An Application of 2D Oil Spill Model to Mersin Coast

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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, oil slick movement, pollution, advection, diffusion.

1 Introduction

Oil spilling on the sea is very important phenomena as the oil industry and oil transportation develop. It has dangerous effects on the ocean ecological environment [1]. In Table 1, the sources of oil pollution into the sea that were estimated by the United Nations Environment Programme have been shown [2].

Table 1: Sources of oil pollution into the sea [3]

Recorded Sources	Distribution (%)
Industrial waste, urban runoffs etc.	60.7
Refineries/ terminals	1.2
Natural sources	10.3
Tanker operations	6.6
Tanker accidents	4.7
Other shipping	14.4
Offshore production	2.1
Total	100

The major source of oil pollution in the seas is industrial waste water discharges. But the accidental oil spills which are caused by the collision of oil tankers and irrational dumping of ballast water from ships are significant source of coastal pollution in Mediterranean Sea [4].

As the maritime traffic increases, oil spill accidents will be occur. The causal distribution of spills for oil tankers between the years 1974-2000 has given in table 2 whose data were obtained from International Tanker Owners Pollution Federation [5].

Table 2 shows the importance of the oil spill clearly. Hazard identification, risk assessment, risk control options, cost benefit assessment and recommendations should be prepared for oil spill accident [3]. Therefore the oil slick movement should be simulated by an oil spill model.

Table 2: Causal distribution of spills for oil tankers [3]

	<7tons	7-700tons	>700tons	Total
Operations				
Loading/ Discharging	2763	297	17	3077
Bunkering	541	25	0	566
Other operations	1165	47	0	1212
Accidents				
Collisions	159	246	86	491
Groundings	221	196	106	523
Hull Failures	561	77	43	681
Fires/Explosion	149	16	19	184
Other	2217	163	35	2415
Total	7776	1067	306	9149

After an oil spill accident, the polluted area must be clean-up immediately. New emerging technologies for the clean-up of off-shore oil spills had been reported. Several research groups are currently working on various ways to develop new alternatives [6]. But firstly, the possible pollution distribution should be known for risk assessment.

Mathematical modeling is an important tool for simulation of pollution in ecosystems, prediction of dispersion and behavior of pollutants related to the local ecosystem characteristics [7]. Ecological systems are generally considered among the most complex ones, because they are characterized by diversity, nonlinear interactions, scale multiplicity and spatial heterogeneity. Forest fire spreading or oil slick movement can be thought as ecological system problems [8].

Several types of oil models are used today. These are simple trajectory, or particle-tracking models, three dimensional trajectory and fate models that include biological effects [9].

Lonin focused on the Eularian and Lagrangian methods for oil spill simulations. The governing equation that describes the vertical movement of an oil droplet in the ocean was proposed based on Langeven equation [10].

Garcia-Martinez & Flores- Tovar proposed a high accuracy numerical model to simulate oil spill trajectories using a particle-tracking algorithm. A fourth-order Runge- Kutta method with fourth-order velocity interpolation to calculate oil trajectories was applied [11].

Chao et al. presented the development and application of two dimensional and three dimensional oil trajectory and fate models for coastal waters. In the two dimensional model, the spreading, advection, turbulent diffusion, evaporation and dissolution were taken into account to describe the oil slick movement on the water surface. Three dimensional oil fate model was proposed that is based on the mass transport equation to simulate the distribution of oil particles in the water column [12].

Wang et al., described of a two layers for simulating oil spills in seas. This model considered the oil in seas as consisting of surface oil slick and suspended oil droplets entrained over the depth of the flow. It is a particle approach model. The model takes advection, surface spreading, evaporation, dissolution, emulsification, turbulent diffusion, the interaction of oil slick with the shoreline, sedimentation and the temporal variations of oil viscosity, density, surface-tension etc [13].

Wang et al., developed a three dimensional model for transport of oil spills in seas to investigate the vertical dispersion/ motion of the spilled oil slick which simulates the motion of oil spill more realistic. Furthermore, this model includes the processor hydrolysis, photooxidation and biodegradation [14].

Tkalich developed a CFD solution of oil spill problems. A consistent Eularian approach is applied across the model. The slick thickness was computed using layer-averaged Navier- Stokes equations and advection- diffusion equation was employed to simulate oil dynamics in the water column [15].

The eight main weathering processes of oil spill are evaporation, oxidation, emulsification, spreading, dissolution, dispersion, biodegradation, sedimentation. They are shown in the Fig. 1 [16].

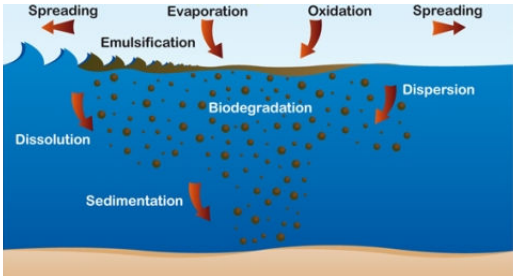


Fig. 1. Main weathering processes of oil spill [16]

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.

Oil moves horizontally under the effect of wind, wave and currents. In two dimensional surface models, constant or variable parameters are used to link wind and current velocities to the velocity of the surface oil slick. Reed et al. proposed in light winds without breaking waves, 3.5% of the wind speed in the direction of the wind gives a good simulation of oil slick drift in offshore areas. As wind speed increases, oil will be dispersed into the water column and current shears become more important [9].

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 [17]. 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 3 [18].

Table 3. Oil Spill Spreading Law [18]

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

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 [19]:

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

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.

The spreading rate in the direction of the wind was determined by an empirical wind factor obtained from observations [9].

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 [17]. Affected the whole weathering process and its duration that depends on the oil type evaporation plays 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 [17].

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 [20]. The equation was mainly developed to govern the oil slick movement in rivers, but later on the formula 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 variable 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 accepted the same as C_s, U_s and V_s are the components of surface drift velocity in x and y directions, 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 accepted 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 is paid utmost attention in order to see its effect on the weathering process. The following formula developed by Mackay et al. is adopted in solving evaporation as a module of the developed oil spill model [21].

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

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

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

Where, K_E is evaporation coefficient, K_M is mass transfer coefficient (m/s), A_e is area of the oil slick (m^2), V_w is wind speed at 10 m. above the water surface (m/s), 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 $8.206*10^{-5}$ atmm^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;

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

Two types of oil having different API values are used in order to see how the API values affect the evaporation process. 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 which represents the vulnaribility indices along with the type of the shoreline. Physical properties of oil ismentioned in brief manner to give a general idea about how the API values should be perceived and which factor affects on API values. the abbreviation API is used to rate oil in accordance with its specific gravity. The following formula relates specific gravity to API value.

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

Where, SG: specific gravity of oil at 15.55^{0}C (60^{0}F).

3 Numerical Solution Method and Oil Spill Model

In numerical model, the computation area is divided into equal 100 m increments in both horizontal directions, namely in the x and y directions. Finite difference approximation is used in solving the governing equation. Explicit central finite difference approximation is adopted to be used for all the terms including time (t) and two spatial (x and y) coordinates. In order to avoid numerical diffusion (artificial viscosity), central finite difference approximation is applied to the equation including all its terms.

Finally the governing equation can be expressed as following;

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

Choosing the appropriate method in solving the governing equation plays a key role in terms of assuring the correct propagation of both advection and diffusion terms in the given wind direction.

4 Model Applications to Mersin Coast

Mersin is located between 36^0-37^0 N altitudes and 33^0-35^0 E longitudes. The coastline of Mersin province is 321km [22]. In Fig. 2 the location of Mersin is shown. Mersin is a modern harbor city and basic connector between Turkey and Cyprus Island. Different ethnicities, different religions have been lived for hundred years in peace in this city. Besides the cultural richness, Mersin is an important industrial city with its industrial harbor and oil refinery.

Fig. 2. Location of Mersin [23]

As is seen from the Fig. 3, the area to which model is applied is of utmost importance since it is occupied by nine oil pipelines and has become one of the most important haunting area by oil tankers from all around the world.

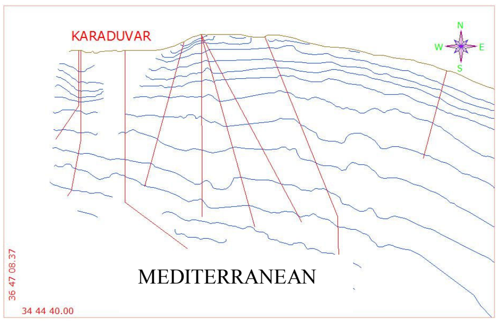


Fig. 3. Model Application area [24]

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

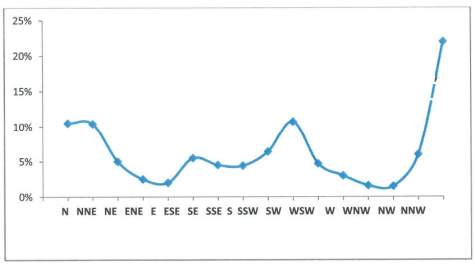


Fig 4. Wind frequencies between 1995-2007 [25]

The wind rose of Mersin between 1995-2007 is presented in Fig. 5.

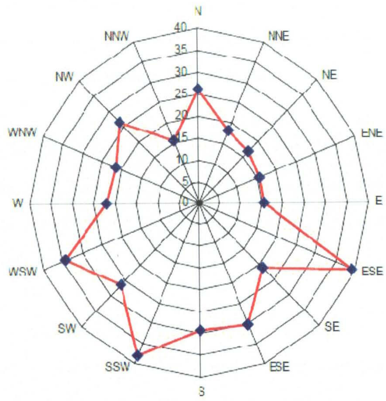
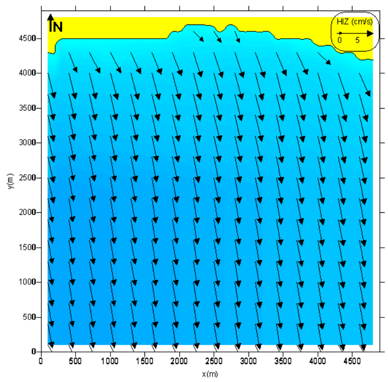
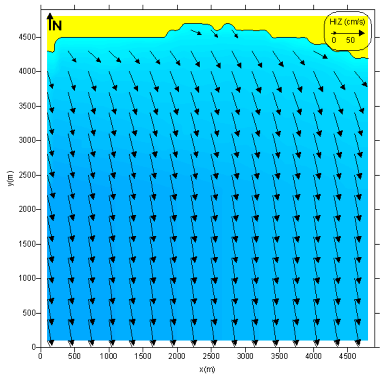


Fig 5. Wind rose between 1995- 2007 [25]

Current patterns for previously identified 25km^2 area on the sea surface are obtained from HIDROTAM3 [26] and used as the main data for running the model developed in the framework of this study. Since there has not been any real diffusion coefficients obtained from field studies, values for between 1 and 20m/sec^2 are used. This study, besides its main output, is also provided and insight into deeply understanding the relation between advection and diffusion and their effects on a pollutant in an aquatics environment. 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 diffussion 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. 6.



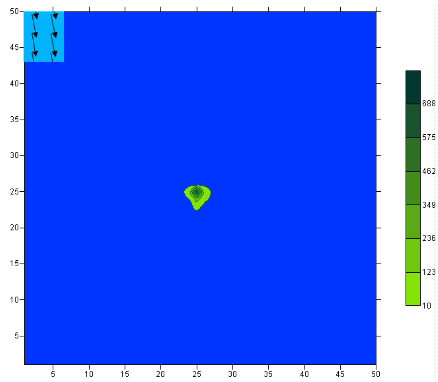
(a)



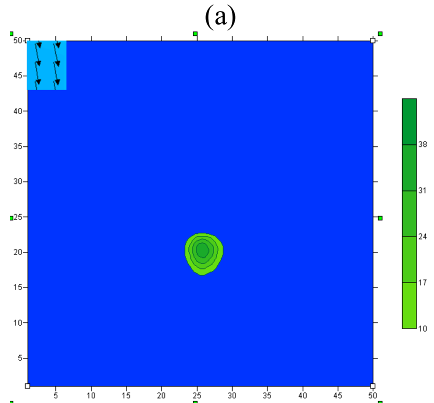
(b)

Fig. 6. 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. 7 and 20m/sec wind speed in Fig. 8. $D_x = D_y = 1m^2/\sec$ are used as diffusion coefficient.

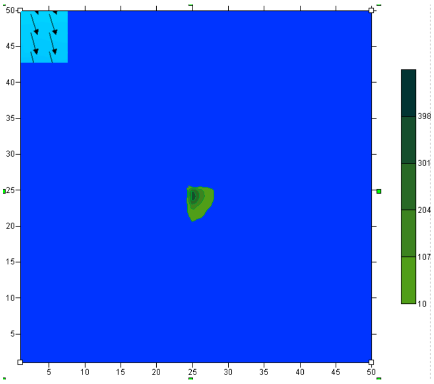


(a)

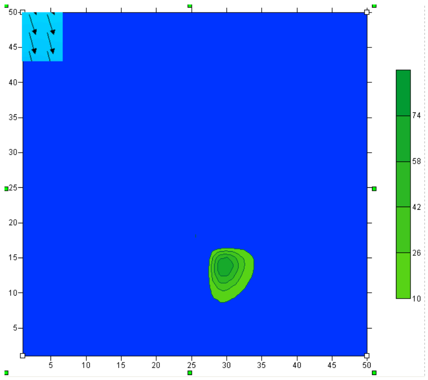


(b)

Fig. 7. (a) after 15 minutes and (b) after four hours for the number one oil type (under 5 m/s wind speed)



(a)



(b)

Fig. 8. (a) after 15 minutes and (b) after four hours for the number one oil type (under 20 m/sec wind speed)

The calculated areas of pollutant cloud for different diffusion coefficients area have been compared with the results of Fay model. Fig. 9 and Fig. 10 show the comparisons for the wind speeds 5m/sec and 20m/sec, respectively.

Slick areas obtained from the model for each time step are compared to ones obtained from the equation given by (1) for verification of the model. Results show differences in diffusion coefficient values depending on the oil type. While the values between 10 and 12m^2/sec for diffusion coefficient are found to be plausible for the first oil type, the model would only produce oil slick area results parallel to values with the formula given by (1) if the diffusion coefficient number is assumed to be between 1 and 2 m^2/sec. In this context, the finding is attributed to evaporation speed which affects the oil amount on the surface as in some cases, causes sharp loses even right after the spillage occurs.

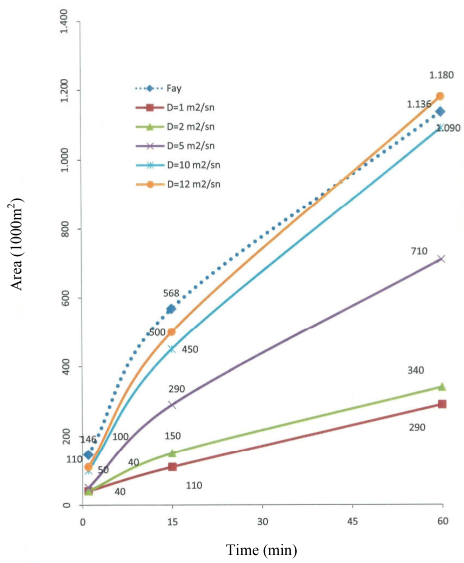


Fig 9. Pollutant cloud areas for 5m/sec wind speed

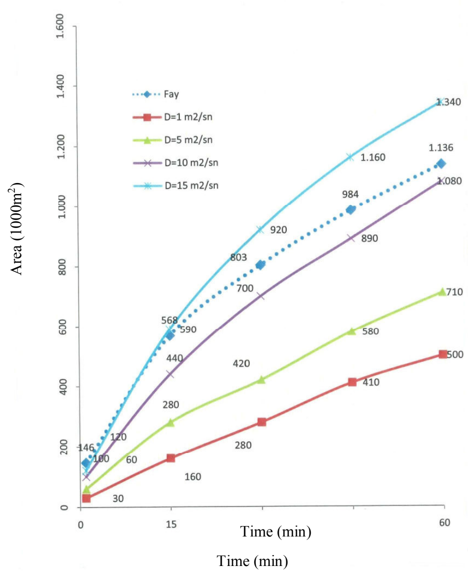


Fig 10. Pollutant cloud areas for 20m/sec wind speed

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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