Journal of Environmental Sciences Vol. 12, No. 4, pp. 482—485, 2000

ISSN 1001—0742
CN11—2629/X

Article ID: 1001-0742(2000)04-0482-04 **CLC number**: X503 **Document code**: A

Biological exposure models for oil spill impact analysis

XIONG De-qi[1], Mark Reed[2], Narve Ekrol[2]

(1. Department of Marine Environmental Engineering, Dalian Maritime University, Dalian 116026, China; E-mail: deqi@china.com; 2. Department of Environmental Engineering, SINTEF Applied Chemistry Institute, 7034 Trondheim, Norway; E-mail: iku@chem.sintef.no)

Abstract: The oil spill impact analysis (OSIA) software system has been developed to supply a tool for comprehensive, quantitative environmental impact assessments resulting from oil spills. In the system, a biological component evaluates potential effects on exposed organisms based on results from a physico-chemical fates component, including the extent and characteristics of the surface slick, and dissolved and total concentrations of hydrocarbons in the water column. The component includes a particle-based exposure model for migratory adult fish populations, a particle-based exposure model for spawning planktonic organisms (eggs and larvae), and an exposure model for wildlife species (sea birds or marine mammals). The exposure model for migratory adult fish populations simulates the migration behaviors of fish populations migrating to or staying in their feeding areas, over-wintering areas or spawning areas, and determines the acute effects (mortality) and chronic accumulation (body burdens) from the dissolved contaminant. The exposure model for spawning planktonic organisms simulates the release of eggs and larvae, also as particles, from specific spawning areas during the spawning period, and determines their potential exposure to contaminants in the water or sediment. The exposure model for wild species calculates the exposure to surface oil of wildlife (bird and marine mammal) categories inhabiting the contaminated area. Compared with the earlier models in which all kinds of organisms are assumed evenly and randomly distributed, the updated biological exposure models can more realistically estimate potential effects on marine ecological system from oil spill pollution events.

Key words: oil spill; biological exposure; acute effects; chronic accumulation; migration of fish; spawning of eggs and larvae; habitat

1 Brief description of oil spill impact analysis system

As long as crude oils are produced offshore and transported across the seas by ships or pipelines, there is a risk of oil spills with the potential to cause significant environmental damage. The "Exxon Valdez" incident in Alaska, and other oil spills in recent years, have demonstrated high risk and damage to the local economics and environment caused by oil pollution. There is a growing need for quantification of impacts of oil spills on marine ecological system, for oil spill risk assessment, damage assessment, and contingency planning. Therefore, the oil spill impact analysis (OSIA) software system has been developed to supply a tool for comprehensive, quantitative environmental impact assessments in the marine environment resulting from oil spills. The software system is embedded within a graphical user interface in WINDOWS NT/95/98, which facilitates linkages to a variety of databases and tools. The latter allow the user to create or import wind time series, current fields, and grids of arbitrary spatial resolution.

The OSIA software system consists of physical fates models for oil and chemical behavior simulation, biological exposure models for biological effect analysis and a series of databases supplying chemical and toxicological parameters required by the models (Fig. 1). Key components of the physical system are a data-based oil weathering model (Aamo, 1993; Daling, 1999), a three-dimensional oil trajectory and chemical fates model (Reed, 1995), and an oil spill combat model (Aamo, 1996; Reed, 1999).

The physical model employs surface spreading, advection, entrainment, and volatilization algorithms to determine transport and fate at the surface. In the water column, horizontal and vertical advection and dispersion are simulated by random walk procedures. Partitioning between particulate-adsorbed and dissolved states is calculated based on linear equilibrium theory. The contaminant fraction adsorbed to suspended particulate matter is assumed to settle at a rate typical

---

Foundation item: the China Scholarship Council (CSC) and Oceanographic Scientific Funds for Youth from the State Oceanographic Administration (No. 96801), has attended the 3rd International Marine Environmental Modeling Seminar held at Lillerhammer City of Norway during 1999/04/11 - 1999/04/14

for the environment. Contaminants at the ocean bottom are mixed into the underlying sediments according to a simple bio-turbation equation. Degradation in water and sediments is represented as a first order decay process. Results of model simulations are stored at discrete time-steps in computer files, which are then available as input for biological exposure models.

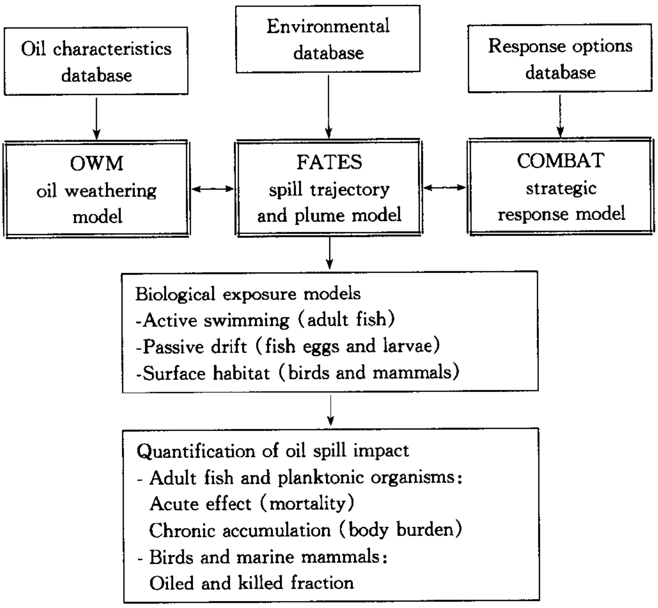

Fig. 1 Schematic overview of oil spill impact analysis system

2 Description of biological exposure models

The biological exposure models are used to evaluate the potential effects of hydrocarbons in the water column and on the surface on exposed organisms. Included are an exposure model for migratory adult fish populations following their specific migration routes, an exposure model for spawning planktonic organisms (eggs and larvae) spawning from their specific spawning areas, and an exposure model for wildlife species (sea birds or marine mammals) inhabiting at their specific habitat sites.

2.1 Exposure model for migratory adult fish populations

The exposure model for migratory adult fish populations simulates the migration pattern of fish populations migrating to or remaining within their feeding areas, over-wintering areas or spawning areas. Each fish population, represented by a user-defined number of particles, has its own horizontal and vertical average migration speed, and its own swimming depth range while moving along a specific migration route. Each particle representing a fish school moves at a speed normally distributed around an average migration speed, and in a determined direction within its acceptable depth range. If the fish encounter concentrations greater than a minimum threshold level, the time and concentrations of exposure are calculated and summed until the particle leaves the toxic zone. If the fish remain in the toxic zone for more than 4 days, the maximum exposure concentration over the 4 days is saved. Once out, the portion of living fish represented by the particle is reduced by the mortality induced by the toxicity. Mortality is calculated using laboratory acute toxicity test data (LC_{50}, 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. Mathematically, this model may be expressed as follows (French, 1996):

$$P_o = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Y_o} \exp\left(-\frac{1}{2}u^2\right)\mathrm{d}u, \qquad (1)$$

where P_0 is the portion expected to respond (die) at an environmental concentration c_0; Y_0 is the normal equivalent deviate of the concentration c_0, defined as:

$$Y_o = \frac{x_o - \mu}{\sigma}, \tag{2}$$

where $x_0 = \log_{10}(c_0)$, $\mu = \log_{10}(LC_{50})$, σ = standard deviation of the response; and $u = (x-\mu)/\sigma$, where x is concentration.

In the toxicity model, the LC_{50} is corrected for temperature and time of exposure and the integral is approximated by trapezoidal integration using 200 intervals, allowing accuracy to 0.1% mortality. LC_{50} value for each species can be changed and put in by the user, or derived from the toxic databases as default values.

The body burden for the chronic biological accumulation of different fish populations is computed by means of a simplified food web in which the uptake, depuration and grazing rates of representative organisms are taken into account (Reed, 1996). The migration behavior, the body burden of each fish particle and the histograms of total body burdens of the fish population can be animated simultaneously in the Graphical User Interface with the movement of the surface spill and contaminant plume. Also the time series (daily averaged) histograms of total body burden are archived for further analysis.

2.2 Exposure model for spawning planktonic organisms

The exposure component for spawning planktonic organisms (eggs and larvae) simulates the temporal and spatial spawning pattern of adult fish, and determines potential exposure to the dissolved contaminants in the water column as the ichthyoplankton drift with the current. Eggs for each species are released stochastically throughout the relevant spawning area at each time step during the specific spawning period. Benthic eggs remain stationary in the sediment until hatching. During this time the eggs are subject to exposure from contaminants in the sediments as well as the overlying water. Demersal larvae remain stationary in the bottom 1m of the water column. Pelagic larvae stay in the upper water column, drifting with both the surface currents and wind-driven currents in the horizontal direction, and move vertically by random dispersion. Both advective and turbulent processes are consistent with those used in the fates component. After hatching, benthic eggs are transformed into pelagic larvae, and rise to the upper water column.

The exposure history of a particle and the percent mortality caused by exposure to toxic concentrations are calculated in a similar manner as for adult fish populations. As long as a particle remains within a volume of water in which the concentration exceeds the threshold value, the time and average concentration of exposure are recorded. If the time of exposure exceeds 96 hours, the maximum 96 hour average concentration is retained. Upon leaving the toxic zone, the percentage mortality is calculated based on this maximum value. The behaviors of spawning and drifting, the body burden of each particle and the histograms of total body burdens of the planktonic organisms (eggs and larvae) can also be animated and shown visually on the screen for direct analysis.

2.3 Exposure model for birds and marine mammals

The exposure model for birds and mammals calculates the exposure to surface oil of birds and mammals inhabiting specific areas. This component is not at present a particle-based movement and exposure module, but assumes homogeneous distribution of organisms over specific polygonal areas. Exposure is based on the fraction covered by surface oil of each specific area used by each population. Wildlife populations are assumed to be in equal abundance across their specific habitat sites and to remix each day. At each time step, the number of individuals remaining alive intersecting the trajectory of surface slicks is estimated to calculate the number of adults exposed (oiled). The calculations are summarized as follows:

$$N = P_w \sum_{t=0}^{t=\infty} A_s N_t \Delta t, \tag{3}$$

where N is the total killed portion of each type of wildlife species, P_w is the probability of oiling and dying given that a surface slick is encountered by the wildlife behavior group of the species, A_s

is the portion of the specific habitat area swept by slicks over the time interval Δt, and N_t is the portion remaining alive at time t (for the species of concern). For shoreline exposure, the swept area is obtained by summing up the area of oiled grid cells. For surface spills at sea, a better method is to calculate the oil swept percentage of the specified area. For shoreline exposure, the area affected is obtained by summing up the area of oiled shoreline. For surface slicks at sea, the percentage of the specified area swept by oil is calculated.

To determine a dose obtained by a wildlife individual swimming through oil, the area of slick and thickness of oil intersected need to be estimated. The fates model provides an estimate of slick size (radius of a "spillet" treated as a circle) and thickness at any given time and location for the exposure model. According to the field and laboratory studies (French, 1996), if the volume of the spillet is less than 20 ml, no effects are assumed; if the diameter of the spillet is less than 230m, a thickness of 100 μm is assumed as a threshold thickness for oiling mortality; if the spillet is larger than 230m in diameter, 10 μm is assumed as a threshold thickness for oiling mortality.

The time series percentage oil-covered area and oil swept area for each wildlife specific habitat site, and the killed fraction for each wildlife type are archived for further analysis.

3 Conclusions

Earlier biological exposure models for general injury assessment (French, 1996; Reed, 1996) assumed evenly and randomly distributed organisms, without reference to known spawning or feeding areas, or migration patterns. The assumptions of simulation and assessment are not in good accordance with the actual situation. Since the volume of the ecosystem habit grid generally is so huge that the number of the particles representing the fish population and planktonic organisms may not be able to satisfy the lower limit, the injuries and exposure levels to the fish and planktonic resources are likely to be underestimated. Also the pervious model assumes that the marine wildlife populations are in equal abundance across each ecosystem. This may result in an incorrect percentage of wildlife killings, since the wildlife is not likely to exist everywhere within the habitat grid. Moreover, if an oil spill occurs, concern is frequently limited to the spill's effect on some defined priority areas or sensitive resources, aside from general injuries to the overall region. Therefore, the biological exposure models for specific habitat ecosystems and species the paper proposed are more useful in quantification analysis of oil spills impacts on marine environment.

References:

Aamo O M, Reed M, Daling P S *et al.*, 1993. Proceedings of the 1993 Arctic and marine oil spill program (AMOP) technical seminar [C]. Alberta, Canada, October 23—26, 1993. 617—626.

Aamo O M, Downing K, Reed M, 1996. Calibration, verification, and sensitivity analysis of the IKU oil spill contingency and response (OSCAR) model system [R]. Report No. 42.4048.00/01/96. Norwegian. 87 p. Trondheim, Norway. 43—48.

Daing P S, StrΦm T, 1999. Spill Science and Technology Bulletin[J], 5(1):63—74.

Daling P S, Brandvik P J, Mackay D *et al.*, 1990. Oil & Chemical Pollution [J], 7:199—224.

Daling P S, Brandvik P J, 1991. Characterization and prediction of the weathering properties of oil sat sea——a manual for the oils investigated in the DIWO project [R]. DIWO-report No. 16 IKU Petroleum Research, 1991. Trondheim, Norway. 67—78.

French D P, Reed M, Rines H *et al.* 1996. Technical Document, Vol. I. Model Description, Final Report (Contract No. 14-0001-91- C-11) [R], Washington DC: Office of Environmental Policy and Compliance, US Dept of the Interior. 415—425.

Reed M, Ekrol N, Rye H *et al.*, 1999. Spill Science and Technology Bulletin [J], 5(1):29—38.

Reed M, Johnsen S, Rye H *et al.*, 1996. Proceedings of 1995 International Produced Water Seminar [C], Trondheim, Norway, September, 1995. NY: Plenum Press. 317—332.

Reed M, Aamo O M, Daling P S, 1995. Spill Science and Technology Bulletin [J], 2(1):67—74.

Reed M, French D, Rines H, 1994. Journal of the Advanced Marine Technology Conference [J], (11): 65—90.

(Received for review September 9, 1999. Accepted May 8, 2000)