Literature Review of Oil Spill Trajectory and Weathering Models for Inland Waters

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Introduction

A study was conducted to obtain further understanding of new oil spill response technologies to meet the needs of the inland spill response community. Part of the study was to evaluate the effectiveness and availability of current technologies related to oil weathering and trajectory modeling in various environments. To evaluate existing oil spill models for inland waters, a review of the major physical and chemical processes resolved by the models was completed. We provide an overview of the advantages and considerations of oil spill models currently available, a description of the physical and chemical processes included in each model evaluated, and a list of recommendations to improve oil weathering models and trajectory models for the conditions that occur in inland waters.

Main Results

Oil spill numerical models were initially developed decades ago in coastal and offshore waters to rapidly forecast an event to help first responders. Accordingly, fewer models have been designed to address the challenges of oil spills in rivers or lakes. Some differences to consider between modeling oil spills in marine and inland water environments include lower water density, smaller/narrower waterbodies, shallower depths, faster currents, larger areas for shoreline-oil interactions, and terrain effects on wind at the water surface. While oil spill models developed for coastal and marine applications can be applied to inland oil spills, several key characteristics of inland spills affecting the fate and transport of oil, such as slower rates of spreading and evaporation, reduced dilution, abrupt mixing during turbulence flow over dams and waterfalls, increased emulsification, and increased dilution, need to be considered. Table 1 describes these key modeling aspects for inland waters.

Table 1. Physical, Chemical, and Environmental Processes to be Reproduced by an Oil Spill Model.

Type of Process	Processes to be simulated
Physical transport and mixing processes	– Advection – Dispersion by turbulence, current shear, and groundwater inflow (3D mixing) – Mechanical spreading of the oil slick floating on the water surface – Coalescence of oil droplets – Entrainment of oil droplets in water column – Resurfacing of entrained oil – Diffusion of dissolved component from higher to lower concentrations
Chemical/weathering processes	– Degradation (bio- and photo-) – Dissolution of water-soluble components into water column – Emulsification (forms water-in-oil mousse) – Evaporation of volatile components from surface oil to atmosphere – Volatilization of dissolved components to atmosphere

Type of Process	Processes to be simulated
Interactions with the environment	– Oil-ice interaction – Shoreline habitat interactions (reed beds, mangroves, tidal flats) – Standing and refloating of shoreline stranded oil – Adherence of oil droplets to suspended particulate matter (SPM) – Adsorption of dissolved components to SPM – Sedimentation and resuspension of oil-mineral-aggregates (OMA) – Bioturbation of settled sediments – Hyporheic flow (movement of water through stream bed sediments)

Key Modeling Aspects for Inland Waters

One of the major differences between modeling oil spills in marine and inland water environments is the more variable nature of inland waterways on smaller and shorter spatial and temporal scales. River flow regimes involve areas with fast currents mixed with those of low-flow, as well as times of high flux versus receding flood waters. Inland waterway spills are often more frequent but involve smaller spill volumes. They are also closer to populated areas, intense industrial activities (power plants, industry, or thermal intake/discharges), and drinking water intakes, making them higher risk despite the smaller volumes of spilled oil. As such, it is critical that the oil spill model should be able to track the oil-soluble components (e.g., monoaromatic hydrocarbons, polynuclear aromatic hydrocarbons, and soluble aliphatics). Some of the physical characteristics of inland waters that potentially affect oil spill transport and fate processes include lower water density/salinity leading to more sunken/subsurface oil behavior; smaller/narrower water bodies leading to increased oil-in-water concentrations; shallower depths, faster currents; proportionally larger areas for shoreline-oil interaction; snow/ice cover affecting transport; variable water level (i.e., flooding and drying); changing slick area extent with water level changes; and terrain effects on wind at the water's surface.

These physical characteristics impact the chemical/weathering processes occurring in lakes and rivers. Some of the key aspects of weathering in inland waters can include slower rates of spreading and evaporation on water bodies with less surface area and more surrounding vegetative cover; reduced dilution in shallower water bodies with slower currents; abrupt mixing in particular areas from turbulent flow over dams and waterfalls; increased emulsification due to potentially more intense surface mixing; increased dissolution due to formation of smaller droplet sizes from higher turbulence; and higher adsorption/oil-mineral-aggregation (OMA) formation, settling, and resuspension.

Evaluation of Oil Spill Models for Inland Waters

Most widely available oil spill models were initially conceived for ocean/coastal applications. Marine spills were the most common type of oil spill events due to high frequency of maritime transport of petroleum and refined oil products. The key challenges for modeling in the marine environment have been to: a) properly characterize the driving metocean conditions; b) evaluate the long-term fate of oil and its interaction with the marine habitats; and c) validate the model inputs with difficult-to-perform experiments.

These generally applicable oil spill models can also be applied to spills in inland waters (lakes and rivers). However, as noted above, there are key characteristics of inland spills that affect the fate and transport of oil in the freshwater environment that differ from the marine spills. The following model review includes a general overview of some of the advantages and considerations of the major oil spill models currently available. Models were chosen for evaluation based on their inclusion in review papers (Vos, 2005; Foreman et al., 2005; Yapa and Shen, 1994) and whether they were in use or outdated as of the year of their review. The models included in this evaluation have been classified into two categories 1) **2D**

models: *OSIS* (BMT Cordah and NCEC (commercial)), *ROSS3* (Yapa et al., 1994), *NRDAMs* (including NRDAM/ CME Version 2 (French et al., 1996), NRDAM/ CME Version 1 (Reed et al., 1989), NRDAM/ GLE (Reed, 1996)), and *WPMD* (Fingas and Sydor, 1980), and 2) **3D models**: (*SIMAP* (RPS ASA (commercial); French McCay 2003, 2004), *OILMAP* (RPS ASA (commercial), *OSCAR* (SINTEF (commercial); Reed et al., 2000), *DELFT3D-PART* (Deltares, 2014 (publically available), *MIKE 21 & MIKE 3 FM Oil Spill Module* (Danish Hydraulic Institute, 2015 (commercial)), *MOHID* (Technical University of Lisbon (publically available)), and *GNOME* (NOAA OR&R (publically available).

Table 2 provides an overview of the physical and chemical processes included in each category (2D vs. 3D models), as well as the environmental interactions included in each. The list of processes and interactions assessed are listed in Table 1. Other considerations include whether the model assesses trajectory uncertainty or stochastic predictions and whether it incorporates response options.

Table 2. Summary of Physical, Chemical and Environmental Processes in the Models Evaluated.

Process/Interaction	2D Models	3D Models
Physical Processes		
Advection	100%	100%
Dispersion (horizontal and vertical mixing)	100%	75%
Mechanical spreading on water surface	100%	75%
Entrainment of oil droplets in water column	86%	25%
Resurfacing of entrained oil	43%	25%
Chemical Processes		
Degradation (bio- and photo-)	71%	25%
Dissolution of soluble components	43%	50%
Emulsification	86%	50%
Evaporation of volatile components from surface oil to atmosphere	100%	75%
Volatilization of dissolved components to atmosphere	14%	25%
Interactions with the Environment		
Oil-ice interactions	57%	50%
Shoreline-habitat interactions	100%	100%
Refloating of shoreline stranded oil	86%	0%
Adherence of droplets to suspended particulate matter (SPM)	29%	0%
Adsorption of dissolved components to SPM	29%	25%
Sedimentation of oil-mineral aggregates (OMA)	71%	0%
Resuspension of OMA	43%	0%
Other Features		
Trajectory uncertainty/stochastic predictions	57%	25%
Biological Effects Model	14%	25%
Response Options	71%	0%

Key knowledge gaps and considerations for trajectory and oil weathering models evaluated

In general, oil weathering models and oil trajectory models for inland waters need further research and understanding of the weathering rate and fate of oil residues in these environments. Additionally, improvements could be made to the currently available oil models to assess the transport and fate of oil and oil:particle aggregates in a variety of environments with a range of oil and sediment types. The majority of the models included in this evaluation could also be better validated through the use of appropriated designed experiments and during actual spills. Lastly, if further development were to occur on a river-specific oil and fate trajectory model, it would be recommended to update the processes that are currently in the ROSS3 model and similar models and integrate them into the other existing oil spill models that have been developed for ocean/coastal applications, as evaluated herein.

Conclusion

The fate and weathering processes that affect released oil depends principally upon several factors, including but not limited to the type of oil (specifically the exact mixture of hydrocarbon compounds present), the volume released, and the characteristics of the receiving environment. Other considerations when modeling inland water spills include the input location (which greatly affects trajectory due to spatially variable geography and currents), whether the oil travels over land before reaching water (affects mass balance and could involve sediment uptake), oil stranding on large woody debris that can then travel (affects transport), and seasonal pulses of water flow and suspended particulate matter (SPM) in runoff.

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