USE OF HYDRAULIC MODELING FOR RIVER OIL SPILLS. 1. TRAVEL TIME COMPUTATION FOR QUICK RESPONSE

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Lucrarea prezintă utilitatea folosirii unui model hidraulic 1D ca metodă simplă şi rapidă de estimare a timpului de sosire a frontului unei pete de petrol, informaţie necesară planurilor de urgenţă aplicate în cazul poluărilor accidentale cu hidrocarburi produse pe râuri. Sunt prezentate datele necesare realizării şi calibrării modelului. Durata de parcurs a frontului undei poluante rezultată din modelare s-a calculat pe baza vitezei medii în secţiune. Autorii prezintă o modalitate simplă de prognoză a timpului de parcurs al frontului undei poluante, cunoscând timpul calculat şi raportul dintre viteza medie şi viteza maximă în fiecare secţiune, corespunzătoare debitului de calcul.

Present paper shows how a 1D hydraulic model can be used as a simple and quick tool in finding the right time and location to apply immediate response measures in case of oil pollution accidents on rivers. The necessary data to develop and calibrate the model are presented. Computed travel time from the source to each cross-section is based on mean velocity. Authors present a simple way to predict an estimate of the real oil slick leading edge travel time by knowing the computed time and the ratio of mean velocity to maximum velocity in each cross-section and given discharge.

Keywords: river oil spill**,** travel time**,** HEC-RAS, 1D hydraulic modeling, oil slick, oil pollution accident

1. Introduction

During the last decades, the economic development involving oil (and its unsoluble derivatives) consumption and transport had a boost. This led to a higher risk of producing oil spill accidents in aquatic environments, either on rivers or oceans/seas. Therefore, the interest regarding the modeling, management and control of oil pollution accidents has continuously increased.

Internationally, this issue was approached by the numerous researchers from the different points of view. Some authors analysed the oil slick trajectory in the marine environment [1], [2], [3], [4], [5]. Others focused on physical, biological

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and chemical processes of the oil slick and tried to model its transport and fate in order to quantify the environmental impact [6], [7], [8], [9], [10]. Different oil transport software were developed (such as: 1D – RIVERSPILL, 2D – WPMB, NRDAM, ROSA, ROSS, ROSS2, MIKE 2.1, 3D – ROSS3, MIKE 3 PA/SA, etc.) and used to model real oil spill accidents [11], [12], [13], [14], [15].

In Romania, the frequency of accidental oil spills has shown the same growing concern as on the international level, during the last two decades (Fig. 1). Despite that, the number of publications on oil spill research is low, existing papers treating mostly with cleanup measures [16], [17], and very few with numerical simulations applied to oil slick transport on water surface [18], [19].

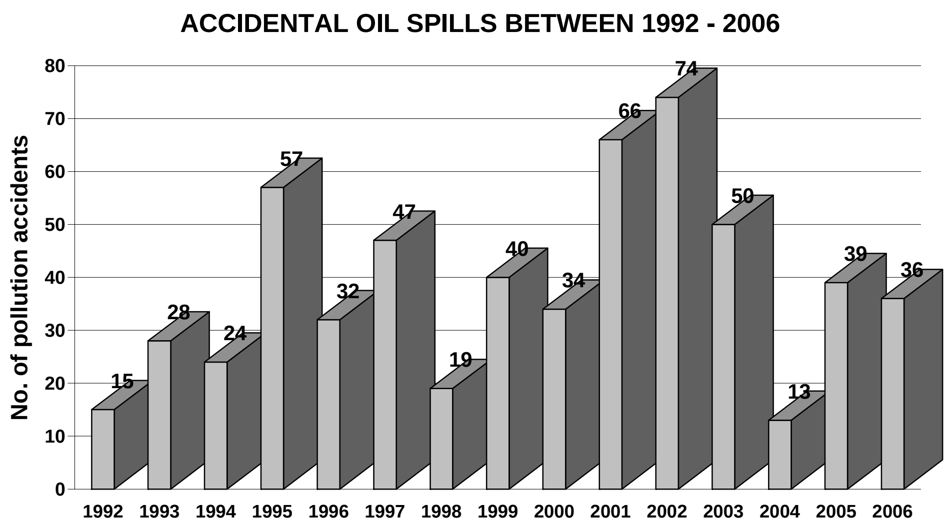

Fig. 1 Number of oil spill accidents happened in Romania between 1992 and 2006

Most of the oil pollution accidents in Romania (Fig. 1) happened on rivers, as opposed to the international situation, where the number of spills in marine environment is dominant. The former are known to generally have a quicker and higher anthropic impact, as the rivers usually flow through or nearby inhabited areas.

An accurate oil spill model is supposed to take into account the most important physical-chemical processes which describe the pollutant transport and fate phenomena. These processes depend on oil properties, hydraulic, hydrologic and environmental conditions. In Fig. 2 are schematically presented the main oil slick drifting and weathering processes.

The most important mechanism for oil pollutions transport in riverine environment is the stream advection component [20]. This is why it is of utmost importance to be able to forecast the exact moment in which the oil slick leading edge arrives in a certain cross section downstream the location where the pollution accident happened.

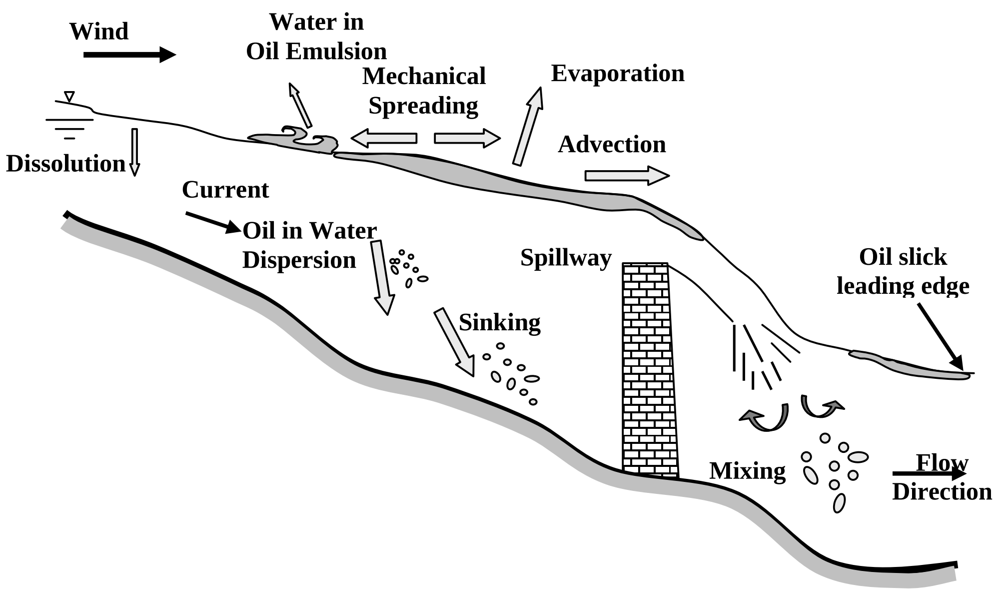

Fig. 2 Oil slick physical-chemical processes

Whereas for marine environments a 2D model is all that is needed, for long river reaches a 1D model describes with sufficient accuracy the main phenomena [11]. Also, time factor to apply control and cleanup measures is crucial for river spills. Therefore, in such accidents a rapid information on the moment when the dissolved fractions or the oil slick will reach a certain location is more useful even though it may have a degree of incertitude than no information at all.

Currently the particle-tracking method is the state of the art in accurately modeling the drifting mechanism of oil slick. However it is not an easy task to develop and use such a model in a short time. Also, since the other physical-chemical processes are less important than advection for the short period of time such a pollution evolves, for the sake of simplicity one can assume the oil is conservative and it drifts with the maximum velocity, V_{max}, in each river cross section.

Present paper suggests a simple and quick method to estimate the travel time of the oil slick leading edge by applying a 1D hydraulic model for the specific river reach. In principle, any 1D hydraulic software may be used, under steady or unsteady assumption, according to the study case.

In a subsequent paper the authors chose to use the HEC-RAS code [21] to apply and verify this travel time predicting method for a real oil spill accident case.

2. Data

Topo-bathymetric data are necessary to build the geometry of the model along the river reach under consideration: river system schematic with tributaries, junctions; closely spaced cross section and longitudinal profiles for all branches, maps (with bridges, access roads, etc.), bed gradation curves and aerial photos or ortophotoplans (with vegetation for calibration of the roughness parameter). Previous site inspection and knowledge of the reach are essential.

Hydrologic data are needed to perform the flow simulations: discharge and stage hydrographs (preferably hourly) in as many cross-sections as possible, rating curves, measured cross-section maximum velocities for different discharge values.

3. Hydraulic model

Under the unsteady flow assumption, the Saint-Venant equations

$$\frac{\partial h}{\partial x} + \frac{\alpha V}{g}\frac{\partial V}{\partial x} + \frac{1}{g}\frac{\partial V}{\partial t} = J - J_f \qquad (1)$$

$$A\frac{\partial V}{\partial x} + V\left(\frac{\partial A}{\partial x}\right)_{h=ct.} + B\frac{\partial h}{\partial t} = 0 \qquad (2)$$

may be solved by different numerical methods, the finite differences ones, being the most common. In previous equations, t is the time, h is the depth, V is the cross section mean velocity, x is the distance along flow direction, A is the wetted area, B is the top width, J is the longitudinal (geometric) slope and J_f is the friction slope [22].

Under the steady flow assumption, the gradually varied flow equation for non-prismatic river reaches reads

$$\frac{dh}{dx} = \frac{J - \dfrac{Q^2}{K^2}\left(1 - \dfrac{\alpha C^2 R}{gA}\dfrac{\partial A}{\partial x}\right)}{1 - \dfrac{\alpha Q^2}{g}\dfrac{B}{A^3}} \qquad (3)$$

where Q is the flow rate, K is the conveyance, C is the Chezy coefficient and α the Coriolis coefficient. In terms of water surface elevations, y, energy equation written in finite differences for each elementary computation reach, becomes:

$$\Delta y = -\frac{Q^2}{\overline{K}^2}\Delta x - \Delta h_v - \overline{\zeta}\left|\Delta h_v\right|, \quad (4)$$

where in addition to previous equations:
$\Delta h_v = \frac{\alpha Q^2}{2g}\left(\frac{1}{A_{i+1}^2} - \frac{1}{A_i^2}\right)$ is the variation of the velocity head, h_V, and $\overline{J}_f$, $\overline{K} = \frac{1}{n}\frac{\overline{A}^{5/3}}{\overline{P}^{2/3}}$ are the mean values of friction slope and conveyance (expressed in terms of mean wetted area and perimeter), respectively, for each elementary reach [23]. Equation (4) is solved by iterations, through the predictor-corrector procedure (step method).

As boundary conditions, generally a flow hydrograph (for the unsteady flow simulations) or a discharge value (for the steady flow simulations) are prescribed at the upstream boundaries and a rating curve or a known water surface corresponding to a given discharge value, respectively, are applied downstream. At the junctions, care must be taken to meet the continuity equation demands. Also, if changes in flow values occur along the main reach or its tributaries (due to precipitations, small tributaries or consumption), these changes must be taken into account as discharge injection or sink points.

After calibrating the roughness Manning parameter on measured values of water stage (surface elevation) in certain cross-sections, for one hydrologic event, the model should be able to represent any other event. Therefore, a validation process is necessary for a different set of hydrologic data. After validation, the model is considered to accurately describe the real flow and hydrodynamic parameters along the studied river reach [24].

4. Results

Mean velocities, V_c, in each cross section are computed by the 1D model run under the conditions (geometric, hydrologic and boundary) of the pollution accident. With these values and the cumulated distances, computed values of cumulated travel time, T_c, may be obtained, in each cross-section:

$$T_c = \frac{x}{V_c} \quad (5)$$

On the other hand, in a certain cross section, the real velocity of the oil slick, V_r, may be considered to be equal to the maximum value of the velocity distribution ($V_r \cong V_{max}$). Therefore, the cumulated travel time of the oil slick leading edge may be expressed in terms of this velocity value:

$$T_r = \frac{x}{V_r} < T_c \,. \tag{6}$$

From equations (5) and (6), an expression of real travel time of the oil slick leading edge is obtained as a function of computed travel time and the velocity ratio, α.

$$T_r = T_c \frac{V_c}{V_r} = T_c \cdot \alpha \tag{7}$$

By plotting on the same chart both computed and measured travel times (for a given value of discharge) in terms of cumulated distance, they appear as two segmented lines with constant slope for each elementary reach, x_i - x_{i+1} (Fig. 3). The difference between computed and real travel time, increases along the river. For larger values of discharge, the slopes of segmented lines decrease, as the mean velocities along each elementary reach rise, leading to smaller travel time values and vice versa [25].

5. Conclusions

By measuring the maximum velocity in each cross-section for different discharge values (at least three, for example: 100 years, 50 years and ten years or annual flood events) and by performing 1D hydraulic computations under the same conditions, one can obtain a series of values of the $V_c/V_r < 1$ ratio. Therefore, for another similar flow event, an estimate of this velocity ratio may be calculated and after computing the travel time with the hydraulic model, a prognosis of the real travel time of the oil slick may be made with the help of equation (7).

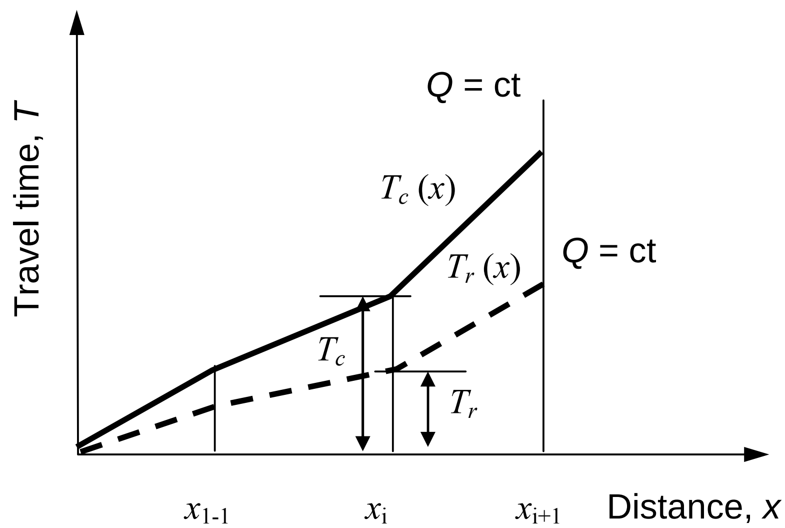

Fig. 3 Difference between computed and real travel time

This method shows how a simple 1D hydraulic model (for clean water) may be used to quickly have an information on the arrival time of the leading edge of the pollution plume in a certain location, in order to apply the right control/removal methods in due time.

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