OIL SPILL DRIFT AND FATE MODEL

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Abstract. This paper describes an operational forecasting model of oil spill drift and fate. The model is aimed at predicting the behaviour of oil spills in the St. Lawrence River, and at providing decision support for planning responses and clean-up operations. A software system links the spill model to environmental data, wind forecasts and hydrodynamic models. The present paper focuses on the formulation and algorithms of the oil spill drift and fate model. Processes of mechanical spreading dispersion, weathering, as well as adhesion to shorelines are included. A discrete parcel approach is also employed to track the spill.

Keywords: oil spill drift, modelling, dispersion

1. Introduction

Knowledge of oil spill spreading, weathering and interaction with shorelines is important for contingency planning and directing response operations. The National Research Council Canadian Hydraulics Centre (NRC-CHC) has collaborated with Environment Canada (EC) in the development of an operational forecasting model for the St. Lawrence River. The model brings together the mechanics of oil slick behaviour, detailed environmental input, and a software environment that provides linking among various models and utilities for decision support.

Many studies have examined oil spill spreading and the weathering processes that change the chemical and physical properties of the oil. Expressions for oil spreading under the forces of gravity, surface tension, inertia and viscous resistance were first developed by Fay (1971). Numerous subsequent studies have examined and verified those formulas.

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Horizontal dispersion of an oil slick also takes place under the action of waves, wind and water current. It is difficult to adequately review the literature that addresses those processes here. However, comprehensive reviews and descriptions of oil spill drift and fate models were given by Spaulding (1988) and by Christiensen (1994). Dispersion of oil spills has also been examined by Shen *et al.* (1993).

As an oil spill drifts and spreads, a number of weathering processes takes place. They include evaporation, dissolution, emulsification, biodegradation and adhesion to shorelines. Evaporation rates for various oil types were measured, for example, by MacKay and Matsugu (1973) and Stiver and MacKay (1984). Other weathering processes, particularly in cold waters, were thoroughly examined by Payne *et al.* (1991). A thesis by Cantin (1992) reviewed available literature and developed a model of oil spill drift and fate. The approach of Cantin (1992) was used, to a large extent, in the present model.

The objective of the work reported here was to employ the available formulation of oil spreading and fate, and to customize the model for the conditions of the St. Lawrence River. An essential part of the work focused on providing accurate input of water current and wind predictions, as well as shoreline information. The software includes interfaces to hydrodynamic models of the St. Lawrence River, wind forecasts of EC, and Geographical Information Systems (GIS) data of shorelines. The output is designed to provide the users with the information required for decision support concerning clean-up operations. More details of the software system can be found in a report by Serrer *et al.* (1996). The following sections of this paper focus on the oil drift and fate model. The governing equations are reviewed, and the numerical approach is described. Examples of test cases are also shown.

2. Governing Equations

The present formulation follows the general approaches of Cantin (1992) and Shen *et al.* (1993). Additionally it includes a new treatment of oil interaction with shorelines and weed beds, integrates input environmental conditions which are specific for the study area, employs efficient search schemes which allows relatively large numbers of parcels to be used, and includes a customized user interface designed for operational use. Serrer *et al.* (1996) outlined the approach used in the present work. This approach is based on simulating the drift and weathering of oil in response to the environmental conditions. Input to the solver includes the results of hydrodynamic models, wind data, shoreline information, spilled oil properties, and initial spill conditions.

The solution of the mass transport equations of the oil is achieved by using a discrete-parcel approach. The oil is divided into a large number of discrete parcels. Each parcel is assigned several time-dependent attributes including mass, thickness, and spatial coordinates. The parcels are first advected by the ambient water current and wind. Next, random fluctuations are applied to the parcels to account for turbulent diffusion. The diffusion coefficient is determined by local shear velocity and water depth. Oil thickness for each parcel is then determined from the mass and distance of neighbouring parcels. Finally, evaporation is calculated for each parcel. As parcels encounter shore-lines or weed beds, deposition may occur depending on the capacity of the shoreline (or weed beds) to retain oil. This retention capacity is modelled by considering two separate values. The first is an absorption probability, that is, the probability that a parcel will be retained at this location. The second value is a maximum thickness of oil allowed at the current location. The discussion below addresses the governing equations used to model the following processes:

- Advection and diffusion
- Mechanical spreading
- Evaporation
- Shoreline and weed bed adhesion

2.1. ADVECTION

The advective velocity has two components. The first is due to the mean wind and currents, and the second accounts for local turbulent diffusion.

$$\vec{V} = \vec{V}_m + \vec{V}_t \tag{1}$$

The mean advective velocity $\vec{V}_m$ of each parcel is calculated as:

$$\vec{V}_m = \alpha_w \vec{V}_w + \alpha_c \vec{V}_c \tag{2}$$

where $\vec{V}_w$ is the wind velocity at 10 m above the water surface, $\vec{V}_c$ is the depth averaged mean water current, α_w is wind drag coefficient (the default value is 0.03), and α_c is the current drag coefficient (the default value is 1.15).

The velocity component $\vec{V}_t$ accounts for turbulent diffusion fluctuations in the drift velocity. Based on the random-walk analysis Fischer *et al.* (1979)

$$\vec{V}_t = R_n e^{i\theta'} \sqrt{\frac{4(D_e + D_T)}{\Delta t}} \tag{3}$$

where Δt is the time step, R_n is a normally distributed random number of mean value of 0.0 and standard deviation of 1.0, θ' is a uniformly distributed random angle between 0 and π, D_e is a dispersion coefficient due to mechanical spreading, and D_T is a diffusion coefficient.

In rivers, the diffusion coefficient is affected by the shear velocity $\vec{U}$ and the depth of flow h, Fischer *et al.* (1979) and Sayre and Chang (1969).

$$D_T = 0.6h\vec{U} \tag{4}$$

The diffusion coefficient D_T for surface dispersants can be written using Manning's constant, n_b Shen *et al.* (1993)

$$D_T = 0.4 n_b V_c h^{5/6} \sqrt{g} \tag{5}$$

where h is water depth, and g is the gravitational acceleration.

2.2. MECHANICAL SPREADING

The spreading of surface slicks may correspond to one of three regimes defined by Fay (1971) according to the dominant forces, namely: *gravity-inertia, gravity-viscosity*, and *surface tension-viscosity*. A number of studies have determined a spill's spreading rate as a function of time for each regime. The approach of Cantin (1992) is followed here in order to determine the spreading regime and spreading rates. He considers that oil thickness determines the spreading regime. The spreading rate for each regime is accounted for by including an additional diffusion coefficient to be applied to each parcel. The transition between spreading regimes is considered to depend on oil thickness as follows:

Regime 1 – oil thickness is greater than or equal to $E_{1\min}$
Regime 2 – oil thickness is greater than or equal to $E_{2\min}$
Regime 3 – oil thickness is less than $E_{2\min}$. The oil thickness also has a minimum value which may be taken as 10 μm.

The transition values of oil thickness are given by:

$$E_{1\min} = \sqrt{\gamma_w t_e} \tag{6}$$

and

$$E_{2\min} = \sqrt{\frac{\sigma_n}{\rho_w (1 - sg_{oil}) g}} \tag{7}$$

where γ_w is the kinematic viscosity of water, t_e is the exposure time of the parcel in seconds, σ_n is the spreading coefficient or net surface tension, ρ_w is the mass density of water, and sg_{oil} is the specific gravity of the oil. Oil thickness has to be calculated in order to determine the spreading regime.

The local thickness is determined by assuming that the mass in each parcel follows a Gaussian distribution with a standard deviation, σ_P. Contributions from neighbouring parcels are included in the calculations of the thickness for each parcel. The value of the standard deviation for each parcel, σ_P is difficult to directly estimate. The observations of Elliot and Wallace (1989), however, indicate that σ_P for a parcel is proportional to the standard deviation of the entire slick, as follows:

$$\sigma_p = 0.3\sigma_{Slick} \tag{8}$$

The standard deviation of the slick can be estimated from the diffusion coefficient and elapsed time using:

$$\sigma_{Slick} = \sqrt{\sigma_{Initial}^2 + 2(D_e + D_T)t_e} \tag{9}$$

where $\sigma_{Initial}$ = 0.0 for a spill from a point source. For existing slicks where the history of the parcel is unknown, the initial σ_P is approximated by the parcel radius.

The local thickness of each parcel T_p is calculated using:

$$T_p = \sum_{q=1}^{N} \frac{V_q}{2\pi\sigma_q^2} e^{-\left[\frac{r^2}{2\sigma_q^2}\right]} \tag{10}$$

where V_q is the volume of parcel q, σ_q is the standard deviation of the neighbouring parcel q, and r is the distance between centers of parcels.

Having determined the spreading regime, the spreading coefficient D_e is calculated as follows:

Regime 1: *gravity-inertia*

$$D_e = \frac{K_{2i}^2}{18}\sqrt{\Delta g V_p} \tag{11}$$

Regime 2: *gravity-viscosity*

$$D_e = \frac{K_{2v}K_{2t}}{18}\left(\frac{\Delta g V_p^2 \sigma_n^3}{\rho_w^3 \gamma_w^2}\right)^{1/6} \tag{12}$$

Regime 3: *surface tension-viscosity*

$$D_e = \frac{1}{18}\left(\frac{10^5 V_p^{3/4} K_{2t}^4 \sigma_n^2}{\pi \rho_w^2 \gamma_w^2}\right)^{1/3} \tag{13}$$

where K_{2i} is a proportionality constant = 1.14, K_{2v} is a proportionality constant = 1.45, K_{2t} is a proportionality constant = 2.30, V_p is the current parcel's volume, $\Delta g = \rho_w(1 - sg_{oil})g$, and γ_w is the kinematic viscosity of water.

2.3. EVAPORATION

Oil evaporation Cantin (1992) is a function of temperature, time, surface area and wind speed. The volume fraction evaporated ΔF_v is expressed as:

$$\Delta F_v = \left[\frac{KA_p\Delta t}{V_p}\right] e^{\left(6.3 - \frac{10.3(T_o^o + G_T F_v)}{T_w^o}\right)} \tag{14}$$

where:

K = $0.0025V_w^{0.78}$, and V_w is wind speed (m/s)

A_p = surface area of the parcel (m^2)

Δt = time step (s)

V_p = instantaneous parcel volume (m^3)

T_o^o = initial boiling temperature from the oil catalogue (°K)

G_T = gradient of the distillation curve, from the oil catalogue

F_v = fraction evaporated

T_w = water temperature (°K).

2.4. CHANGES IN OIL PROPERTIES WITH AMBIENT CONDITIONS

The density and dynamic viscosity of the oil in a spill changes in response to the ambient temperature and the evaporated fraction. Those variations are expressed by the following formulas:

$$\rho_p = \rho_{p0} + C_1 F_v - C_2 (T^0) \tag{15}$$

$$\mu_p = \mu_{p0} e^{(C_3 F_v)} e^{\left(\frac{C_4}{T^0}\right)} \tag{16}$$

where ρ_p is the oil density, ρ_{p0} is the initial density of the oil, μ_p is the dynamic viscosity, μ_{p0} is the initial dynamic viscosity of the oil, F_v is the evaporated fraction of the oil, T^0 is the ambient temperature [°K]. Calibration constants are given the symbols C_1, C_2, C_3, and C_4.

2.5. SHORELINE AND WEED BED ADHESION

As drifting oil encounters shorelines and weed beds, part of the oil may get deposited (or absorbed). The remaining oil continues to drift. Studies of shoreline interaction with oil (Shen *et al.*, 1993) have examined the oil retention capacity of a number of beach types. That capacity is usually expressed in terms of vulnerability indices which correspond to three categories: full retention of oil, full rejection, and partial retention. The estimates, however, appear to be qualitative. There are no data to differentiate between the capacities of the various beaches which are classified as having partial capacity for oil retention.

The fraction of deposited oil is determined here by assigning an "absorption probability" to each shoreline or weed bed type. Those probabilities are in input data files. A probability of 1 means that every parcel which encounters the shoreline is deposited. Such parcels are not allowed to drift, and remain stationary. Alternatively, a probability of zero corresponds to full rejection of the oil. In that case, all parcels encountering a shoreline are returned back into the stream. Also, parcels passing through weed beds of zero absorption probability continue to drift, unhindered by the weeds. The intermediate case of an absorption probability between zero and 1 correspond to partial deposition of the oil. A uniform random number between zero and 1 is generated for each parcel which encounters the shoreline. If the random number is less than the absorption probability, the parcel is deposited. Otherwise, the parcel continues to drift. Weed beds are treated similarly. The present model allows the possibility of specifying a physically based maximum capacity for different areas inside the model domain. This capacity is defined as a maximum allowed thick-ness of deposited oil.

An alternative approach was used by Shen *et al.* (1993) based on using a half-life value to describe the ability of the shoreline to retain oil. In that case all oil parcels are initially deposited upon encountering a shoreline. The volume fraction, which is re-introduced into the stream, is calculated using an exponential function which depends on the half-life of oil retention. Initial simulations using that approach, however, revealed that estimates of rejected oil would depend on the lengths of the arbitrarily chosen shoreline segments. Therefore, the "absorption probability" approach was employed, which avoided that problem.

3. Implementation

The computer code, named Particle Oil Spill Model (POSM), is implemented as a Langrangian discrete parcel solution. Each parcel in the simulation represents a small quantity of oil which is independently transported and weathered by environmental forces. Local parcel concentration is used to determine each parcel's local thickness and surface area. The local thickness is required to determine the dispersion coefficient and the surface area is used to calculate the evaporation. Local thickness is also used in determining weed and shoreline adhesion. Each parcel has a set of time dependent attributes including spatial coordinates and volume, which are computed at each time step.

One of the design objectives for POSM was to make it easy to use hydrodynamic data from various sources. Since there are a number of grid schemes by which hydrodynamics are modelled, it was decided that a triangular mesh was the most flexible way of handling spatial data. Both rectangular and curvilinear grid solutions can be easily mapped to a triangular mesh and interpolation of node data such as currents or wind to a point inside a triangle is straightforward.

The spatial reference frame for POSM is therefore a triangular mesh in UTM coordinates. Each node in the mesh can be assigned static or temporally varying properties such as current, water depth, oil absorption probabilities, etc. These properties are spatially and temporally interpolated at the location of each parcel during the course of the simulation.

To allow the user to define a spatially varying wind field, POSM accepts a second triangular mesh in the same UTM coordinate space as described above. This wind grid is typically much coarser than the hydrodynamic grid. Again each node is assigned static or temporally varying wind data. This data is spatially interpolated to each parcel's location. Temporal variations in wind are optionally interpolated allowing the wind data to be supplied at a much larger interval than the simulation time step.

Finally, in order to evaluate oil spill clean up strategies, a simple oil skimmer has been implemented in POSM. This device is defined as a circular area in the simulation domain which retains all parcels encountered. This skimmer has an infinite holding capacity and an infinite input flux capacity. When this device is enabled, POSM generates a separate time-series file containing the volume of oil retained by the skimmer over time.

4. Examples

Examples of simulation runs are shown here. They consider idealized cases in order to help with model verification. We note that verification of the model performance is undertaken by EC. That verification cannot be adequately addressed within the scope of the present paper.

4.1. AXISYMMETRIC SPILL

This case represents an instantaneous spill in quiescent water. Both wind and water current have zero values. Each parcel is assigned a volume of 1 L, and a total of 10,060 parcels are instantaneously released (i.e., the volume of the spill is 10.06 m^3). Properties of Norman Wells Crude were used in the simulation. The spill is assumed to take place over water of 5 m depth and 10° C. The time step is 120 s, and the total duration of the test is 21 h.

The results are illustrated in Figures 1a, b and c by showing positions of the parcels after 3, 12, and 21 h from the release of the spill. Colours of the parcels show the thickness distribution for the spill. Figure 2 shows the evolution of thickness profile along a cross section of the spill. A cursory examination of the resulting extent and thickness values indicates that the results are within the expected range (e.g., compared to the results of Cantin (1992)).

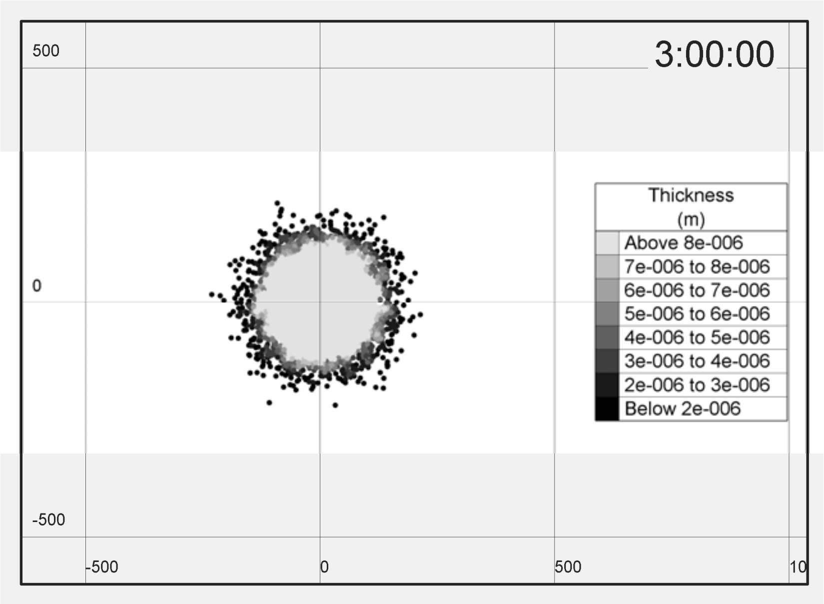

Figure 1a. Parcel positions and thickness after 3 h.

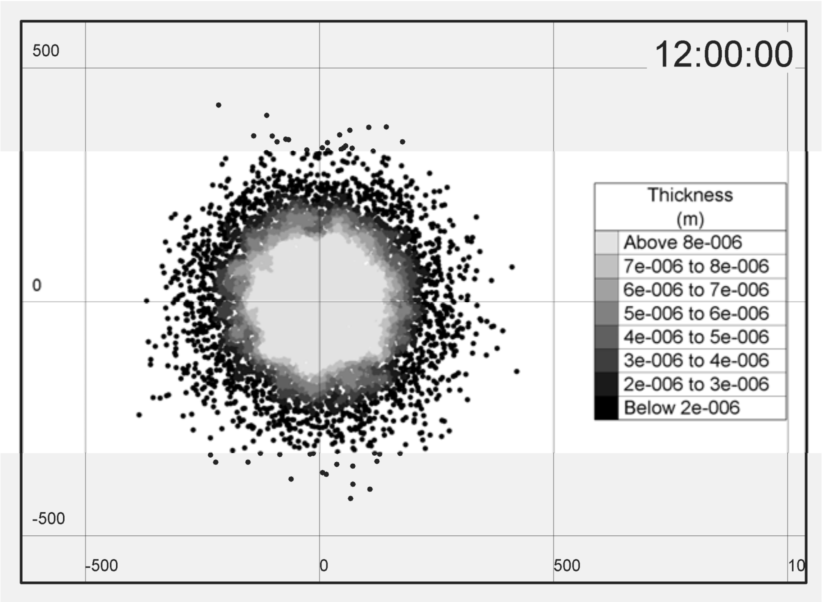

Figure 1b. Parcel positions and thickness after 12 h.

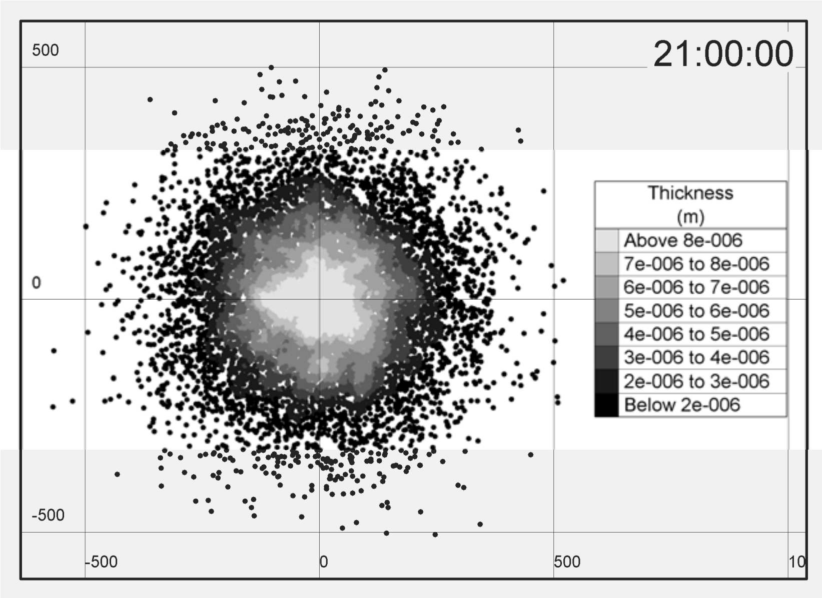

Figure 1c. Parcel positions and thickness after 21 h.

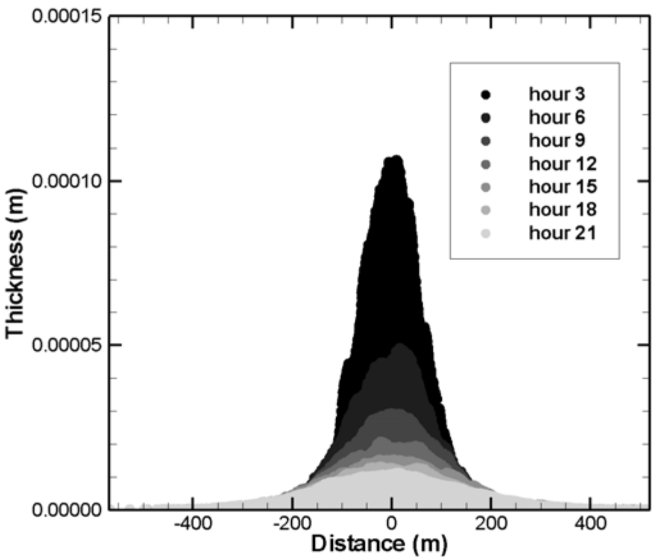

Figure 2. Profiles of oil thickness at several increments for an instantaneous axisymmetric spill.

4.2. CONTINUOUS SPILL IN A CHANNEL

This case considers a continuous spill at a rate of 1 L/s in a wide channel of uniform 5 m depth. A water current of 0.15 m/s is assumed to be uniform and steady. Again, properties of Norman Wells Crude were used in the simulation. Water temperature is 10° C, and wind velocity is zero. The time step is 60 s.

The resulting positions of the oil parcels are shown in Figures 3a, b and c after 30 min, 2 h, and 3 h. The colours of the parcels give the thickness of the oil. The extent of the spill and dispersion are in general agreement with expected values (e.g., Sayre *et al.,* 1969; Fischer *et al.,* 1979). Quantitative comparisons with measurements of oil spill spreading and other models are conducted by EC, and are beyond the scope of this paper.

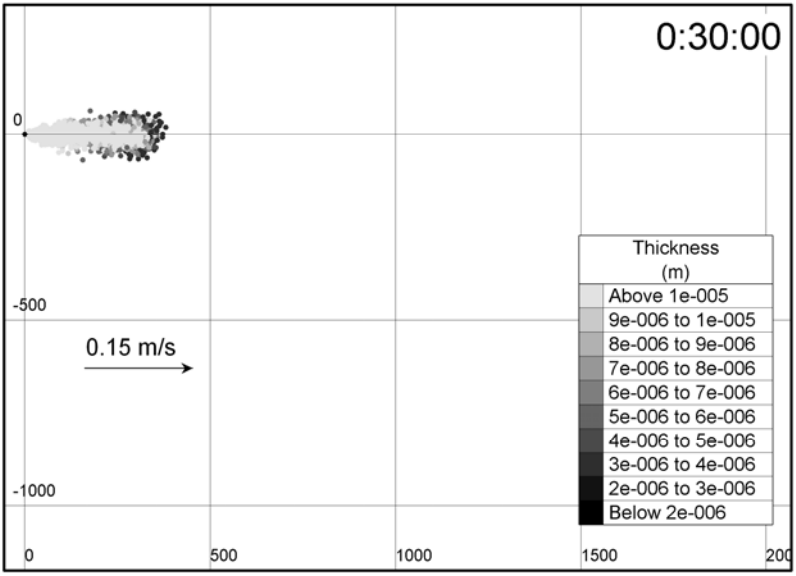

Figure 3a. Oil parcel positions and thicknesses after 30 min.

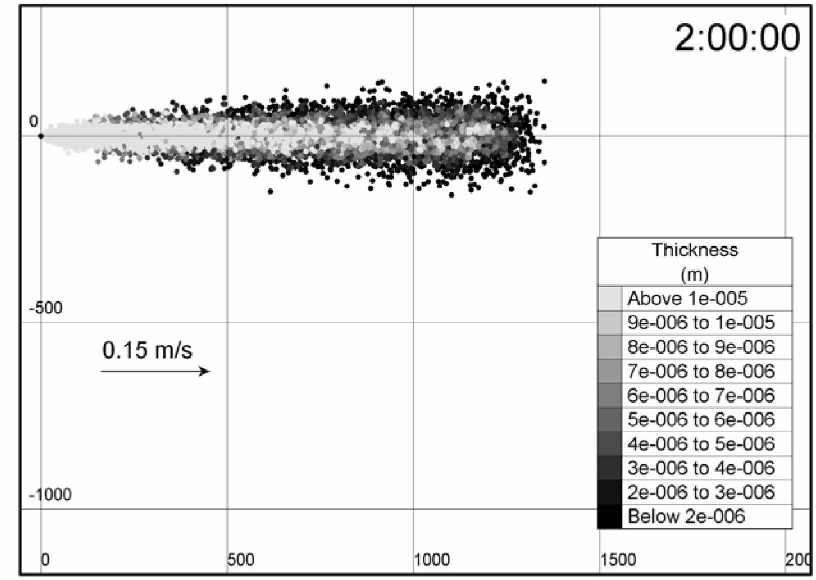

Figure 3b. Oil parcel positions and thicknesses after 2 h.

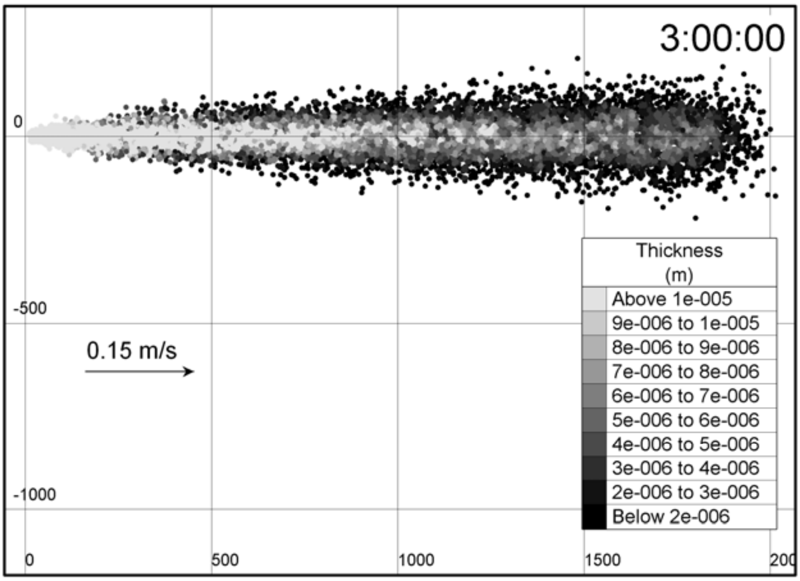

Figure 3c. Oil parcel positions and thicknesses after 3 h.

5. Conclusions

The present model was developed to provide operational forecasts of oil spills drift and fate in the St. Lawrence River. The model also provides decision support for contingency planning and for directing clean-up operations. The governing equations and algorithms were reviewed in the preceding sections of the paper. Available formulas for mechanical spreading, dispersion, evaporation and adhesion to shorelines were incorporated in the model. A discrete parcel approach was employed to simulate the drift of the oil spill.

The software system was designed to link the oil spill model to hydrodynamics models of the St. Lawrence River, wind forecasts, and GIS data on shorelines. The user interface was also designed to provide the "utility tools" needed for directing response operations.

Validation of the model has been carried out by Environment Canada (EC). The results of such tests and comparisons to available measurements are not included in this paper, but can be directly obtained from EC.

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