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Numerical Experiments of Prediction of Contaminant Diffusion in Kura River

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Abstract

Numerical simulation of distribution of contaminants discharged to Kura River is elaborated using nonstationary linear three-dimensional equation of transition-diffusion of substances in continuous medium. Model is meant for study of distribution of polluting agents in Kura River in the first approximation. Kura River is divided in 10 conventionally uniform linear sections and annual average values of hydrological parameters specific for the river are used for each section.

Ammonium ions (NH_4^+ *) distribution discharged from cities situated at Kura River is modeled. Distribution pattern for ammonium ions concentration in Kura River is received using numerical experiment. It is shown that values of concentration received via mathematical modeling with permissible accuracy are coincided with data of field observations.*

Distribution of passive polluting agents thrown to Kura River near Georgian-Turkish state border is modeled using numerical experiment in case of stationary source. Using the modeling there is determined the time, which is necessary for polluting agent to reach points placed along the river, to pass various sections of river, to reach Georgian-Azerbaijan border and Mingachevir reservoirs. Distribution pattern of polluting agent concentration in the river bed, as well as concentration change when passing from one section to another are determined, and relative change of concentration in 10 conventional river sections is estimated.

Distribution of passive contaminant thrown to Kura river by salvo during 6 hours near Georgian-Turkish state border is studied. Pattern of gradual shift of the contamination plume in Georgian section of Kura River and gradual concentration change are shown.

A possibility of using the model for prediction aims is considered.The correspoding tasks are determined.

Key words**:** numerical simulation, equation of mass transfer, pollution of Kura, ammonium, passive contaminant.

Introduction

The Kura River has an important role in the economy of the Georgian and Azerbaijan Republics. It is one of main sources of the drinking water in the South Caucasus and is intensively used for agricultural and industrial purposes. Georgian part of the Silk Road – main traffic artery of Georgia, the oil and gas pipelines, railways and highways are passing along it. Therefore, it is the water object of high ecological risk factor.

Annually rising turnover between the Europe and China and Middle Asia causes a threat of the ecological disasters in this transport corridor and therefore ecological protection of Kura River is one of main topical problem of the Georgian government.

Scientific and nongovernmental organizations of Georgia [1, 2] are carrying out the natural observations and experimental measurements of the water quality of the River Kura. These investigations are very important and give us the static picture of the river pollution. But there are some other ecological tasks, the solution of which can't be made only on the basis of observation data. In particular, the complications of distribution of contaminant in the river, forecast of the river pollution, and optimal management of the surface waters, e. t. are related to such problems.

The developed countries are widely used the software packages of water pollution forecast, investigation of surface water pollution and the optimal control systems [3-8]. These packages are mainly elaborated for large waters, require a special personnel training and are difficult for use in case of mountains rivers.

According to [7, 8], we elaborated a simple numerical method for calculation of diffusion of passive admixtures to Kura River and we investigated a kinematics of propagation of contaminants. This work is considered as first stage of elaboration a method of prediction of pollution of Georgian mountain river in case of disasters

Formulation of the Problem

For numerical modeling of the pollution distribution the Georgian section of Kura River 513 km length from Georgian-Turkish border to the Mingachevir Reservoir is divided into ten conventionally uniform sections [9] (Fig. 1). It is assumed that each of the river's section is a linear canal and river's hydrologic parameters are constant along it. Therefore, the distribution of pollution may be described by transfer-diffusion equation [10]

$$\frac{\partial C_1}{\partial t} + u_1 \frac{\partial C}{\partial x} + w_o \frac{\partial C_1}{\partial z} = \mu_x \frac{\partial^2 C_1}{\partial x^2} + \mu_y \frac{\partial^2 C_1}{\partial y^2} + \mu_z \frac{\partial^2 C_1}{\partial z^2} \qquad (1)$$

where t is time; x, y, and z are the Cartesian coordinates; x axis is horizontally directed along the river flow; y is the horizontal axis directed perpendicularly to the canal; z axis is directed upward vertically from river bottom; u_i is the river's flow velocity at i section along x axis; river flow velocity is equal to zero along y axis; w_o is the velocity of sedimentation of polluting agent; μ_x, μ_y and μ_z are kinematic coefficients of turbulent viscosity along the x, y and z axes, respectively; C_i is the concentration of the contaminant in the i section of river; α is a velocity of chemical transformation of polluting agent.

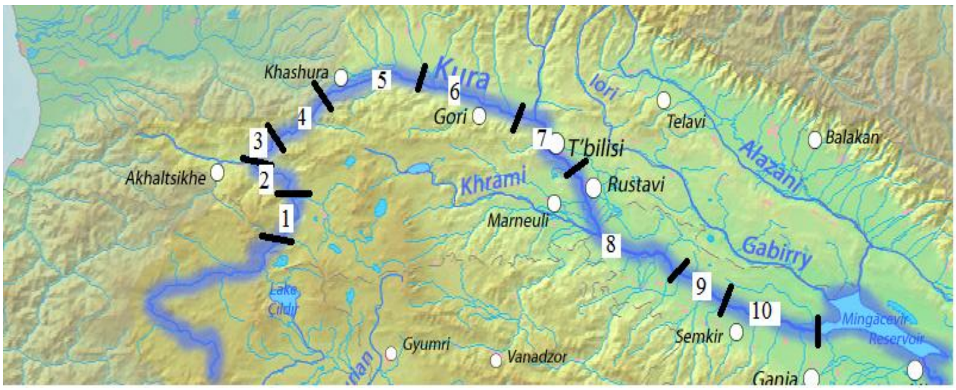

Fig. 1. The scheme of Kura River division into conventional sections.

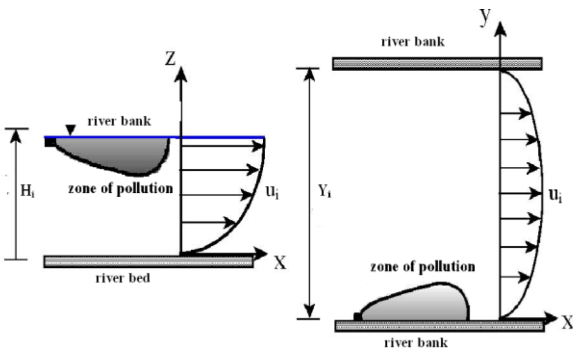

Fig. 2. The scheme of the river flow, velocity and contaminant in vicinity of discharge source.

The river water velocity u_i in each river section is a known and constant value along the axis x, and changes along the y and z axes as follows: $u_i(x,y,z) = 1.5U_{i,0} * \sin(\pi y/Y_i)\sin(0.5\pi z/H_i)$ (Fig. 2). $U_{i,0}$=const is the known value of the river water velocity in the i section. Y_i and H_i are the width and depth of the section i. $U_{i,0}$, Yi, Hi are taken from [9]. Since the values of coefficient of turbulent diffusion for Kura River were not determined on the basis of observation data, we used the values given in [11] as follows: $\mu_x = 5\times 6.4\times 10^4$ m²/s and $\mu_y = \mu_z = 5\times 5{,}57\times 10^{-3}$ m²/s for territory with complex mountain relief (sect. 1-4) and $\mu_x = 6.4\times 10^4$ m²/s and $\mu_y = \mu_z = 5.57\times 10^3$ m²/s for sections placed at plain territory (sect. 5-10).

Table 1

The hydrological parameters of sections.

Section No.	Section name	Length (km)	Width Y_i(m)	Depth H_i(m)	Velocity of flow Uo (m/s)
1	The Georgian-Turkish state border – R. Faravani	27	40	1.0	1.1
2	R. Faravani –V. Minadze-	42	45	1.2	0.9
3	V. Minadze- V. Atskuri	20	35	1.2	1.2
4	V. Atskuri –V. Qvishkheti	47	40	1.3	1.2
5	V. Qqvishkyeti-T. Gori	61	75	1.2	1.2
6	T. Gori-V. Dzegvi	51	85	1.0	1.5
7	V. Dzegvi-V. Soganlughvi	39	80	1.5	1.5
8	V. Soganlughvi – V. Poili	94	90	1.6	1.4
9	V. Poili – R. Dzegmachai	70	95	1.8	1.3
10	R. Dzegmachai – Mingechavir Reservoir	62	100	2.0	1.2

For integrating of equation (1) the corresponding initial and boundary conditions are used: the concentrations of the contaminant in the points of discharge source, in the beginning of section and at the initial time are known values. The gradient of concentration in the end points of sections $x_i = K_i$, in the river bank and bed points y_i = 0, 10 and z_i = 0,10 are equal to zero, respectively. The concentrations of the contaminant during the whole interval of time of spilling at the source points are known values. An inflow of tributaries into Kura River is taken into account using change in the parameters $U_{i,0}$, Y_I and H_i . In the table 1 the values of the hydrological parameters of the River Kura for the sections 1-10 are given.

The numerical integration and solution of equation (1) is made using the split method and balance numerical scheme [10] on the rectangle numerical grid. The grid step along the x axis depending on goals of concrete numerical experiment varies within interval of 20 m – 1000 m; the grid steps along y and z axes are equal to Yi /11 and Hi /11, respectively.

Results of simulation

Accidentally, full real data of natural measurements of the distribution of contaminants discharged in Kura are absent. Therefore, the accuracy of simulation we determine by using the standard observation data is.

The quantitative accuracy of calculation will made by means of numerical simulation of ammonium diffusion, for which modeling of h the values of river discharge and concentrations obtained by natural observation are known. In Tab. 2 the mass of ammonium discharged per second to Kura River from Georgian towns is shown. These data are calculated by means of formula $Q = (7 \times N)/(24 \times 3600)$ (g/s) ,where N is a number of city residents. This formula implies that one citizen discharges about 7 g NH_4^+ per day [12]. On the basis of experimental measurement the value of background concentration near the Georgian-Turkish state border is taken equal to $C_{1,0}$ = 0.4 mg/lit.

Table 2

Mass of NH_4^+ discharge per second to Kura River from Georgian towns.

№	1	2	3	4	5	6
Towns	Borjomi	Khashuri	Gori	Mtskheta	Tbilisi	Rustavi
Civilians (thou.)	14.4	28.5	46.7	7.7	1 200.0	122.0
NH_4^+ (g/s)	1.17	2.31	3.78	0.62	97.20	9.88

In Fig. 3 the distribution of ammonium along the Kura River obtained using numerical modeling is given. When comparing these results with data of Tab. 3 we can conclude that results of numerical simulation are in good correspondence with observation data.

Table 3

Concentration (mg/lit.) of ammoniun obtained via natural measurement.

Point of observation	Borjomi	Gori	Mtskheta	Tbilisi	Rustavi
Average Multiyear value of 2007-2010	0.49	0.52	0.53	0.95	0.88
September of 2013	0.48	0.51	0.47	1.02	0.72

The analysis of the distribution of the contaminant along the river shows the ammonium concentration gradually increases from t. Borjomi to Rustavi (Fig. 3). The rapid growth of concentration takes place in vicinity of the points of discharge. The maximum growth of concentration is obtained in vicinity of Tbilisi in the areas of sewage network attaching to the river. The area of rapidly increased concentration is about 5 km near small towns and 25 km for Tbilisi. With increase of distance from the discharge points due to diffusion and dilution caused by waters of influent rivers the concentration gradually decreases. As the calculations show, the concentration of ammonium in Georgian part of Kura River gradually increases along the river and exceeds twice the maximum permissible concentration (MPC) near Mingechavir Reservoir.

The series of numerical experiment are conducted for investigation of kinematics of contaminants propagation in Kura River and possibility of pollution forecast. First, is considered the case when the contaminant is discharged into Kura River in the points located near Georgian-Turkish state border (sect. 1).The concentration of polluting agent is equal to 100 conventional units

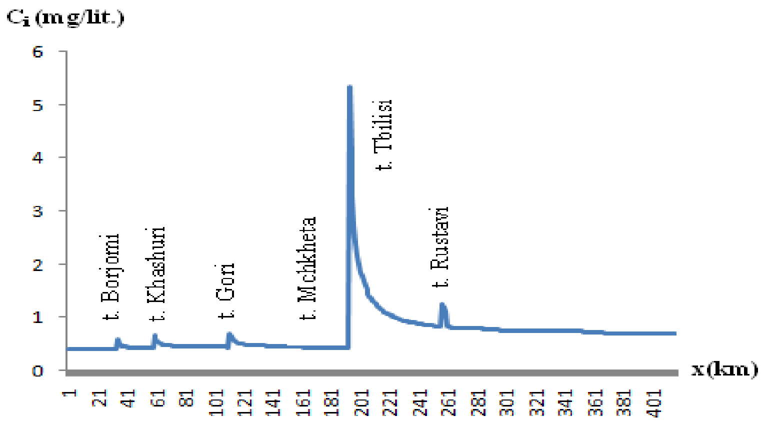

Fig. 3. Distribution of ammonium concentration in the Kura River. City names show discharge points.

(c.u.) in the area of the pollution source during all modeling time. Fig. 4 shows a qualitative picture of distribution of contaminants during the first 6 minutes of the pollution process. As we can see the polluted area is of elliptic form and it is distributed at the distance of about 300 m in the direction of flow and takes the whole width of the river. But the main part of polluting agents is located along the bank where takes place the discharge and is spread approximately at $0.6H_i – 0.7H_i$ distance in width.

Fig. 4. The pattern of distribution of the polluting agents in section 1 within first 6 min. The step $\Delta x = 20$ m.

In Fig. 5 the distribution of the contaminant during first 25 hours of discharge is shown. By means of this figure and Tab. 4 we can see that a pollution is distributed in sections 1, 2 and is reached the section 3. The contaminant passes the first rivers section in 6 hours, the section 2 in 17 hours etc. The average velocity of passing the section 1 is equal to 0.8–1 m/s and is in correspondence with the average river flow velocity in first section. The similar results are obtained for the other sections of the river. The times of reaching the river section beginning by contaminants and establishment of their constant concentration in these sections are given in the Tab. 4.

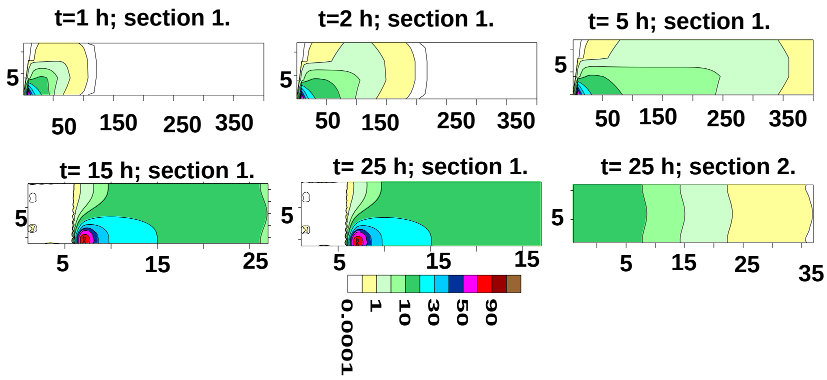

Fig. 5. The distribution of the concentration (in c.u.) on river surface in the sections 1 and 2,when t = 1, 2, 5, 15 and 25 h. The step $\Delta x = 20$m when $t \le 5$h, and $\Delta x = 1$ km when $t \ge 15$ h.

Table 4

Time of reaching the section beginning by pollution substance (t_{min}) and time of establishment ofconstant concentration (t_{max}).

Section №	1	2	3	4	5	6	7	8	9	10
t_{min} (h)	0	6.2	17.8	23.4	37.1	53.7	65.8	74.7	98.1	117
t_{max} (h)	83.3	91.0	103.3	122.1	178.6	196.8	210.7	247.7	277.6	307

Simulation of propagation of the passive pollutant accidentally discharged during a short interval of time (6 h) is conducted. On Fig. 6 the results of numerical modeling are shown. We see that contamination plume that is formed in discharge place, is getting wider due to transfer and diffusion processes and after 75 hours its length reaches 80km. Calculations shown the it is necessary roughly 190 hours for contamination plume to pass the Georgian part of Kura River.

The numerical modeling of diffusion of the petroleum product spilled in River Kura in vicinity of Tbilisi is prepared (Fig. 7). The modeling shows that about 30 minutes are required for pollution diffusion on all width of the river and 1.5 km along the river. The concentration is maximum on the upper surface of river water and its value gradually decrease in the depth – by 50% on the half depth and 75% near of the river bottom.

Discussion

On the basis of nonstationary three-dimensional equation of mass transfer the numerical model of transfer of contaminant through Kura River is elaborated. The model is created for the area of Kura River from Georgian-Turkish state border to Mingechavir Reservoir that is divided into ten parts. For each part the river flow velocity is taken as well-known value and is taken from the materials of hydrological observation. The study of river pollution by ammonium ions is carried out. Comparison of simulation results with observation data shows that model quantitatively correctly describes the average pattern of pollution.

The numerical experiments that investigate the kinematic features of distribution of pollution are carried out. Some parameters characterizing the process of pollutants’ diffusion are obtained by means of these experiments, namely: times necessary for passing Georgian section and its separate areas by contaminants etc.

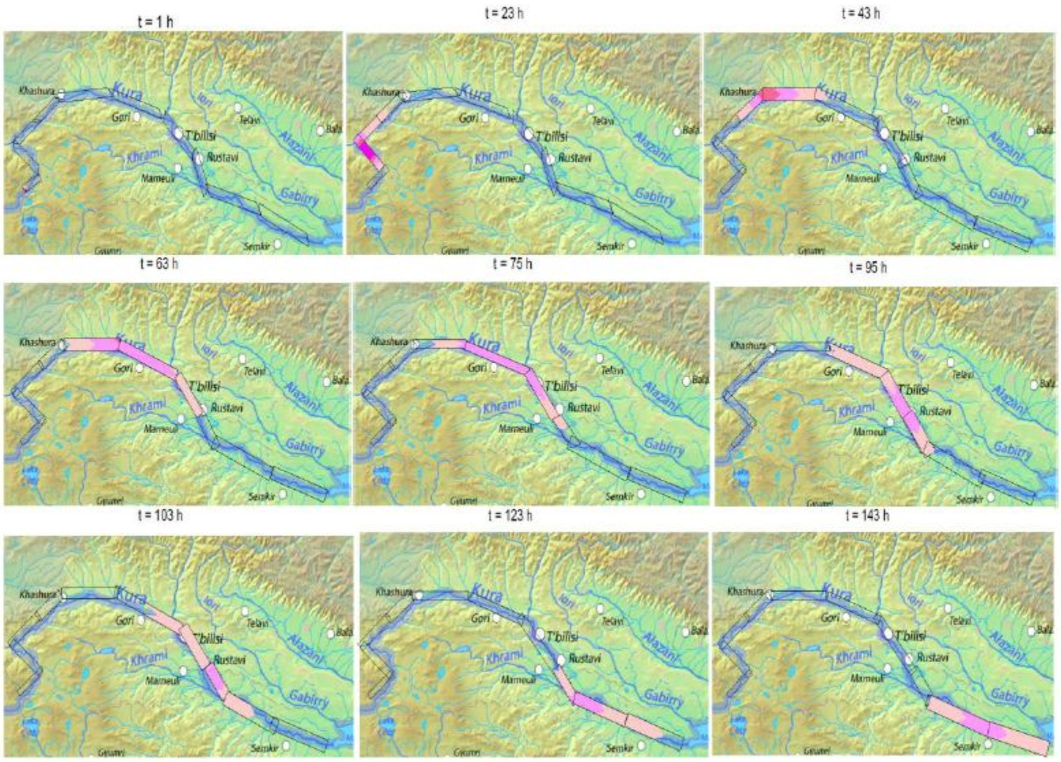

Fig. 6. Displacement of contamination plume in Kura River during 143 hours.

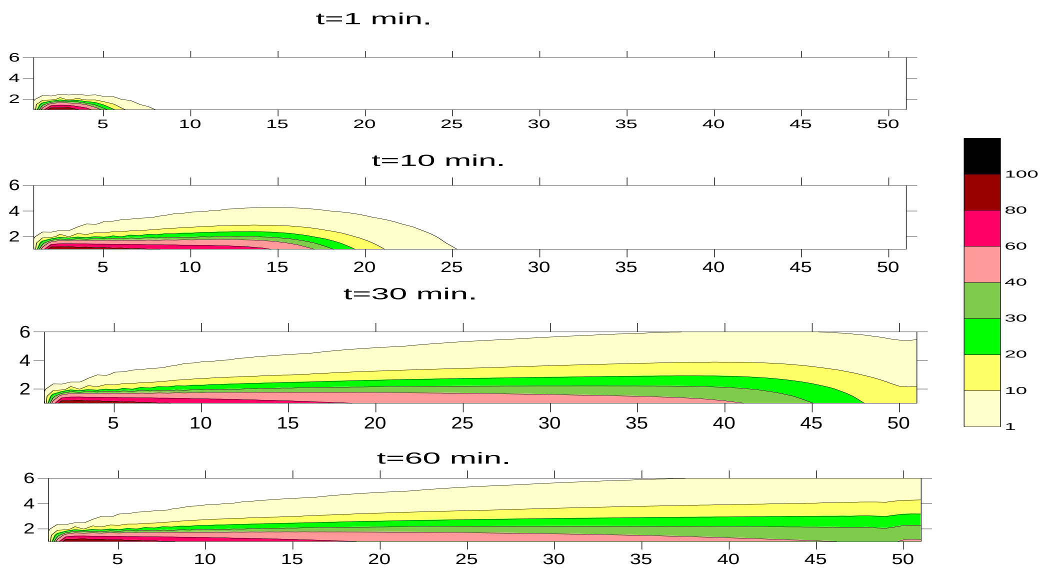

Fig. 7. Concentration of oil products C (mg/lt.) on the surface level at t = 1, 10 , 30 and 60 min. Horisontal grid steps are equal to Δx=20m; Δy=10m.

It should be noted that calculations are carried out for average annual river flow velocity. This fact limits the area of application of this model because the velocity of water flow for mountain rivers may change in wide area in relation with the precipitations taking place in the basin of the separate tributaries. Such limitation can be overcame by two ways: first, for each section the velocity of flow can be calculated using the equation of river water momentum, or second – by database for velocities of flow observed in different situations must be created by means of hydrological observation and these data must be used in equation (1). It is necessary also to obtain semi-empirical formulas for kinematic coefficients of vertical and horizontal turbulence of Kura River and to conduct numerical simulation with the use of them.

The used numerical model can be considered as first experiment of prediction of pollution diffusion in River Kura. After taking into account the comments made above and comparison of the data of the real observations with results of numerical simulation final conclusion can be made about the possibility of using the proposed model for the forecasting aims.

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მდ. მტკვარში ჩაღვრილი დამაბინძურებელი ნივთიერების გავრცელების პროგნოზირების რიცხვითი ექსპერიმენტი

ა. სურმავა

რეზიუმე

უწყვეტ გარემოში ნივთიერების გადატანა-დიფუზიის არასტაციონალური წრფივი სამგანზომილებიანი განტოლების გამოყენებით დამუშავებულია მდ. მტკვარში მოხვედრილი დამაბინძურებელი ნივთიერების გავრცელების რიცხვითი მოდელი. მოდელი გათვალისწინებულია პირველ მიახლოებაში მდ. მტკვარში დამაბინძურებელი ნივთიერების გავრცელების შესწავლისათვის. მდ. მტკვარი დაყოფილია 10 პირობითად ერთგვაროვან წრფივ უბნად და თითოეული უბისათვის გამოყენებულია მდინარის მახასიათებელი ჰიდროლოგიური პარამეტრების საშუალო წლიური მნიშვნელობები.

მოდელირებულია მდ. მტკვარზე განლაგებული ქალაქებიდან ჩაშვებული ამონიუმის (NH_4^+) იონის გავრცელება. რიცხვითი ექსპერიმეტით მიღებულია მდ. მტკვრში ამონიუმის იონის კონცენტრაციის განაწილების სურათი. ნაჩვენებია, რომ მათემატიკური მოდელირებით მიღებული კონცენტრაციების მნიშვნელობები დასაშვები სიზუსტით ემთხვევა ნატურული დაკვირვებების მონაცემებს.

მოდელირებულია საქართველო-თურქეთის სახელმწიფო საზღვართან მდ. მტკვარში ჩაღვრილი პასიური დამაბინძურებელი ნივთიერების გავრცელება სტაციონალური წყაროს შემთხვევაში. მოდელირებით განსაზღვრულია დრო, რომელიც საჭიროა იმითვის, რომ დამაბინძურებელმა ნივთიერებამ მიაღწიოს მდინარეზე განლაგებულ პუნქტებს, განვლოს მდინარის სხვადასხვა უბანი, მიაღწიოს საქართველო-აზერბაიჯანის საზღვარს და მინგეჩაურის წყალსაცავს. განსაზღვრულია დამაბინძურებელი ნივთიერების კონცენტრაციის მდინარის კალაპოტში განაწილების სურათი, კონცენ¬ტრაციის ცვლილება მდინარის ერთი უბნიდან მეორეში გადასვლისას, შეფასებულია კონცენტრაციის ფარდობითი ცვლილება მდინარის 10 პირობით უბანში.

შესწავლილია საქართველო-თურქეთის სახელმწიფო საზღვართან მდ. მტკვარში 6 სთ განმავლობაში ზალპურად ჩაღვრილი პასიური დამაბინძურებელი ნივთიერების გავრცელება. ნაჩვენებია დაბინძურების ლაქის თანდათანობითი გადაადგილების სურათი მდინარის საქართველოს მონაკვეთში და კონცენტრაციის თანდათანობითი ცვლილება.

განხილულია მოდელის პრიოგნოსტიკული მიზნით გამოყენების შესაძლებლობა. დასახულია შესაბამისი სამუშაოები.

Численный эксперимент прогноза распространения сброшенного загрязняющего вещества в р. Кура

А. А. Сурмава

Резюме

С помощью линейного нестационарного уравнения переноса вещества в сплошной среде разработана модель распространения загрязнения в р. Кура. Модель предназначена для исследования загрязнения и оценки возможности прогноза распространения загрязняющего вещества, сброшеного аварийно в р. Кура. С этой целью грузинская часть р. Куры разделена на 10 условно однородных линейних участков. Для каждого участка в качестве входных даных используются среднегодовые значения гидрологических параметров.

Смоделирована распространение аммоний (NH_4^+), сброшеной в реку из городов расположенных на р. Кура. Путем численного моделирования получены распределение концентрации аммония в воде р. Кура. Показано, что расчетние значения концентрации с достаточной точностью совпадают с данными натурных наблюдений.

Смоделировано распространение пассивного загрязняющего вещества, поступающего в реку из стационарного источника в окрестностиях Грузинско-Турецкой границы. Определены временные интервалы, за которые вещество достигает отдельных пунктов, расположенных на реке и вливается в Мингечаурское водохранилище. Рассмотрена возможность использования модели в прогностических целях и намечены соответсвующие мероприятия.