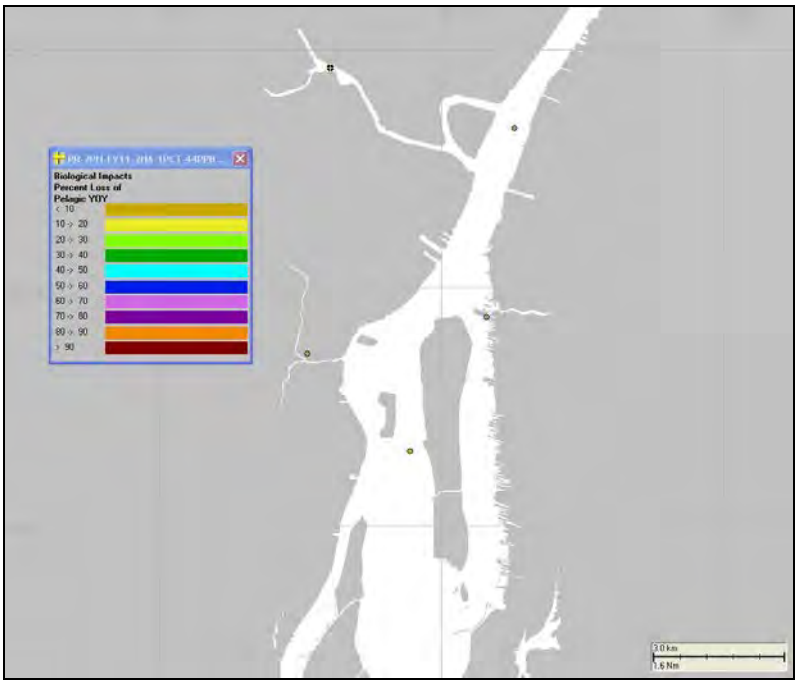

Figure E-6 Percent loss of pelagic young-of-year at the end of the base case simulation.

E.3 References

Soulliere, G. J., B. A. Potter, J. M. Coluccy, R. C. Gatti., C. L. Roy, D. R. Luukkonen, P. W. Brown, and M. W. Eichholz. 2007. Upper Mississippi River and Great Lakes Region Joint Venture Waterfowl Habitat Conservation Strategy. U.S. Fish and Wildlife Service, Fort Snelling, Minnesota, USA.