# Numerical Modelling of Oil Spill

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*Abstract* Oil tanker accidents in seas cause serious problems to marine environment, especially when these accidents occur close to coastlines. To minimize the impact of tanker accidents on marine environment some measures might be taken if oil slick movement could be predicted in advance. Oil spill trajectory and fate models have been developed since the early 1960's to simulate oil movement on the water surface in order to take immediate action and some necessary measures after such accidents. Mediterranean Sea being among the world's busiest waterways is many times subject to oil spill accidents. In this connection a study has been carried out by giving special attention to Mersin coastlines. In this study, a 2-D Oil Spill Model has been developed and applied to Mersin Coastlines. The model is based on the 2-D oil spreading equation and considers horizontal dispersion, advection, diffusion, evaporation and shoreline deposition. Since evaporation process is the main cause of rapid volume reduction during the fate of oil spill, a special emphasize has been given to its modeling.

*Key-words:* Numerical modeling, oil spill, accident, advection, diffusion

## 1 Introduction

The eight main weathering processes of oil spill are evaporation, oxidation, emulsification, spreading, dissolution, dispersion, biodegradation, sedimentation. They are shown in the Fig. 1 [1].

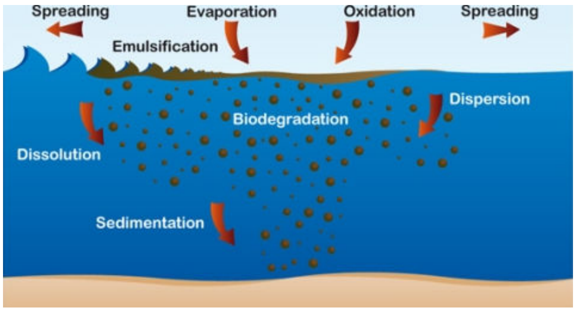



Fig. 1. Main weathering processes of oil spill [1]

Most of the weathering processes, such as evaporation, dispersion, dissolution and sedimentation, cause the loss of oil from the sea surface, on the other hand others lead to the formation of water-in-oil emulsions. The rate and importance of the processes change according to the oil spill volume, oil spill location (sea bottom or surface), oil type, the speed and direction of wind and sea currents.

Because of gravity, inertia, viscosity and surface tension forces, there occurs the horizontal expansion of an oil slick called as spreading. The early behaviour of oil when spilled on sea is dominated by its spreading behaviour [2]. Gravity force and surface tension causes increasing oil spreading, while inertia and viscous forces retard it. Oil slick passes through mainly three spreading phases; gravity and inertia forces, gravity and viscous forces and surface tension and viscous forces. The spreading diameter of the oil slick on the water surface in each of the phases can be defined as in Table 1 [3].

Table 1. Oil Spill Spreading Law [3]

| Spreading Phase | 1-D Spreading Length (Le) | Axissymmetrical Spreading Radius (R ) |
|---|---|---|
| Gravity-Inertia | $1.39(\Delta\rho gAt^2)^{1/3}$ | $1.14(\Delta\rho gVt^2)^{1/4}$ |
| Gravity-Viscosity | $1.39(\Delta\rho gA^2t^3\upsilon^{-1/2})^{1/4}$ | $0.98(\Delta\rho gV^2t^3\upsilon^{-1/2})^{1/4}$ |
| Surface Tension - Viscosity | $1.43(\sigma^2t^3\rho_w^{-2}\upsilon^{-1})^{1/4}$ | $1.60(\sigma^2t^3\rho_w^{-2}\upsilon^{-1})^{1/4}$ |

Dominant forces during each phase also identify the oil slick radius. In the first phase of the spreading, the change of the oil spill radius is determined mainly by gravity and inertia. In the intermediate phase gravity and viscous forces will dominate and in the final phase viscous forces balance the surface tension. However, Fay formulations do not consider the influence of wind on the oil slick area and associated with the turbulence, therefore they underestimate the horizontal spreading in diameter compared to that observed from field measurements. Lehr et al. developed a modified Fay-type spreading equation considering the influence of wind [4]:

$$A = 2270\left(\frac{\Delta\rho}{\rho_0}\right)^{2/3} V^{2/3} + 40\left(\frac{\Delta\rho}{\rho_0} V U_w\right)^{1/3} t \qquad (1)$$

where A is the area of the oil slick ($m^2$); $\Delta\rho=\rho_w-\rho_o$, V is the total volume of the spilled oil in barrels, $U_w$ is the wind speed in knots; and t is the time in minutes.

Evaporation to the atmosphere is important during the early stages of an oil spill. The rate of evaporation depends on the oil vapor pressure, which is influenced by the mixture of components in the oil, size of the spill, temperature, solar radiation, wind speed and sea conditions. In general, oil components with a boiling point below 200°C will evaporate within a period of 24 hours in temperate conditions. Strong winds, rough seas and high air temperature increase the rate of evaporation. The evaporation rate will furthermore increase as the oil spreads, due to the increased surface area of the oil slick [2]. Effects of weathering process and its duration depending on the oil type evaporation play a key role in modeling studies. Given its importance on the process, evaporation is mentioned in a wider manner in the following section.

After the oil evaporation the other important process that removes oil from the sea surface is the vertical dispersion caused by turbulence and buoyancy. With the dispersion oil slick breaks-up into small droplets and those are mixed down into the water column. Some small droplets are kept in suspension by the turbulent motion of the sea and larger oil droplets can rise back to the surface to reform a slick again or spread out in a very thin film. After dispersion oil slick has a greater surface area. This promotes other natural processes such as dissolution, biodegradation and sedimentation. The nature of the oil and the sea state conditions affect the rate of oil dispersion. If the oil is light and of low viscosity, dispersion occurs at a higher rate. In time when oil slick viscosity increases caused by the evaporation and emulsification processes the natural dispersion rate will be reduced. The combination of oil and water is called as emulsification; one suspended in the other without separation of oil and water. The emulsion can be either oil-in-water or water-in-oil. Both types of emulsification require wave action and occur only for specific oil compositions. When the oil take up water droplets and form water-in-oil emulsion the volume of the oil slick can increase by a factor of up to four. The emulsion formed is usually very viscous and more persistent than the original oil and is often referred to as chocolate mousse because of its appearance. The viscosity increases as a result of the emulsification process and the rate of other weathering processes decreases [2].

Dissolution is the break down of water-soluble compounds in the oil slick. The most soluble compounds in seawater are the light aromatic hydrocarbons compounds such as benzene and toluene. However, these compounds are also the most volatile and are the first to be lost through evaporations which is 10-100 times faster than dissolution. The dissolution process is the one of less important weathering process since only a very small percentage of oil is lost through oil dissolution. In general the concentrations of dissolved hydrocarbons in seawater rarely exceed 1ppm and dissolution does not make a significant contribution to the oil removal from the sea surface. The force of gravity will cause some of the oil to sink through the water and settle on the sea bottom. Dispersed oil droplets can interact with sediment particles suspended in the water column and thus become heavier and sink. However, adhesion to heavier particles most often takes place when oil strand on beaches. Particles reaching the coast or seabed are considered “stranded” and are not considered in the subsequent model drift calculations.

## 2 Governing Equation

A two dimensional equation was used as governing equation [5]. It describes the oil slick movement in rivers, but later it was used by many for oil slick movement on the water surface.

$$\frac{\partial C_s}{\partial t} + \frac{\partial}{\partial x}(U_s C_s) + \frac{\partial}{\partial y}(V_s C_s) = \frac{\partial}{\partial x}\left(D_x \frac{\partial C_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C_s}{\partial y}\right) - \gamma C_s - C_a S_E - D_s(x, y) \quad (2)$$

Where x and y denote horizontal spatial, t is time in second, $C_s$ is the local volumetric oil concentration on the water surface per unit surface area; $C_a$ is area concentration of oil and assumed to be equal to $C_s$, $U_s$ and $V_s$ are the components of surface drift velocity in x and y directions, respectively. $D_x$ and $D_y$ are the diffusion coefficients in the x and y directions, γ is coefficient of the rate at which the surface oil is dispersed and dissolved into the water column and assumed as $10^{-5}$1/sec, $S_E$ is rate of evaporation per unit area of the surface slick, $D_s$ (x, y) is the effect on the distribution of surface oil by shoreline deposition. As evident from the governing equation, only three main processes are included in this study among eight of them and these are, mechanical spreading of the oil slick on the water surface with the effect of advection and diffusion, evaporation and shoreline deposition. Among others, evaporation has the most important role on the weathering process. The following formula that was developed by Mackay et al. is adopted in solving evaporation as a module of the developed oil spill model [6].

$$F_v = [\ln P_0 + \ln(C_e K_E t + 1/P_0)]/C_e \quad (3)$$

$$K_E = \frac{K_M A_e V_M}{RTV_o} \quad (4)$$

$$K_M = 0.0025 V_w^{0.78} \quad (5)$$

Where, $K_E$ is evaporation coefficient, $K_M$ is mass transfer coefficient (m/sec), $A_e$ is area of the oil slick ($m^2$), $V_w$ is wind speed at 10 m. above the water surface (m/sec), $V_M$ is molar volume ($m^3$/mol), the value of it varies between $150*10^{-6}$ and $600*10^{-6}$, t is time in second, R is the gas constant and is equal to $8.206*10^{-5}$ atm$m^3$/Kmol, T is surface temperature of the oil (K), which is usually close to the ambient air temperature $T_E$, $V_0$ is initial oil spill volume in $m^3$. The initial vapor pressure $P_0$ in atmosphere at the temperature $T_E$ is;

$$\ln P_0 = 10.6\left(1 - \frac{T_0}{T_E}\right) \quad (6)$$

Although the shoreline deposition module is included in the model, no results are achieved due to lack of data necessary to give information about half-life of the shoreline on which the oil that reaches the coastline is deposited. For ease of understanding, the following formula is given for the shoreline deposition.

$$\frac{\Delta \forall_b}{\forall_b} = 1 - 0.5^{\Delta t/\lambda} \quad (7)$$

Where, $\Delta \forall_b$ is the volume of beached oil re-entrainedinto the sea during each of time step, $\forall_b$ is the volume of oil on the beach, λ is half-life
In the oil industry, API value is used instead of density to describe the physical property of oil. API value and specific gravity have inverse ratio. As specific gravity decreases, API value and quality of the oil increases. The following formula relates specific gravity to API value.

$$AP = \frac{141.5}{SG} - 131.5 \quad (8)$$

Where, SG is specific gravity of oil at 15.55$^0$C.

## 3 Numerical Solution Method and Oil Spill Model

In numerical model, grid sizes are selected as 100m in both horizontal directions.
Finite difference method is used to solve the governing equation. The solution procedure is explicit. Forward finite difference method is applied to the time derivatives and central finite difference method is used for the spatial derivatives to prevent from numerical diffusion and provide more stable solution.

Finally the governing equation can be expressed as following;

$$C_{i,j}^{t+1} = \begin{bmatrix} a_3\left(C_{i+1}^t - 2C_{i,j}^t + C_{i-1,j}^t\right) + \\ a_4\left(C_{i,j+1}^t - 2C_{i,j}^t + C_{i,j-1}^t\right) \end{bmatrix} - \begin{bmatrix} a_1\left(C_{i+1,j}^t - C_{i-1,j}^t\right) + \\ a_2\left(C_{i,j+1}^t - C_{i,j-1}^t\right) \end{bmatrix} \quad (9)$$

Thanks to the selected numerical method, advection and diffusion depending on the wind direction can be simulated successfully.

## 4 Model Applications to Mersin Coastline

Mersin is located at the Mediterranean Coast of Turkey and has beaches with the length of 106km. as shown in Fig. 2.

Fig 2. Map of Turkey [7]

Mersin coast has great importance in terms of oil hazard. There are nine oil pipelines as given in the Fig. 3. Furthermore Mersin coast is one of the most important loading/ unloading area of oil tankers.

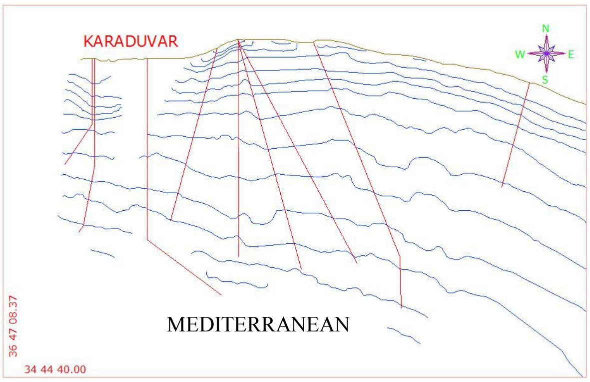


Fig. 3. Model Application area (Mersin coastline, Turkey) [8]

Two main directions are identified in accordance with wind frequencies of which NNW direction has the highest frequency value as shown in Fig. 4.

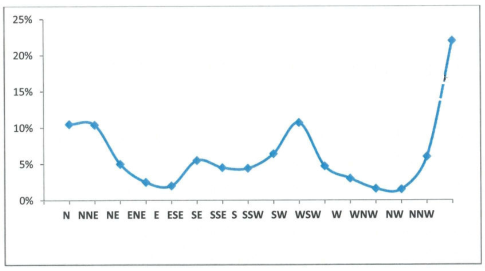
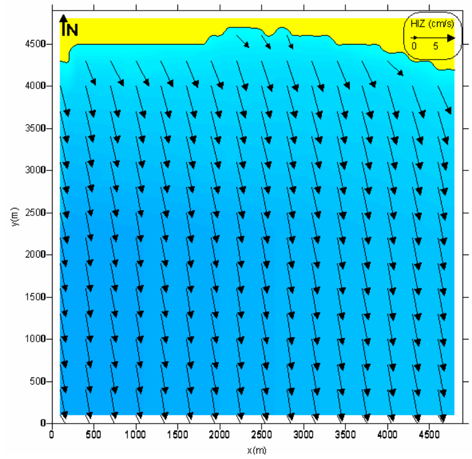
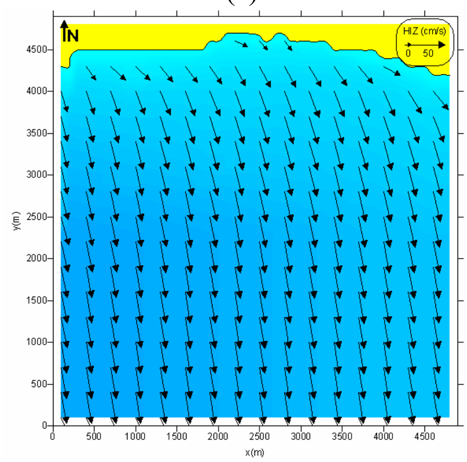



Fig 4. Wind frequencies between 1995- 2007 [9]

Current patterns for previously identified 25km$^2$ area on the sea surface are obtained from HIDROTAM3 [10] and used as input data for the numerical model. Since there has not been any real diffusion coefficients obtained from field studies, values for between 1 and 20m/sec$^2$ are used. The Fuel Oil that has 42.9API and 0.8111 m$^3$/ton density has been applied as pollutant. 5m/sec and 20m/sec wind speeds are used as input wind data and diffusion values vary between 1 and 20 m$^2$/sec. Current pattern is obtained from HIDROTAM in NNW direction under the effect of the wind speed 5 and 20m/sec and are given in the Fig. 5.



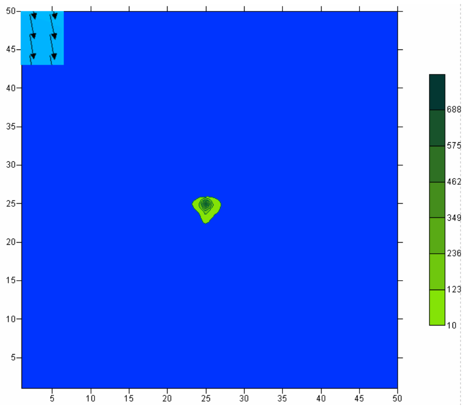
(a)



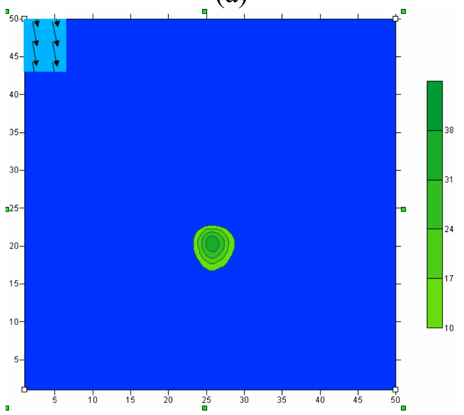
(b)

Fig. 5. under 5 m/sec (a) and 20m/sec (b) wind speed

Slick movement of 10 000 ton spilled oil on the water surface from NNW direction under 5 m/s wind speed given in Fig. 6 and 20m/sec wind speed in Fig. 7. $D_x = D_y = 1m^2/\sec$ are used as diffusion coefficient.

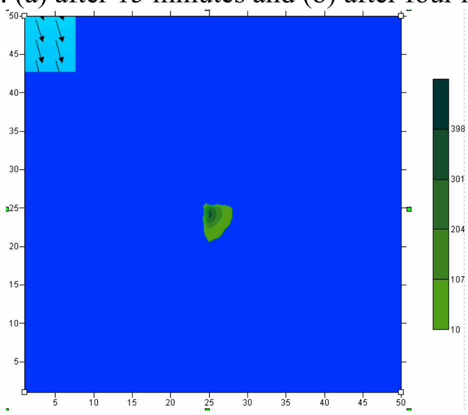


(a)

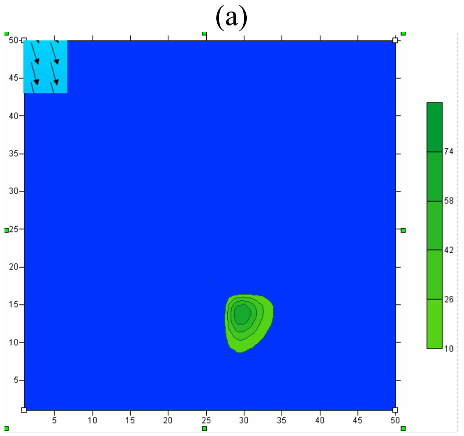


(b)

Fig. 6. (a) after 15 minutes and (b) after four hours



(a)



(b)

Fig. 7. (a) after 15 minutes and (b) after four hours

The calculated slick areas for different diffusion coefficients area have been compared with the results of Fay model. Fig. 8 and Fig. 9 show the comparisons for the wind speeds 5m/sec and 20m/sec, respectively.

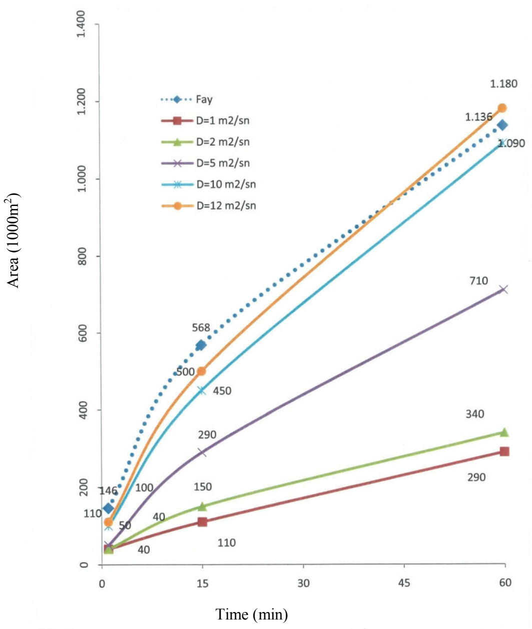



Fig 8. Slick areas for 5m/sec wind speed

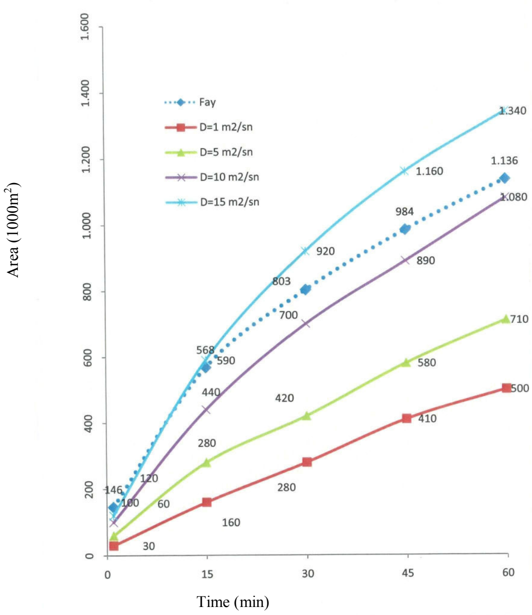



Fig 9. Slick areas for 20m/sec wind speed

Slick areas that are obtained from the model for each time step are compared with the calculated slick areas obtained from the equation given by (1) for the verification of the numerical model. When the diffusion coefficient is between 10 and 12m$^2$/sec, the results of the numerical model and Lehr model are in consistency as shown in Fig. 8

and Fig. 9 although wind blows with different speeds. But it can be observed that the predictions of numerical model give more accurate results in lower wind speeds.

## 5 Conclusion

In this study, a 2-D oil spill model is developed to simulate oil slick movement in the coastal water under mainly the effects of wind speed, current pattern, ambient air temperature and applied to Mersin coastline. Obtained results are compared with the results produced by the Lehr formula given by (1) in terms of slick area on the water surface. Among others, evaporation process is found to be the most effective factor on weathering of the oil depending on the given oil type. Special attention should be given to choosing diffusion coefficient in order to see the appropriate movement of the oil slick under both advection and diffusion effects. If this is not provided, for instance, diffusion effect could prevail the whole process and advection effect can only be discerned slightly or vise versa.

The following recommendations are made for the future modeling studies;
Coastal areas should be classified with respect to their physical and geotechnical characteristics and a record of inventory should be kept in accordance with this classification .Chemical characteristics of oil types should be included in modeling studies. Diffusion coefficients should be identified accurately by field studies.

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