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Mathematical Modeling of Oil Pollution Dissemination in River and Sea Waters of the Western Georgia

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Abstract

There was made the mathematical modeling of river waters pollution dissemination, for example at dumping of oil from the railway bridge across Rioni River (Western Georgia). The information about the quantity of oil, which reached the river outlet, was taken as starting and boundary conditions for modelling of oil dissemination and transformation in the Black Sea waters. The study of the dissemination of oil pollution at possible disastrous oil spill from tankers in the open sea near Kulevi oil terminal was also conducted. For modelling the river pollution the analytical solution of no steady-state diffusion equation in three-dimensional case was used. The study of sea pollution was made on the base of statistic simulation method (Monte Carlo method) – the computer tracing of transfer and transformation of oil portions–comparatively coarse particles intwo-dimensional case, the calculation of probabilistic characteristics of these processes. The data were provided about the spatio-temporal evolution of river and sea waters oil pollution. The features and the differences of ecological consequences of oil dumping in winter and summer conditions were marked. The results of the studies were included in the projects on assessment of environment influence of Tengiz oil railway transit over the territory of Georgia and functioning of Kulevi sea oil terminal.

Keywords: pollution, aerosol, precipitation, Zmiinyi Island, organic nitrogen.

Introduction

Since the richest reserve of fossil fuel in the region of the Caspian Sea was explored and extracted, the intense works to transport the energy carriers across the territory of Georgia have started at the end of the XX century and are still continuing. The existing reserves of oil and gas have been renewed; new Baku-Supsa and Baku-Tbilisi-Ceyhan oil pipelines and Baku-Tbilisi-Erzurum gas pipeline have been constructed and put into operation; the volumes of oil and oil products from Tengiz (Kazakhstan) and Khanchagal (Azerbaijan) fields transported by railway from Baku to the Black Sea coast have increased. The swift extension of the scope of works has necessitated the establishment of new terminals in addition to the operating Batumi and Poti ports on the Black Sea coast, and accordingly, Supsa and Kulevi terminals have been put into operation. In addition, the oil exploration and industrial mining works are accomplished on the territory of Georgia.

The mentioned activity may have a strong impact on the ecological state of the natural environment and sustainable development of the social-economic branch of the country. In terms of the increasing anthropogenic load on the environment, the risk of emergency and catastrophic oil spills increases drastically what may cause severe ecological outcomes. For instance, based on the analysis of the data of accidents along the railway of Georgia for the last 20 or 30 years, the daily probability of oil spills may be assessed as the value of 5×10^{-4} and the maximum amount of the spilled oil does not exceed 300 or 400 tons (overturning of 4 or 6 tanks and oil spill). The daily probability of the accident having taken place at Batumi oil terminal and Port was fixed at 7.5×10^{-3}, and the amount of the spilled oil did not exceed 800 kg (Anonymous, 2000). The risk of catastrophic spill of the possible load in the open sea, for example at the accesses to Supsa or Kulevi terminals is known from the world experience of transporting the oil with tankers. It may be assessed with $3.5. \times 10^{-7}$ annual probability and the amount of the spilled oil may be fixed at 10^4 (Anonymous, 2001).

In the situation like this, in order to protect the ecological safety of Georgia, identify the ecological impact on the environment and undertake proper environmental protection measures, the determination of the spatial-and-time scales of oil spread in the river and sea waters caused by emergency/catastrophic spills, by using the mathematical modeling, is particularly urgent.

Study Methods

For the first problem, which aimed to describe the spread of the emergency oil spills in the river waters, a non-stationery equation of passive admixture transfer and turbulent diffusion in a three-dimensional case was used:

$$\frac{\partial c}{\partial t}+U\frac{\partial c}{\partial x}+V\frac{\partial c}{\partial y}+(W-W_0)\frac{\partial c}{\partial z}=-\sigma c+\frac{\partial}{\partial x}\left(\gamma_1\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(\gamma_2\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(\gamma_3\frac{\partial c}{\partial z}\right). \qquad (1)$$

where *c*- is the concentration of oil hydrocarbons, kg/m^3; *U*, *V*, *W* are the components of the speed of water current along *x*, *y*, *z* coordinate axes; W_o is the speed of the oil sludge sedimentation; σ- is the speed of admixtures loss due to evaporation for instance; γ_1 γ_2 γ_3- are kinematic coefficients of turbulence along *x*, *y*, *z* coordinate axes, respectively.

We fix the origin of the coordinate system at the bottom of the river, with axis 0z directed vertically upwards, axis 0x directed along the current and axis 0y directed along the normal to the bank. We take the river current speed as follows: $U = U_o + b_x$ -. Then, we gain the speed components from the continuity equation as follows: $V= -(b_y / 2)$, $W=-(b_z / 2)$. Here *b = const* is the value of speed change or the gradient of it. If the river speed increases (*b*>0), due to the bed narrowing for example, then the convectional components are originated against the axes 0y and 0z (from the bank towards the center of the current and downwards, towards the bottom), which hamper the transportation of admixture to the bank and try to sink it. If the current speed decreases (*b*<0) in case of the river bed widening, then an opposite thing happens, in particular, the originated components help the admixture stay on surface and its deposition on the bank. If *b* = 0, i.e. the lines of the banks of the bed are parallel to each other, only the turbulent transfer of oil takes place along the axes 0_y and 0_z.

The initial and boundary conditions necessary to solve eq.1 for the instantaneous source are gained as follows:

$$c= M\,\delta(x)\,\delta(y)\,\delta(z-H), \quad t=0 \qquad (2)$$
$$c = 0 \quad x\to\infty$$
$$c = 0 \quad z = 0$$

here *M* is the mass of spilled oil, *L* is the width of the river; *δ* is Dirac delta function.

Eq. 1 was solved by considering the initial and boundary conditions (2), with the gained analytical solution as follows [1 - 3]:

$$c=\frac{Mb^{\frac{3}{2}}\exp\left[\left[-(\sigma-b)t-\frac{bU_0^2e^{bt}t^2}{\gamma_1(e^{bt}+1)}\right]\right]}{8\pi^{\frac{3}{2}}\sqrt{\gamma_1\gamma_2\gamma_3}\,(e^{bt}-1)\sqrt{e^{2bt}-1}}\exp\left\{-\frac{be^{-bt}}{2\gamma_1(e-e^{-2bt})}\left[xe^{-bt}-\frac{2U_0(e-e^{-bt})}{b}\right]^2--\left(\frac{y^2be^{bt}}{4\gamma_2(e^{bt}-e)}\right)\right\}\left[e^{-\frac{be^{bt}(z-H)^2}{4\gamma_3(e^{bt}-1)}}-e^{-\frac{be^{bt}(z+H)^2}{4\gamma_3(e^{bt}-e)}}\right]$$

(3)

Eq. 1 was also solved for the instantaneous linear source (Anonymous, 2000; Anonymous, 2001; Begalishvili *et al*., 2009).

Based on analytical expression (3), the concentrations of the oil spilled from the railway bridge over the river Rioni was calculated for different moments of time. In addition, the area of the film originated during the oil spread, the amount of oil deposited on the bank and amount of oil transferred from the river mouth into the sea were calculated (Anonymous, 2001; Begalishvili *et al*., 2009).

Under the second problem, the pollution of the sea waters with the oil was studied. In particular, the further spatial and time evolution of the oil in the sea waters, which occurred as an emergency spill in the river Rioni and reached the confluence, was studied. In addition, a possible tanker accident in the sea near Kulevi terminal with an emergency oil spill is described. The second problem is solved by using equation of type (1), written for a two-dimensional case (sea surface) (Anonymous, 2001; Begalishvili *et al*., 2009). By considering the sources, the numerical solution to the advection transfer and turbulent diffusion non-stationery equation is made for the area with the dimensions of 160 x 280 km^2. The value of a spatial spacing is $\Delta x = \Delta y = 2$ km. Thus, the size of each network cell on the water surface is 2x2 km^2, and the time spacing is 10-30 min. The idea of solving the equation with the Monte Carlo method is based on conducting a computer-aided statistical experiment, in particular, the trajectory of each portion (‘pseudoparticle’) of the spilled oil mass and change of its physical-chemical properties are observed. The numbers of N_{jki}^{tl} particles identified in x_i, y_i, m_k) phase space cells by a given t_l time moment are proportional to the distribution of the sought concentration. Here x_i and y_i are the cell coordinates, and m_k is the mass of kth portion (particle). Identification (statistical sampling) of the trajectory of each particle and consideration of its physical-chemical transformation is of the same value as the conduction of a computer-aided experiment, with the further registration and statistical analysis of quantitative values.

During the modeling of the spatial-and-time evolution of the oil spot originated due to the emergency oil spill we consider the hydrodynamic field of the constant currents in the sea, which is applied to by the surface currents caused by the wind (drift, flow and ebb, wave activity - Stokes flow), as well as horizontal turbulent diffusion caused by the friction of wind pulsations with the water surface.

In addition, after the statistical sampling of transfer of each particle and identification of the trajectory of each particle, we consider its transformation under the influence of the following physical-chemical processes, such as evaporation, solution in water, dispersion, emulsification, destruction and sedimentation.

The initial information contains the data of the marine hydrographic and climatic observations about constant currents, wind direction and value, and air and water surface temperatures in different months.

The numerical solution to the problem is gained via the statistical modeling of the trajectory of movement of at least 500 'pseudoparticles' and statistical modeling of their physical-chemical transformation. For each variant of the problem, the modeling is made for 100 cases (realizations) followed by the calculation of the parameters of the sea pollution with oil by averaging the gained characteristics of all realizations.

It should be noted that the results of mathematical modeling do not allow evaluating the scales of individual real spills, which depend on the current, water and air temperature and specific wind conditions in the post-accidental period. The results of statistical modeling show the probability of the transportation of oil particles up to the given site, and the calculations are made to gain the value of spatial-and-time distribution of probability of the oil identification in every cell (with the area of 2x2 km^2) of the sea basin and its amount.

Results and Discussions

In the first problem, the distance from the railway bridge over the river Rioni, the point of spilling of 200 tons of oil, up to the sea does not exceed 4 km. Due to the existing speed of water current, it takes the oil approximately 1 hour to reach the sea. The mass of oil evaporated and deposited on the bank in the given time is little. Therefore, the river transfers 70-80% of the initial mass of the spill into the sea through the confluence. The calculations show that in the situation like this, the oil concentration in the river waters exceeds the maximum permissible concentration (MPC) by several hundreds. Table 1 shows the maximum oil concentrations in the waters of the river Rioni for different moments for different water discharges.

The data in Table 1 shows that the oil concentration in the water in the short time periods is extremely high. During the flood, the concentration maximum reaches the sea in 15 or 20 minutes. The evaporation and deposition on the bank are insignificant in the given time. In the low-water period, the time of movement of the oil spot increases resulting in the increased deposition of oil mass on the bank and bottom (Begalishvili *et al*., 2009).

Table 2 is given as an example and shows (a) the spread of oil over the sea water surface, (b) oil sedimentation on the bottom and (C) oil transfer to the shore, which occurred as an emergency spill of 200 tons of oil in the river Rioni and was transferred to the sea in winter time (in January) 24, 48 and 72 hours after the spill. The value of concentration is given in terms of portions of the initial mass. As we can see, the surface concentrations fall below the maximum permissible concentration after 2 days (after 3 days in summer) (Begalishvili *et al*., 2009).

The winter balance of oil spread after 3 days is as follows: 46-50 tons of oil on the surface; 9-13 tons of oil deposited on the bottom; 42 tons of oil drifted to the shore; 100 tons of evaporated oil. The maximum concentrations are as follows: surface 0.008 g/m^3 over the area of 5 thousand km^2, bottom 0.07 g/m^3 over the area of 20-25 km^2 and 11-12 t/km on the shore.

Conclusion

The results of the study have demonstrated that there is a major difference between the winter and summer models of the oil spill in the sea. In winter, the spread of oil is very intense. Therefore, the oil concentration on the sea surface decreases faster than in July and as a result, the admixture on the sea surface remains in fewer amounts in winter. This causes an increase in the mass transferred to the shore and more intense pollution of the coastal line. The maximum amount of oil transported to the bank is observed at the river confluence, within the area of action of the source of pollution. The length of the polluted bank is greater in winter than it is in summer.

Due to little speeds of the background currents in summer causing weak turbulent diffusion, the oil mostly travels together with the surface current in the north-western direction. In terms of greater speeds of the background currents in winter, resulting in the increased intensity of turbulent diffusion, a part of oil occurs in the cyclonic current west of the city of Poti. Therefore, the direction of oil transfer in January is southwards, towards the shore of Turkey.

Table 1. Transformation of oil spot in the waters of the river Rioni

Current speed (m/sec)	Time from the moment of spills (min.)	Maximum concentration, (g/m^3)	Spot area, (10^4 m^2)	Spot layer thickness, mm	Mass deposited on the river banks, (kg/kg/km)
Flood duration 2, 3	10	380.2	44.0	0.53	0
	20	149.7	61.8	0.37	1.15/0.38
Duration of low-water period 0,4	10	426.8	41.0	0.57	0
	30	80.8	71.0	0.33	2.04/0.41
	60	27.8	88.0	0.26	2.18/0.44

Table 2. Spread of oil in the sea from the outlet of the river Rioni due to the emergency oil spill: sea water surface and seabed

N	Initial mass portion in the zone of boundaries	Oil distribution on water surface				Oil distribution on seabed			
		Zone Area, (km^2)	Total mass in the zone, ton	Concentration: Absolute value of concentration in the zone of boundaries, (mg/L)	Concentration: Average concentration in the zone, (mg/L)	Zone Area, (km^2)	Total mass in the zone, (ton)	Concentration: Absolute value of concentration in the zone of boundaries, (g/m^2)	Concentration: Average concentration in the zone, (g/m^2)
24 hours									
1	0.1-1.0	0	0	2.5-25	0	0	0	2.5-25	0
2	10^{-2} - 10^{-1}	8	3.2	0.25-2.5	0.3972	0	0	0.25-2.5	0
3	10^{-3} - 10^{-2}	636	32.6	$2.5x10^{-2}$-$2.5x10^{-1}$	0.0512	12	1.2	$2.5x10^{-2}$-$2.5x10^{-1}$	0.0958
4	10^{-4} - 10^{-3}	2012	21.5	$2.5x10^{-3}$-$2.5x10^{-2}$	0.0107	176	1.2	$2.5x10^{-3}$-$2.5x10^{-2}$	0.0066
5	10^{-5} - 10^{-4}	1292	1.4	$2.5x10^{-4}$-$2.5x10^{-3}$	0.0011	1216	1.0	$2.5x10^{-4}$-$2.5x10^{-3}$	0.0008
6	10^{-6} - 10^{-5}	992	0.1	$2.5x10^{-5}$-$2.5x10^{-4}$	0.0001	1212	0.1	$2.5x10^{-5}$-$2.5x10^{-4}$	0.0001
sum		4940	58.8			2616	3.5		
48 hours									
1	0.1-1.0	0	0	2.5-25	0	0	0	2.5-25	0
2	10^{-2} - 10^{-1}	0	0	0.25-2.5	0	0	0	0.25-2.5	0
3	10^{-3} - 10^{-2}	392	11.6	$2.5x10^{-2}$-$2.5x10^{-1}$	0.0295	20	1.4	$2.5x10^{-2}$-$2.5x10^{-1}$	0.0712
4	10^{-4} - 10^{-3}	3564	37.2	$2.5x10^{-3}$-$2.5x10^{-2}$	0.0104	384	1.9	$2.5x10^{-3}$-$2.5x10^{-2}$	0.0050
5	10^{-5} - 10^{-4}	2516	2.7	$2.5x10^{-4}$-$2.5x10^{-3}$	0.0011	2612	2.5	$2.5x10^{-4}$-$2.5x10^{-3}$	0.0009
6	10^{-6} - 10^{-5}	1984	0.2	$2.5x10^{-5}$-$2.5x10^{-4}$	0.0001	2340	0.2	$2.5x10^{-5}$-$2.5x10^{-4}$	0.0001
sum		8456	51.7			5356	6.0		
72 hours									
1	0.1-1.0	0	0	2.5-25	0	0	0	2.5-25	0
2	10^{-2} - 10^{-1}	0	0	0.25-2.5	0	0	0	0.25-2.5	0
3	10^{-3} - 10^{-2}	0	0	$2.5x10^{-2}$-$2.5x10^{-1}$	0	20	1.4	$2.5x10^{-2}$-$2.5x10^{-1}$	0.0716
4	10^{-4} - 10^{-3}	4924	39.2	$2.5x10^{-3}$-$2.5x10^{-2}$	0.0079	584	2.6	$2.5x10^{-3}$-$2.5x10^{-2}$	0.0044
5	10^{-5} - 10^{-4}	6208	7.4	$2.5x10^{-4}$-$2.5x10^{-3}$	0.0012	4292	4.1	$2.5x10^{-4}$-$2.5x10^{-3}$	0.0010
6	10^{-6} - 10^{-5}	2116	2.2	$2.5x10^{-5}$-$2.5x10^{-4}$	0.0001	4568	4.5	$2.5x10^{-5}$-$2.5x10^{-4}$	0.0001
sum		13248	48.8			9464	12.6		

If considering the increased rates of transportation of oil and oil products across the territory of Georgia, development of oil-extracting and processing industry in the country and outcomes of modeling of pollution of the river and sea waters with oil, we may make a conclusion about the necessity for establishing a special service charged with mitigation and liquidation of harmful results of the emergency/catastrophic oil spills on land and in river and sea watersand their prevention.

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