Chapter 16
Case Study: Using a Combined Laboratory, Field, and Modeling Approach to Assess Oil Spill Impacts

Sandy Raimondo, Jill A. Awkerman, Susan Yee, and Mace G. Barron

Abstract The *Deepwater Horizon* (DWH) spill was the largest oil spill in US history, requiring an assessment of injuries to nearshore habitats and estuarine organisms. Developing a model of appropriate complexity is critical in an environmental assessment; models should be complex enough to adequately address the assessment objectives without being more complex than is needed. We present an approach that starts with a sensitivity analysis of an initial assumption-based model to prioritize model parameters and focus research efforts to reduce model uncertainty. We then develop a targeted research strategy that utilized laboratory, field, and intermediate modeling efforts to parameterize a final set of models of varying complexity to evaluate risk. We demonstrate this process in a case study of the small estuarine fish, the sheepshead minnow (*Cyprinodon variegatus*), exposed to weathered oil in Barataria Bay, LA, following the DWH oil spill.

Keywords Population-level risk assessment · Model complexity · Uncertainty · Spatially explicit

16.1 Introduction

The *Deepwater Horizon* (DWH) spill was the largest oil spill in US history, with 507 million L of oil released over a period of 87 days beginning April 22, 2010 (Barron 2012). The salt marshes of Louisiana were among the most heavily oiled habitats, with the greatest oiling occurring in northern Barataria Bay (Michel et al. 2013). Sediments, shorelines, and marsh vegetation mats and substrates remained heavily oiled in areas of Barataria Bay beyond 2011 (Lin and Mendelssohn 2012;

S. Raimondo (✉) · J. A. Awkerman · S. Yee · M. G. Barron
US Environmental Protection Agency, Gulf Ecology Division, Gulf Breeze, FL, USA
e-mail: Raimondo.sandy@epa.gov; Awkerman.jill@epa.gov; yee.susan@epa.gov; barron.mace@epa.gov

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Silliman et al. 2012; Michel et al. 2013) and provided exposure routes to estuarine fish and other organisms (Awkerman et al. 2016; Brown-Peterson et al. 2017). For the DWH natural resource damage assessment, injuries to nearshore habitats and estuarine organisms were previously assessed using a hypothesis-driven approach of determining exposure, observing field effects, testing toxicity, and inferring impacts (Baker et al. 2017).

For complex assessments such as those for DWH, moving beyond deterministic approaches toward predictive, population-level assessments has been advocated (US EPA 2009). Ecological complexities (e.g., heterogeneous habitat and contaminant distribution) require models that include relevant scenarios and an understanding of the associated uncertainty. Coupled with sensitivity analyses, which identify the parameters with the largest influence on model outcome, predictive models have the potential to provide assessors a known confidence space in which decisions can be made (Lehuta et al. 2010).

Developing a model of appropriate complexity is a critical first step in an environmental assessment; models should be complex enough to adequately address the assessment objectives without being more complex than is needed (Schmolke et al. 2010). Model complexity can be either quantitative (e.g., empirical functions fit to observed data) or qualitative (e.g., categorical inclusion lacking empirical underpinnings), and the level of model complexity represents trade-offs in generality, realism, and precision (Raimondo et al. 2018). Qualitative complexity increases when functions are added to a general model that increases environmental realism, whereas quantitative complexity increases the precision in model output. Additional data may provide both qualitative and quantitative complexity, increasing both realism and precision, while other functions may increase model realism without the ability to evaluate confidence of the prediction. Understanding the trade-offs of generality, realism, and precision in developing a model of appropriate complexity is necessary to ensure the model appropriately addresses the objectives of the assessment.

As an assessor develops a model of appropriate complexity, they must identify important elements to include in the model and obtain the best data available to inform those functions or estimates. We present an approach that starts with a sensitivity analysis of an initial assumption-based model (herein, initial model) to prioritize model parameters on which to focus research efforts and reduce model uncertainty. We then develop a targeted research project that combines laboratory, field, and intermediate modeling efforts to parameterize a final set of models of varying complexity to evaluate risk. We demonstrate this process in a case study of the small estuarine fish, the sheepshead minnow (*Cyprinodon variegatus*), exposed to weathered oil in Barataria Bay, LA, following the DWH oil spill. Sheepshead minnows were selected because of their small home ranges (high site fidelity) and high levels of exposure from heavy oiling, due to close association with sediments (Raimondo et al. 2016).

16.2 Case Study Overview

16.2.1 Target Species

The sheepshead minnow is a euryhaline, eurothermic fish in the family Cyprinodontidae commonly found in estuarine areas along the Atlantic coast and in the Gulf of Mexico and may be the most abundant fish in some estuaries (Haney 1999). Sheepshead minnow burrow in the substrate and are highly territorial, with males displaying courtship behavior to attract females. Abundant toxicity information is available for this model species, and population models have been developed based on laboratory observations and experiments (Raimondo et al. 2009). The sheepshead minnow life cycle comprises four life stages representing embryo (within egg), larval (hatchling to development of swim bladder), juvenile (through sexual maturation), and adult. Fish life stages may be determined by size, age, or environment; however, size is most clearly linked to maturation (Kinne and Kinne 1962; Hardy 1978; Nordlie 2000; Cripe et al. 2009). The average size of fish at the larval-juvenile and juvenile-adult life stage transitions are 1.5 cm and 2.6 cm, respectively (Cripe et al. 2009; Nordlie 2000). Adults range from >2.6 to approximately 5.5 cm in size.

16.2.2 Conceptual Model

An initial model was developed for the sheepshead minnow in Gulf Coast estuaries that included layers for habitat suitability, distribution of a hypothetical contaminant, concentration response, and population dynamics. Initial fish distribution in the spatially explicit model was determined from pre-existing layers of salinity, temperature, dissolved oxygen, depth, and the observed range of their values, for sheepshead minnow obtained from the literature (Hardy 1978; Bennett and Beitinger 1997). A spatial layer of hypothetical contaminant distribution was used as input for hypothetical concentration-response curves to estimate the effect of exposure on fecundity, survival, and growth rates. Functions reflected percent reductions of individuals "exposed" to varying degrees of contamination relative to "unexposed" individuals.

A deterministic stage-based matrix population model captured population dynamics of sheepshead minnow with data derived from the control treatment of a laboratory toxicity study (Raimondo et al. 2009). The model has a 5-day time step corresponding to the duration of the shortest life stage (embryo), with the population growth rate, λ, determined as the dominant eigenvalue of the matrix (Caswell 2001). The matrix includes the estimated probability of survival within each of the four life stages (embryo, larval, juvenile, and adult), as well as the probability of transitioning to the next stage for each of the three developmental stages. The derivation of these parameters followed Caswell (2001) and is discussed in detail in

Raimondo et al. (2009). The estuary was divided into 90x90 m grids, with a fraction of the population moving between cells in each time step. Migration was modeled as the probability of fish moving between grids based on a decreasing function of habitat suitability. Density dependence was added to survival, reproduction, and movement, as both a ceiling on abundance (100 fish/m^2) and as an exponential relationship, in which fecundity and survival were dependent on habitat suitability.

16.2.3 Sensitivity Analysis

Model simulations with and without the contaminant were run to include interactions between all the model layers as appropriate. A global sensitivity analysis revealed which parameters and model assumptions had the strongest impacts on model predictions. A Monte Carlo analysis was performed that randomly drew parameters from ±10% of their model value. All parameters were modified simultaneously since some parameters are autocorrelated. The sensitivity of each parameter is defined as the proportional change in model outcome relative to the proportional change in the parameter.

Results of the sensitivity analysis are shown in Fig. 16.1. Larger values indicate that small changes in the parameter had large impacts on the model outcome. The analyses indicated that, in the absence of a contaminant, habitat suitability and density-dependent survival had the largest impacts on model predictions. Other parameters, including movement, larval survival, and larval development, also had strong impacts on model predictions. When the contaminant was included in the model, predictions also depended strongly on habitat suitability and larval survival, as well as the spatial distribution of the contaminant.

16.2.4 Developing a Targeted Research Strategy

Based on the results of the sensitivity analysis of the initial model, a targeted research strategy was developed to obtain the best available data from field, laboratory, or intermediate modeling to use in parameterizing a final set of models. The strategy included field observations to inform habitat suitability, contaminant distribution, and polycyclic aromatic hydrocarbon (PAH) composition, laboratory research to inform concentration-response relationships of each life stage exposed to weathered oil and density-dependent relationships, a hybrid field-laboratory study to identify differences in basic life history parameters (fecundity, size) in fish from laboratory and natural populations, and intermediate modeling to evaluate the interaction of density dependence and contaminant exposure and the influence of seasonally varying demographic rates.

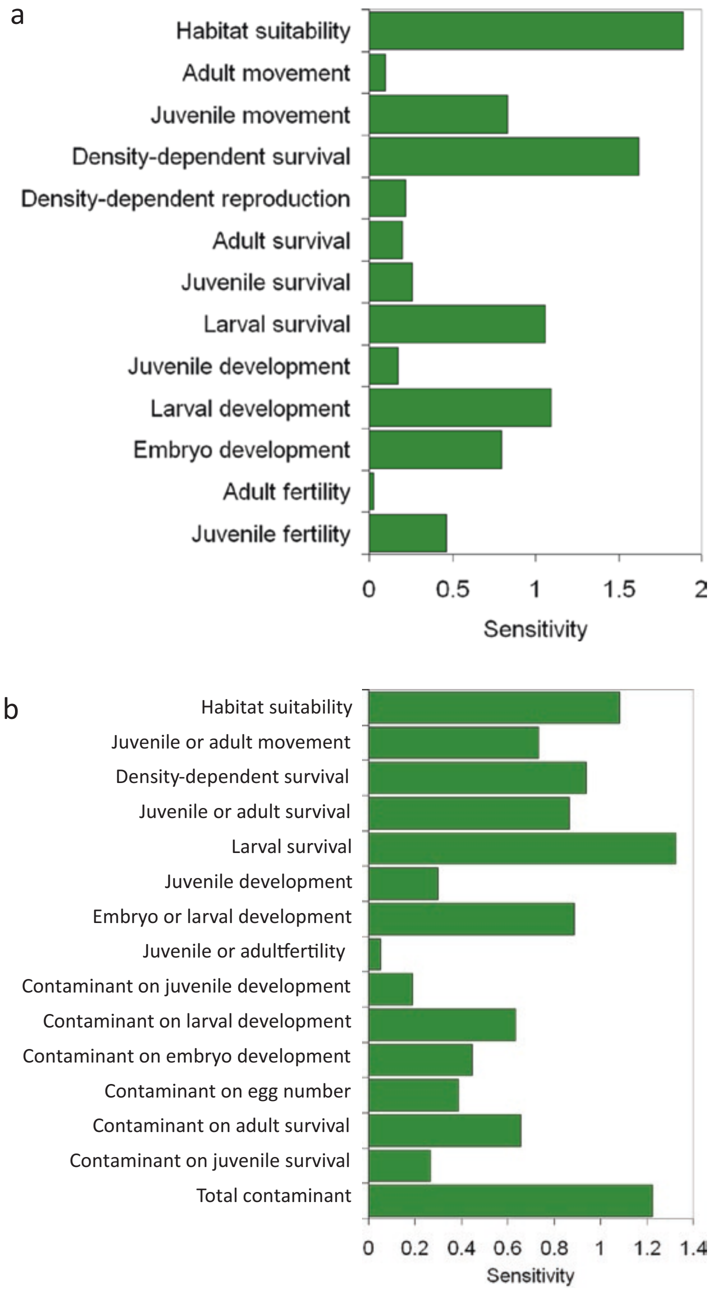

Fig. 16.1 Sensitivity analysis of initial models for fish dynamics (**a**) without contaminant exposure and (**b**) with contaminant exposure

16.3 Targeted Research

16.3.1 Field Research

16.3.1.1 Habitat suitability

A field study was conducted to develop a habitat suitability model for the sheepshead minnow in Gulf Coast estuaries. Data from areas classified as "Estuarine or Marine Wetland" by National Wetland Inventory Project in Pensacola Bay, Santa Rosa Sound, and Choctawhatchee Bay were used to determine habitat suitability based on sheepshead minnow abundance measured at these sites. Drop trap ($1m^2$) sampling was used to determine fish presence or absence (Rozas and Minello 1997) from over 300 sites across the estuarine systems. A generalized linear model (GLM) with binomial distribution and logit link was then fit to a model with habitat variables expected to be associated with presence of sheepshead minnows that were available as spatial layers for Barataria Bay (kriged values of bathymetry, salinity, and dissolved oxygen data). Sheepshead minnow was more probable in shallow areas with lower salinity and dissolved oxygen, and gridded locations within Barataria Bay were assigned habitat suitability scores using this model.

16.3.1.2 Contaminant Distribution and Composition

Sediment sampling locations were selected using a generalized random-tessellation stratified design, in which random sampling locations throughout Barataria Bay were chosen to be uniformly distributed within five Shoreline Cleanup Assessment Technique (SCAT) categories representing coastal oiling severity (no oil, very light, light, moderate, heavy). Sediment samples were collected in December 2010 and analyzed for PAHs, saturated hydrocarbons (SHC), and petroleum biomarkers. The relative ranking of PAH concentrations in collected samples did not always correspond with the SCAT observations in closest proximity at the time of sampling (Awkerman et al. 2016). Because PAHs were highly variable at finer spatial resolution, SCAT categories were used to define PAH concentrations in model simulations in two separate ways after gridded locations in our simulations had been categorized according to the closest SCAT observation for each time step. First, PAH concentrations were randomly chosen from empirical sediment sample values classified within the same SCAT category at the time of sampling, even though concentrations varied widely among categories. Data included all sediment samples analyzed within a year of the oil spill and documented in the Deepwater Horizon Information Management Portal. Second, the PAH range of sampled sediment was divided into quantiles, and the median value of each quantile was used to represent probabilistic exposure associated with each SCAT category. PAH estimates were then used in the final set of models as a basis from which to modify growth and survival rates of early life stage fish, using dose-response curves generated from laboratory exposures to weathered oiled sediment (Awkerman et al. 2016).

16.3.2 *Laboratory Research*

16.3.2.1 Toxicity Effects

Toxicity effects were determined from a life cycle exposure (from larvae through adult reproduction) of sheepshead minnows to laboratory-oiled sediment (Raimondo et al. 2016) and an embryonic development test using zebrafish as a surrogate (Raimondo et al. 2014). Both tests examined the impacts on fish exposed to sediment contaminated with weathered oil since oil binds to the sediment and burrowing fish, such as the sheepshead minnow, are most at risk through exposure to contaminated sediment. For both experiments, reference (uncontaminated) sediment was spiked with laboratory-weathered South Louisiana crude (SLC) oil at various concentrations to derive dose-response relationships of exposure and effects at each life stage. Zebrafish embryos were also exposed to sediment collected from an oiled site in Barataria Bay, Louisiana, in December 2010.

The embryonic development test is described in detail in Raimondo et al. (2014). Briefly, oiled sediment caused developmental malformations in embryos including yolk sac and pericardial edema, craniofacial and spinal defects, and tissue degeneration. No toxicity was observed in Barataria sediment, which contained 2 mg TPAH/kg 1% OC. Raimondo et al. (2016) described a 19-week complete life cycle experiment exposing sheepshead minnow to five concentrations of spiked sediment as well as one unspiked sediment control and one seawater (no sediment) control. The test was initiated with newly hatched larvae and ran through the reproductively active adult phase, measuring hatch rate, growth (e.g., length, weight), survival, and reproduction. Significant effects included reduced larval and juvenile standard length and wet weight and reduced fecundity. Dose-response relationships from both the embryonic and life cycle studies were used to describe the effects of oil in the final set of models.

16.3.2.2 Demographic Endpoints

Sheepshead minnow growth, survival, and reproduction for the initial model were estimated from cultured populations, which may not be representative of rates in wild populations. Rutter et al. (2012) compared four standard health condition metrics (hepatosomatic index, HSI; gonadosomatic index, GSI; fecundity, condition factor) between cultured and wild caught sheepshead minnow to determine if laboratory cultured fish were representative of wild populations. Wild fish yielded fewer eggs per female per unit body weight and were more robust (e.g., higher condition factor) than cultured fish. Fecundity estimates used in the final set of models were adjusted to reflect those from wild populations.

16.3.2.3 Density Dependence

The interaction between density dependence and contaminants can result in responses that range from compensatory to synergistic impacts to population growth (Raimondo et al. 2013). Density dependence (DD) was identified as a critical model component in the sensitivity analysis of the initial model but is difficult to quantify in field studies. A combination of laboratory and modeling research was conducted to quantify density dependence in sheepshead minnow and the potential interactions with chemical stressors. Influence of density on sheepshead minnow survival, growth, maturation, and reproduction was measured in a series of four laboratory studies (Raimondo et al. 2013). Sexual maturation was significantly affected by density but was not related to size, indicating that maturation is a function of both the presence and the density of adults. Fecundity was also density dependent, with significantly less fecund females in the mid-range and high densities compared to the lowest densities tested. Juvenile growth was only affected at extremely high densities (>500 fish m^{-2}), and there was no evidence of density-dependent influences on survival of any life stage. The highest observed field densities of fish in marsh sites were at levels that altered sexual maturation and fecundity in laboratory fish, but not at densities corresponding to laboratory impacts on juvenile growth (Awkerman et al. 2016).

16.3.3 Modeling

16.3.3.1 Interaction of Density Dependence and Contaminant Effects

Following the development of laboratory-based density dependence relationships, intermediate modeling efforts were conducted to evaluate whether density dependence and contaminant effects had additive, compensatory, or synergistic interactions (Raimondo 2013). In these simulations, density interacted with stressors in compensatory and synergistic ways, which were based on the DD functions used in the model and the organism-level impacts of the stressor. For example, the strongest compensation occurred where survival was both DD and impacted by the stressor. When no DD survival was included, DD fecundity and growth had limited compensatory influence. Since laboratory studies showed no evidence of DD survival in sheepshead minnow (Raimondo et al. 2013), compensatory mechanisms were not included in the final set of models, which applied a ceiling-type density dependence based on field data (Awkerman et al. 2016).

16.3.3.2 Temperature-Dependent Demographic Rates

Variation in survival and reproduction, including that attributed to seasonality, can be a large source of prediction uncertainty in models (Nordlie 2000; Raimondo et al. 2009). Temperature-driven functions for survival and reproduction were derived for the sheepshead minnow to account for seasonal variation in these demographic parameters (Raimondo 2012). A temperature-dependent growth rate function was developed for the von Bertalanffy constant, K, measured at various temperatures and fit to a logistic curve to estimate duration of larval and juvenile life stages at different temperatures. Stage-specific mortality was then modeled as a power function of size that included a temperature-dependent modification. Seasonal reproduction was then determined from temperature-dependent functions of embryo survival and stage duration (Raimondo 2012). The temperature-dependent functions for determining survival of immature life stages were then used in the final set of models that simulated population-level effects of sheepshead minnow exposed to weathered oil (Awkerman et al. 2016).

16.4 Assessing Risk Using Models of Varying Complexity

16.4.1 Models to Evaluate Risk

A final set of models were developed from the research described in the previous sections to evaluate the role of model complexity in assessing risk (Table 16.1; Awkerman et al. 2016). For all models in the final set, sheepshead minnow life cycle was divided into three stages based on documentation of length thresholds for juveniles and breeding adults (Nordlie 2000; Raimondo 2012). The set of population models incorporated early life stage oil exposure effects at three different levels of spatial and temporal complexity. The first and most simple assessment was based on a deterministic matrix model used to represent a single exposure event ("simple matrix model"). Relative differences in fish population growth rates at different

Table 16.1 Model scenarios for which simulations were run to compare model complexity and outcome relative to potential application

	Fish dynamics				Oil dynamics	
Model scenario	Fish population	Seasonal fluctuations	Movement	Behavioral response	Temporal	Spatial
Simple matrix model	X					
Seasonal matrix model	X	X			X	
SEPM[a] no oil	X	X	X			
SEPM homogenous oil	X	X	X		X	
SEPM SCAT oil	X	X	X		X	X
SEPM oil avoidance	X	X	X	X	X	X

[a] Spatially explicit population model

exposure concentrations provide an indication of relative impacts but offer no long-term perspective. A second approach repeated the simple matrix model over time with seasonal variation in vital rates based on temperature flux (“seasonal matrix model”; Raimondo 2012) and changing coastal oiling categorization. The extended projection allowed interpretation of exposure effects over time and simulated potential recovery of the population. The third and final approach included more spatial context, recognizing that contaminant distribution varied throughout the bay as well as over time. Spatially explicit population models (SEPM) were developed for four different scenarios: (1) a baseline “SEPM no oil” simulation, (2) a “SEPM homogenous oil” simulation in which exposure throughout the bay is based on a single observation in Bay Jimmy, (3) a “SEPM SCAT oil” simulation in which the nearest observed coastal oiling category was used to determine probable range of PAH exposure, and (4) a “SEPM oil avoidance” simulation in which habitat-based movement criteria were modified to include preference for less oiled locations.

For the spatially explicit population models, migration was incorporated as the probability of staying at a location during each time step, which was determined by an exponential function of habitat suitability (see above), based on sheepshead minnow movement rates documented in the field (Sutton 2002; Chitty and Able 2004). Avoidance of oiled habitat was simulated by applying criteria that included movement to less oiled locations within the same range during each time step. For each model scenario, observed average temperature for each 2-week time step was used to determine rates of growth, survival, and reproduction. Initial distribution of sheepshead minnow population prior to simulations was determined by running the model for 10 years using the 5-year average temperature (from Oct 2009 to Sept 2014) for each 2-week time step.

16.4.2 Model Outcomes

Deterministic models indicated dramatic differences in population growth rate for a single exposure event, based on reduced growth and survival of larval sheepshead minnows (Fig. 16.2a). With longer-term perspective of a seasonally varying model, these impacts are most pronounced during periods of higher reproductive activity, in the summer, and are less detrimental over time as coastal oiling effects are reduced (Fig. 16.2b). Spatially explicit models show minimal long-term impacts on sheepshead minnow abundance when the population dynamics throughout the bay are incorporated with effects corresponding to local oiling severity, suggesting the potential for compensatory effect by areas that are less impacted by oil exposure (Fig. 16.2c).

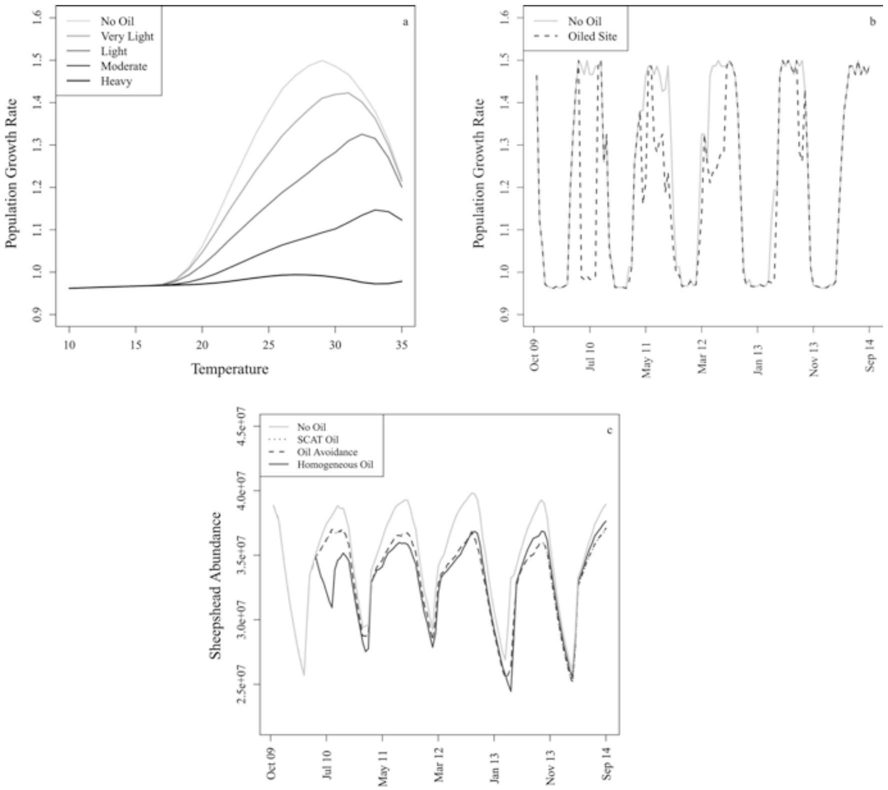

Fig. 16.2 Three approaches to modeling oil exposure effects in sheepshead minnow population: (**a**) including effects of temperature and PAH concentration on population growth rate, (**b**) comparing population growth rate of exposure representing maximally and minimally oiled sites with seasonal temperature variation, (**c**) simulating four spatial scenarios in which no oil is present, SCAT observations indicate spatial and temporal differences in PAH exposure, fish avoid oiled habitat, and PAH concentration from a single oiled site assumes homogenous oil distribution and is used to estimate a potential worst case scenario

16.5 Summary and Recommendations for Future Studies

Weathered DWH oil entered Barataria Bay during the 4 months of the spill and impacted sediments, shorelines, and marsh vegetation habitats (Michel et al. 2013). Oil distribution within the bay was heterogeneous, controlled by the small tidal range and high spatial variability in shoreline geography and density of vegetation. Additional factors affecting oil distribution included variability in composition, degree of weathering and viscosity of the weathered oil, and redistribution of hydrocarbons from storm events (Michel et al. 2013). Sediment PAH concentrations in Barataria Bay were extremely heterogeneous, ranging from non-detectable to greater than 100 mg/Kg (e.g., Turner et al. 2014; Awkerman et al. 2016). The aliphatic and lighter aromatic components of oil were more rapidly biodegraded, whereas higher molecular weight PAHs persisted in sediments for multiple years (e.g., Mahmoudi et al. 2013; Turner et al. 2014).

The relatively data-rich, spatially explicit models of post-spill impacts on estuarine fish populations improved model interpretations from a cost/benefit perspective. The spatial and temporal extent of contaminant data were a rare commodity and yet spatial data still lacked the resolution to adequately incorporate fine-scale modifications to movement based on patchy and variable contaminant distribution. Different levels of model complexity offer endpoints of varying utility – from immediate impacts as estimated in a deterministic matrix model to long-term projections of potential recovery and overall population abundance. Resources are seldom available to empirically analyze changing contaminant distribution and potential impacts in a timely fashion; however, simulations like the examples presented offer a way of assessing different scenarios to establish a range of potential outcomes that could inform the relative impact of contamination effects as well as response strategies.

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