NUMERICAL MODELING OF OIL SPILLS IN THE INLAND WATERWAYS OF THE LOWER MISSISSIPPI RIVER DELTA

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ABSTRACT
The demand for fossil fuels is driving the rapid expansion of the petroleum industry’s infrastructure. Louisiana’s wetlands are the most industrialized in the world. The oil industry has infiltrated every part of the Lower Mississippi River Delta (LMRD) from the fixed facilities and transport vessels traveling along inland waterways, the pipelines and canals running through the wetlands, and the offshore platforms along the Gulf of Mexico coastline. An oil spill could seriously damage the coastal wetlands that are already rapidly degrading, pollute the water supply, destroy wildlife habitat, and impact other natural economic and social resources. Additionally, proposed coastal restoration initiatives such as freshwater diversions could provide a conduit for spills to travel from the river to open wetland areas. Current inland oil fate and transport models cannot automatically be applied in the deltaic environment because they do not represent the high degree of minerals and fines in suspension, the unique characteristics of the shorelines, or the potential flow into the wetland areas. Thus, a three-dimensional oil fate and transport model was developed to investigate the behavior of oil spilled in the unique environment of the LMRD, assess the vulnerability at specific locations such as freshwater diversions from the river, and provide information for contingency and remediation plans.

Simulations of the hydrodynamics of the LMRD were generated using the U.S. Army Corps of Engineers Adaptive Hydraulics (ADH) modeling code. The model simulates the physical and chemical processes affecting the fate of a surface oil spill including slick advection and spreading, the vertical transport of dissolved and emulsified parcels, evaporation, dissolution, adsorption, sedimentation, re-suspension and degradation. The model estimates the distribution of oil in the surface slick, water column, sediments and atmosphere. Almost seventy percent of the Mississippi River’s sediment load is comprised of finer materials. The model is unique in using empirical predictions to describe oil’s interactions with fine suspended material and muddy shorelines. Hypothetical spills representative of the type and location of spills commonly occurring in the region were simulated to investigate the sensitivity of the system to the unique parameters. This model was developed to take advantage of the latest advances in computational fluid dynamics and weathering algorithms, while focusing on the complex hydraulics and sediment characteristics local to the Lower Mississippi River Delta.

INTRODUCTION
The continued demand for fossil fuels is driving the rapid expansion of its industry’s infrastructure. Oil spill rates are likely to increase as the industry expands. Understanding the behavior of the oil and interactions with the natural environment is essential to a sustainable balance between industry, the public and the environment. Louisiana’s wetlands are the most industrialized in the world. The oil industry has infiltrated every part of the Lower Mississippi River Delta (LMRD) from the rivers and lakes, through the wetlands, and Gulf of Mexico coastline. The proximity of the oil industry’s infrastructure to the valuable and sensitive coastal areas of Louisiana requires all possible negative impacts to be investigated. An oil spill could seriously damage the coastal wetlands that are already rapidly degrading, pollute the water supply, destroy wildlife habitat and natural resources and other economic and social resources.

The uniqueness of Louisiana and its relationship with the oil industry make it an interesting location for research and modeling. The wetlands and coastline are part of a morphing delta that formed thousands of years ago by the accumulation of fine sediments from the Upper Ohio River Valley and sand from the Gulf of Mexico. The influx of sediments, nearby continental shelf, salt deposits, temperature and raw phyto-based materials also formed the deep oil deposits under Southern Louisiana. Although this area seems ideal as a source, production and distribution site, the wetlands are being degraded directly and indirectly by the stresses induced by the infrastructure of industry. The installation of canals and pipelines throughout the wetlands has disturbed the delicate fresh and salt water balance the wetland ecosystems required and reduced its ability to endure storms. In addition, civil efforts to control the Mississippi River by implementing a levee system to prevent floods and maintaining navigation channels through dredging have prevented some of the natural replenishment of the delta. To restore and remediate the damage to the coastal areas, the state has initiated many efforts to find solutions. In an effort to divert new sediment, freshwater and nutrients to the degrading coastal areas, the opening of diversions from the river into the wetlands has been implemented as an alternative solution. Although intended to supply beneficial constituents, opening new outlets from the river poses the risk of allowing pollution into the wetlands as well. The
proximity of oil refineries, pipelines, and storage along the river, near potential diversion sites, increases the risk that oil from a spill could enter the wetlands and cause more damage than if contained within the river. Thus, the oil industry could potentially have an even greater negative impact on Louisiana’s wetlands and the local communities; the Lower Mississippi River Delta is a critical location to be studied and modeled for oil spills.

Government agencies and research institutions have developed models capable of modeling inland oil spills such as the National Oceanic and Atmospheric Administration’s (NOAA, 2005; 2007) Automated Data Inquiry for Oil Spills (ADIOS), General NOAA Operating Modeling Environment (GNOME) and Trajectory Analysis Planner (TAP), ROSS3 (Yapa et al., 1994), the Multiphase Oil Spill Model (MOSM) (Tkalich et al., 2003), and OILMAP (Applied Science Associations (ASA), 1997); however, the uniqueness of each spill location prevents a code from being universally applied. The Lower Mississippi River Delta encompasses a variety of coastal landscapes including the river, the wetlands and diversions that are typically not incorporated into model oil spill models. The delta has complex geometry and unique characteristics such as fine sediment load. The fine sediments suspended in the water column and present at the shoreline impact the adsorption and removal processes occurring when the oil and sediments interact and can have long-lasting ecological impacts. Review of the literature revealed there is limited representation of the interactions between shoreline sediments and fine sediments, if included, in models. A three dimensional model for simulating the fate and transport of surface oil releases in the Lower Mississippi River Delta that includes algorithms to describe shoreline removal processes and fine sediment-oil interactions would take advantage of the latest advancements in science and yield a model that includes two mechanisms uniquely important to the study area. This research represents a critical and valuable step towards the ultimate goal of understanding the behavior of oil spills and protecting Louisiana from detrimental oil spills along inland waterways.

**OIL- MINERAL FINES AND SHORELINE INTERACTIONS**

The Mississippi River drains over 1.24 million square miles with a mean annual discharge of 640,000 cfs upstream of its diversion to the Atchafalaya River (Iseri and Langbein, 1974). Draining almost half of the United States, the river carries $2 \times 10^{15}$ kg of suspended matter to the Gulf of Mexico each year (Meade, 1996). The freshwater discharge through the Bird’s Foot Delta study area averages 380 km$^3$ year$^{-1}$ (Meade and Parker, 1985). Seasonal highs in mean monthly discharge can be expected to be three times the seasonal low discharges. The sediment load can vary as much as five orders of magnitude when comparing the maximum high in March to the minimum low in September (Corbett, 2004). The study area includes the lower 78 miles of the Mississippi River from Point a la Hache through the Head of Passes to the low wave energy, low tide range Gulf of Mexico as seen in Figure 1. The shorelines are composed of progressively finer deposits downstream to the Gulf of Mexico (Fisk, 1944). The high suspended sediment concentrations mostly composed of finer materials and large areas of potentially exposed shorelines of the Lower Mississippi River suggest oil released in the study area would be significantly affected by oil-mineral interactions.

![FIGURE 1. LOWER MISSISSIPPI RIVER DELTA STUDY AREA. STUDY AREA IS FRAMED BY YELLOW BOX IN ABOVE FIGURE, REPRESENTING 78 RIVER MILES FROM POINTE A LA HACHE TO GULF OF MEXICO (NASA, 2005).](image-url)
for in modeling. Bragg and Owens (1994) documented natural cleaning due primarily to oil-clay flocculation in two sheltered, low wave energy study sites. The laboratory work associated with the study indicated the aggregates were positively buoyant and not likely to accumulate oil in the nearshore bed. The process of flocculation was understood to be a mechanism to remove oil from shorelines with minimal wave activity. However, laboratory studies show breaking wave energy would enhance OMA formation (Lee and Stoffyn-Egli, 2001).

For the reaches of shoreline characterized by sand, OMA formation can still occur accelerating the removal process. The 1993 Tampa Bay spill demonstrated shoreline removal was possible without clays even in a low energy wave environment. The sediments were predominantly calcareous mineral fines, well sorted fine to coarse sand with a high shell fragment content and no clays present. Wave heights were usually less than 30 cm; cleaned sediments were transported up the beach in only two or three tidal cycles. As a result of this study, the process known as clay oil flocculation became “oil-mineral aggregates” (OMA), expanded to include other types of mineral fines (Owens et al., 1995).

Lee et al. (2002) studied the OSSA II river spill along the Rio Desaguadero in Belize confirmed OMA formation can occur in river water, under low salinity conditions. The salinity of Rio Desaguadero was approximately 1.5 ppt at the time of the spill. An environmental risk assessment conducted after the pipeline break reported they could not account for 27-37% of the oil. Enhanced microbial activity associated with OMA formation may have led to the accelerated removal of the residual oil; laboratory analysis supported this hypothesis (Lee et al., 2002). Le Floch et al. (2002) conducted a series of experiments on a range of salinity values as low as 1.5 to 0.15 ppt (1/20 to 1/200 of ocean water), concluding rates of OMA formation were not significantly different from that of seawater. Depending on oil type and minerals present, OMA formation decreased linearly below these levels. The slightly saline waters in the lower part of the Mississippi River can support this mechanism, similarly to the Belize case study.

Modeling the Lower Mississippi River Delta requires consideration of processes that are not as well understood. Oil sedimentation and oil-mineral aggregate formation are suggested to be significant processes affecting the fate and transport of oil released in the natural environment. Oil released into surface waters with suspended sediments may adsorb to particles, then settle out or form free-phase globules and oil mineral aggregates. Salinity, temperature and oil type influence the rate and extent these processes occur (Khelifa et al., 2002). The oil mineral interactions also influence the natural removal rates of oil from shorelines (Owens, 2003). The meandering nature of the river increases the likeliness of oil to shoreline contact, but its adsorption to the substrate will vary due to oil to mineral interactions. Review of the literature and the characteristics of the lower Mississippi River suggest that the suspended particulates present and potential for OMA formation and shoreline removal will impact the fate and transport of oil in the study area.

In current models, the algorithms describing shoreline and sediment interactions are based on maximum holding capacities and the adsorption to sand if included at all. Previous research and experimentation has led to the ability to integrate OMA formation and shoreline removal rates involving mineral fines into numerical models for the prediction of fate and transport of an oil spill. Data on OMA formation and predictive models have recently become available to determine the time required to form stable aggregates and mass of OMA dispersed oil (Hill et al., 2002; Khelifa, 2002). Results from these models showed a stabilization time of less than one day with adequate sediment concentrations under a range of natural environment conditions. Recently, formulas have been developed to estimate the total oil dispersed by OMA based on mass of the spill, the ratio oil viscosity to density and the asphaltenes/resins content. In addition to laboratory derived empirical relationships, a simple test has been developed to assess the potential of beach sediments to form OMA (Stoffyn-Egli, 2000).

MODEL DESCRIPTION

In general, oil spill modeling can be separated into a three part process: 1) a conceptual model should be developed based on locations of interest, the timing and magnitude of typical or anticipated releases, 2) a hydrodynamic model describing the temporal and spatial distribution of water motion must be developed to determine the trajectory of the main body of the pollutant, 3) a fate and transport model to describe the spread of the pollutant about its center of mass, transport down river, and degradation. Additional modules can be added to describe the environmental impact and other response related occurrences.

Data was collected to describe the bathymetry and topography of the study area, flow conditions, sediment characteristics, and local environmental conditions. The United States Army Corps of Engineers (USACE) New Orleans District Hydrographic Survey maps show the river channel and the overbanks from Black Hawk, LA (RM 324) through the passes into the Gulf of Mexico, using the NAD 1983 horizontal datum. A high quality unstructured finite element mesh was generated to capture the changes in bathymetry. The flow field was generated using the Adaptive Hydraulic (ADH) model developed by the USACE. ADH is an unstructured finite element package capable of modeling 2-dimensional and 3-dimensional shallow water and Navier-Stokes equations for steady and unsteady flow. ADH requires an initial mesh that is fine enough to capture the details of the bathymetry and topography, then uses an adaptive technique to refine the mesh further as necessary to maintain mass conservation. ADH requires input for boundary conditions such as upstream discharge and stage levels and environmental parameters (Tate and Berger, 2006).

The fate and transport model consists of two layers, the surface slick and oil dispersed in the water column. These layers are able to exchange mass between them and with the atmosphere, shoreline and bottom sediments. A popular method to describe an oil slick is to divide it into small grids or elements to which local coordinates are assigned, the Lagrangian Discrete Parcels method. The surface volume is calculated at every time step, accounting for evaporation, dissolution and vertical dispersion (Chao et al., 2003). During the same time step, the slick is moved by advection or horizontal diffusion to a new location (ASCE, 1996; Al-Rabeh, 1989). The new grid coordinates can then be calculated. This procedure is performed at every time step (see Figure 2). When the slick encounters a shoreline, the deposition and entrainment algorithm are used (Humphrey, 1993; Torgrimson, 1980; Gundlach, 1987). The particle concentration distribution is based on the mass transport equation, accounting for vertical dispersion and horizontal mixing. The velocities of the flow field are input to determine the concentration distribution before sediment adsorption. Then, the algorithm developed to describe the suspended sediments interactions in the Mississippi River is employed before a final distribution is calculated.
Model Description

FIGURE 2. FATE AND TRANSPORT MODEL DESCRIPTION. MODEL FLOWCHART CONSISTS OF DATA COLLECTION, MESH GENERATION, HYDRODYNAMIC MODELING USING ADAPTIVE HYDRAULIC (ADH) MODELING, AND FATE AND TRANSPORT MODEL INCLUDING LAGRANGIAN DISCRETE PARCELS METHOD, WEATHERING AND TRANSPORT ALGORITHMS, AND SHORELINE AND FINE SEDIMENT-OIL MECHANISMS.

EXPECTED RESULTS

By modeling the hydrodynamics and fate and transport of an oil release in the Lower Mississippi River Delta, sensitive sites likely to be affected by a spill at a particular location and time can be identified, predictions can be made on how the plume will change and impact sensitive areas over time, thus, providing information for contingency plans. In addition, this research provides a more comprehensive understanding of the local area’s response to an oil release. After obtaining the surface currents from the hydrodynamic model, the advection of the slick can be determined. Based on the trajectory path, the location of shoreline to be impacted can be predicted along with riverbank holding capacity. By including algorithms for suspended particle interaction and shoreline removal rates, more of released oil can be accounted for by including the affects of local mechanisms.

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