COMPUTER SIMULATION OF WITHIN-YEAR CYCLE OF AN AQUATIC ECOSYSTEM LIFE

ИМИТАЦИОННОЕ МОДЕЛИРОВАНИЕ ВНУТРИГОДОВОГО ЦИКЛА ФУНКЦИОНИРОВАНИЯ ВОДНОЙ ЭКОСИСТЕМЫ

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Abstract: *We consider some experience of computer simulation of within-year cycles of aquatic ecosystems, which has group of lecturers and scientists of St. Petersburg State University. The experience includes designing point, reservoir and spatially non-homogeneous simulation models of aquatic ecosystems functioning, and carrying out numerical experiments with the models. The models are applied for investigations in the sphere of ecology, nature protection and nature management. Main attention in the report is devoted up-to-date state of the simulation.*

KEYWORDS*: AQUATIC ECOSYSTEM SIMULATION, ANTHROPOGENIC EUTROPHICATION, TOXIC CONTAMINATION*

1. Introduction

Modern global ecological crisis has been mainly caused by the Earth biosphere poisoning by anthropogenic contaminants. Oil is one of the most harmful one. Prognosis of an ecosystem behaviour and revealing of the weakest chains of the ecosystem is impossible without application to the computer simulation approach [1]. Institute of Earth Sciences of St. Petersburg State University has some experience in designing computer simulation models of aquatic ecosystems. The models were applied for investigations in the sphere of ecology, nature protection and nature management. Thus, Dr. Yuri Sergeev offered the general approach to the creation of simulation models of aquatic ecological systems in 1972 [2].

During 1970-1980s Dr. Yuri Sergeev leaded investigations in the direction. A very active participation in the investigations had Valery Kulesh, and Vasily Dmitriev. In 1970s the North Sea was studied, and as the result of the investigations in 1974 there was built a spatially non-homogeneous simulation model of the ecosystem [3]. Later, in 1980s, there appeared a number of simulation models of ecosystems of eastern part of the Finnish Gulf and the Neva Bay [4]. Victor Tretyakov built an aquatic-bottom reservoir model of the Neva Bay. His next computer model in 1994 was devoted to determination of specific features of Lake Ilmen ecosystem by means of computer simulation. It was a computer reservoir model of the ecosystem, which included blocks of the floodplain and bottom [5, 6]. At the same time Yuri Sergeev and Valery Kulesh designed spatial nonhomogeneous simulation model of Lake Ilmen ecosystem and model of economic and ecological development of Russia [6].

It should be said that all anthropogenic contaminants might be divided into two groups: those of total ecological influence and those of individual toxic impact. The first contaminants do not have any harmful effect on an organism but they change biogeochemical cycle of ecosystems. Eventually this can lead to the change of the ecosystem parameters and even structure. As an example of these contaminants, anthropogenic biogenic elements (that is nitrogen and phosphorus) may be considered. The contaminants of the second group affect directly some vital functions of the hydrobionts. The contaminants in turn may be divided into two groups: those, which stimulate some vital functions at low concentrations and depress these functions at higher concentrations and those, which depress the functions at any concentrations [7, 8, 9].

In 1999, V. Tretyakov designed a simulation model for the prognosis of the sea ecosystem behaviour in conditions of building and functioning of new industrial zone near Byorke-Zund Strait between Karelian Isthmus and Berezoviye islands in the Finnish Gulf. The zone includes a plant for producing liquid ammonia and granulated carbamide obtained from natural gas. In the model, a possible response of the ecosystem was investigated for the increasing of the anthropogenic impact. The model is the system of 102 non-linear differential equations, which are solved by Runge-Kutta method.

Later the model was modified for investigation of consequences of volley of toxicant sewage that is an abrupt discharge of considerable amount of the toxic substance into ecosystems of flowing water reservoirs with changeable volume, depth and river run-off. In addition, the model can reflect consequences of constant discharge of a toxic substance into an aquatic ecosystem. The model may be used for determination of ultimate acceptable anthropogenic impacts on aquatic ecosystems.

2. The model description

The alive components of the model are several groups of phyto- and zooplankton; bacteria, associated with detritus; babies of plankton-eater fishes, predatory fishes, benthos-phage ones, worms of Oligochaete class and molluscs.

The lifeless components of the model are plankton genic detritus, suspended mineral and organic matter, suspended matter of bottom silt; dissolved organic carbon, nitrogen, phosphorus, dissolved ammonia, nitrites, nitrates, phosphates; dissolved oxygen and carbon dioxide; concentrations of toxic contaminant in the organisms bodies, suspended organic matter and water body.

The model can be used for investigations of consequences of the following anthropogenic impacts: 1) Anthropogenic eutrophication of an aquatic ecosystem; 2) Constant discharge of a toxic substance into an aquatic ecosystem; 3) Volley of toxicant sewage that is an abrupt discharge of considerable amount of the toxic substance into an aquatic ecosystem; 4) A toxicant accumulation in the trophic chain of the simulated ecosystem; 5) Joint effect upon an aquatic ecosystem both anthropogenic eutrophication and the ecosystem poisoning by a toxic pollutant.

The model at present can simulate functioning of an aquatic ecosystem of an abstract flowing water reservoir with changeable volume, depth and river run-off. The simulated water body may be divided into two layers: the upper one that is epilimnion and the lower one – hypolimnion, or it can be non-separated aquatic ecosystem considered as a whole.

Temporal variability of the model components ensues both due to translocation processes within the ecosystem that is changes by matter between the model components and by reason of intermixing of the water body with inflowing river run-off which contains some of the ecosystem components.

The translocation processes are influenced by external ecological factors, such as temperature of water environment, solar radiation and so on. Concentrations of some ecosystem components in the inflowing river run-off can be also considered as external ones.

The external ecological factors which temporal dynamics affects the model ecosystem behaviour are: 1) Temperature of the upper layer or all water body as a whole if the model ecosystem consists of only a layer; 2) Temperature of the lower layer; 3) Share of the upper layer thickness relatively to the maximum depth of the reservoir; 4) Share of the river inflow entered into the upper layer; 5) Share of the outflow from the upper layer in the total outflow from the reservoir; 6) Photosynthetically active radiation – PAR; 7) Atmospheric pressure; 8) Wind velocity; 9) Run-off or level of the river inflowing into the reservoir; 10) Concentrations of the three groups of the river phytoplankton; 11) Concentrations of the two groups of the river zooplankton; 12) Concentration of the river bacteria; 13) Concentration of the river detritus; 14) Concentrations of the river dissolved organic carbon, nitrogen and phosphorus; 15) Concentration of the river dissolved organic matter excepting organic carbon, nitrogen and phosphorus; 16) Concentration of the river ammonium, nitrite and nitrate nitrogen; 17) Concentration of the river phosphate phosphorus; 18) Concentration of the river dissolved carbon dioxide; 19) Concentration of the river dissolved oxygen; 20) Concentration of the river suspended mineral matter; 21) Concentration of the river suspended organic matter; 22) Concentrations of the toxic pollutant in the first, second and third groups of the river phytoplankton; 23) Concentrations of the toxic pollutant in the first and second groups of the river zooplankton; 24) Concentrations of the toxic pollutant in the river bacteria; 25) Concentrations of the toxic pollutant in the river detritus; 26) Concentrations of the toxic pollutant in the river terrigenous suspended matter; 27) Concentrations of the toxic pollutant in the river water.

Within-year (annual) variability of the factors must be written into textual files separately for each month. Therefore, annual dynamics of each external factors have to written into 12 files. Extensions of the files must correspond to the month's numbers: January – "01", February – "02" and so on. Before a numerical experiment with the model, a user must prepare files of the initial values of the model components.

The model simulates the following processes: 1) Biosynthesis of the phytoplankton with consumption of biogenic elements in mineral forms and CO2 from the water and oxygen abjection; 2) Breathing and extracting processes of the phyto-, zooplankton, bacteria including destruction of the organisms tissues at metabolism, oxygen consumption, CO_2 and excretes abjection; 3) Bacterial detritus destruction, growth of the bacteria biomass, dissolved organic matter entering into the water; 4) Dissolved organic matter, NH_4 и NO_2 mineralization, oxygen consumption; 5) Zooplankton feeding; 6) Vital processes in the fish fauna including hatching, feeding, growth, breathing and metabolism with excretion, migration between the layers; 7) Vital processes in the benthic society including its influence upon the water body; 8) Turbulence interchange by the dissolved and suspended components between the layers; 9) Bottom silt stirring-up due to wind and waves; 10) Bottom silt organic matter destruction; 11) Change of the components concentrations due to the reservoir water body intermixture with the inflowing river; 12) Toxicant influence upon the vital processes; 13) Organisms dying off.

Formalization of the each simulated process demands setting of values of the process parameters and coefficients. Therefore, a user must prepare files of parameters of the simulated processes.

Besides that, a user must prepare the file of the reservoir parameters. In order to simplify the numerical experiments processing and escape possible mistakes it is better to prepare file of the data configuration. The file contains full addresses of all external data files and their names. The configuration file has rigid structure. A user can edit the file by means of any textual editor. He must not insert and delete the strings and delete in the strings the symbol of hyphen ("-"). Name and full address of a data file is written in each string to the right of the hyphen. In each string to the left of the hyphen, there is a brief explanation of the information, which is stored in the data file. A user can edit the explanation and even change its language. In addition, a user can edit the data file name and address to point new prepared file of data, template or the ones of a new file for the experiment results recording. Results of the numerical experiments are written into files of Microsoft Excel books format according to prepared files of templates. A user by the program interface must set the following features of a numerical experiment: 1) The reservoir type. The possible variants are: flowing, stagnant ones, marine estuary. By default, it is set the variant of a flowing reservoir. The variant of a marine estuary is now in stage of elaboration. 2) The type of the reservoir level. There is no a default variant: a user must make choice. In case of the stagnant reservoir this stage of the experiment features setting is skipped. 3) Simulation of a toxic matter cycle in the ecosystem. By default the feature is skipped. To switch on the feature a user have to switch on the corresponding checkbox in the program interface. 4) If the experiment includes simulation of the toxicant cycle, a user have to set the toxicant type. In case of the first type of toxicants a toxicant does not stimulate vital processes of the aquatic organisms at low concentrations of the toxicant in the organisms' tissues. In case of the second type of toxicants a toxicant stimulates vital processes of the aquatic organisms at low concentrations of the toxicant in the organisms' tissues. By default, the simulated toxicant is one of the first type. A user can set change the toxicant type on the second one. 5) Shape of the reservoir hollow. The possible variants are: cone, frustum of cone, ellipsoid, three-axial ellipsoid, cylinder, spherical segment. The variant of a spherical segment is set by default. 6) Number of the water body layers: one or two. 7) In the case of two layers a user have to select the variant of the layers thicknesses ratio. It can be constant or changeable one. 8) Share of the inflowing river water entering into the upper layer. It also can be constant or changeable during a year. 9) Share of the water from the upper layer in total outflow from the reservoir. It also can be constant or changeable during a year. 10) Windy stirring-up of the bottom silt. By default, the process simulation is checked on. In case of a one-layer ecosystem simulation the stages 7-9 are automatically skipped. After the stage 6 a user passes to the stage 10. In case of simulation of a two-layer ecosystem of a stagnant reservoir the stages 8 and 9 are skipped. 11) Taking into account the flood-plain influence upon the aquatic ecosystem (in the case of flowing reservoir). By default, the influence is checked off. The block of the influence has not yet been included into the program. Therefore, a user passes directly from the stage 10 to the stage 12. 12) Taking into account influence of atmospheric precipitation on the reservoir mirror. By default, the influence is checked off. The block of the influence has not yet been included into the program.

When the determination of the experiment specificity has been performed, a user have to input the experiment identifier into the textual field of the interface. The identifier can include any symbols. Then a user have to check on in the frame "To write the dynamics results" the checkboxes of the parameters sets which will be recorded into the external files of the experiment results. By default the checkboxes are checked off that is no any recording of the experiment results.

A user can check on recording of the following sets of the ecosystem functioning parameters: temporal dynamics of the non-toxic components values, toxic components values, and intensities of the non-toxic components matter interchange processes, intensities of the toxicant interchange processes, parameters of the environment quality estimation. A user can check on the sets in any combinations including all sets or no one.

Then a user by means of the interface have to point the data configuration file. After that, a user clicks the button "All parameters have been set" and the experiment starts.

The model simulates within-year cycle of an aquatic ecosystem life. The cycle begins on January 1 and finishes on December the 31-st. At the very beginning of the iteration body of the cycle the program determines if the ice cover exists or not. Then the program determines the number of the month. The program sets the number of splitting of daily step of the decision of the differential equivalences system by the month number. During the January-March period number of within-day steps is equal to 16, April-October period – 64, and in November and December – 32.

Then the program determines the number of the day within the month. If the day is the first day of a month then the program loads from external files into the main memory arrays of the external ecological factors values for a coming month. Then the program remembers the values of the external factors and the model components at the beginning of this and next day. If the day is the last day of the month, then the main program runs "Sledm" subroutine, which determines the extension of the files of the external factors for the next month. In this case, the next day is the first day of the next month. For the 31 of December it is January 1. The values of the external factors at the beginning of the next year are set as equal to the values at the beginning of this year. Then the main program examines if the temperature of the upper layer or the water body as a whole is enough for spawning or not. If it is enough then this day is set as the date of the beginning of the spawning. Of course, the temperature required for initiation of the spawning of various fishes may differ.

Then in the program, there is a block of automatic doubling of number of fractional steps within a day at the decision of the system of differential equations. This block is only performed in the case when during decision of the equations system at least a component becomes negative. Then the program returns the values of the components to the beginning of the day. At the initial calculation of the equations system for each day, the program skips the block. After that, the program performs the data preparation for decision of the equations system within a day. It is necessary to stress that the realization of the decision within a day does not refer to simulation of diurnal dynamics of the ecosystem processes. The diurnal cycle is necessary for decision of the differential equations system by the numerical Runge-Kutta method. At first, the program determines the size of a fractional step in part of a day by division of one by the number of the fractional steps in the day.

To ensure smoothness of the decision the program determines values of changes on the fractional step of the external ecological factors: water temperature, solar radiation, and atmospheric pressure, wind speed and so on. Then in the program, there is a block of simulation of within-year dynamics of individual weight of Oligochaete worms. This process is realized on the base of data for ecosystem of Ilmen Lake. Here the program also calculates change of the individual weight on a fractional step.

Then the program performs diurnal cycle of the equations system decision by means of iteration Runge-Kutta method of the fourth degree.

This method has the fourth degree of accuracy that is the total error at the final interval of integration is directly proportional to the value of the fractional step in the fourth degree. The above-mentioned method is realized in the subroutine «drob». The main program calls the subroutine 4 times according to the stages of calculation by the Runge-Kutta method. The subroutine calculates values of the external ecological factors. If the model simulates ecosystem of running water body ecosystem the subroutine also calculates values of parameters of the water body flowage and concentrations of the simulated substances in the inflowing river run-off for each fractional step and stage of calculation by the Runge-Kutta method. If the model simulates a cycle of a toxic matter, the subroutine calculates concentration of the toxic matter in the model components flowing into the water body with the run-off and in the river water itself.

Thus, we set the change within a day the following parameters of the model: the water temperature (if the water body has two layers, then in two layers separately), solar radiation, atmospheric pressure, wind velocity.

If we simulate ecosystem of a water body with changeable level then the model likewise calculates the change of the water body volume, its maximum and average depth, and surface area within a day. If the water body ecosystem divides into two layers then the model likewise sets changes within a day the ratio between the upper layer width and the maximum depth of the water body, maximum width of the upper and lower layers, volumes of the layers, and average widths of the layers. If we simulate change within a year the ratio between the input of the river water into the upper and lower layers of the water body then the model also sets change within a day share of the river inflow inputting into the upper layer. Likewise, the model sets change within a day share of water from the upper layer in the total outflow from the water body. At simulation of an ecosystem of a flowage water body the model likewise sets change within a day concentrations of the model components inflowing with the river inflow including a toxic substance, of course, if the model includes simulation of a toxic matter cycle.

After the end of a diurnal cycle of the calculation of the intensities and values of the model components in the main program there is block of the current values setting into cells of tables of Microsoft Excel format.

3. Results and discussion

Let us present some results of computer simulation by the model of functioning of an abstract flowing water reservoir ecosystem under various anthropogenic impacts and without any impacts that is at natural regime of the simulated ecosystem. In the standard (benchmark) numerical experiment with the model, the intra-annual dynamics of biogenic elements and organic matter concentrations in the inflowing river's water reflects generalized seasonal dynamics of the substations upon condition of absence of anthropogenic impact. The reservoir parameters and external ecological factors correspond to conditions of the Russian part of the Finnish Gulf watershed. Parameters of the simulated water reservoir are the following: the rate of conventional water exchange – 4, the maximum depth at average water level of the reservoir – 5 m. As data for building of intra-annual dynamics of biogenic elements and organic matter concentrations in the inflowing river's water, we used data of multi-year monitoring at 25 stations on medium and small rivers within Russian part of the Finnish Gulf watershed. According results of statistical analysis, we divided the rivers into four groups and separately the Mshaga River. There were carried out five benchmark experiments with the intra-annual dynamics of biogenic elements and organic matter concentrations in the inflowing run-off corresponded the generalized dynamics in the four river groups and the Mshaga River because biogenic and organic matter content in these rivers run-off practically does not include anthropogenic component. In the model experiments with anthropogenic eutrophication simulation, we increased the biogenic and the organic matter contents in few times. Intra-year dynamics of the toxicant content in the inflowing run-off was similar the one of chrome in the Smolyachkov stream in the Kurortnyiy district of St. Petersburg. The numerical experiments with the model included both separated simulation of anthropogenic eutrophication and toxic substance inflow, and joint impact of the eutrophication and the toxicant inflow.

4. Conclusions

Simulation of natural regime of the aquatic ecosystem with the intra-year dynamics of the biogenic elements and organic matter in the inflowing river water, which correspond the ones in the four groups of rivers of the Finnish Gulf watershed, shows intensive spring growth of the phytoplankton biomass. The reason of it is increased content of the biogenic elements during flood caused by streams of snowmelt water [10].

Dynamics of the biogenic elements content in these four groups of rivers show decrease of the content in the beginning of June. It results decrease of the phytoplankton biomass. Die-away of the phytoplankton leads to increase of the bacterial plankton biomass. There is autumn increase of the phytoplankton biomass caused by increase of inflowing run-off with the biogenic elements that is autumn flood. The maximum average annual phytoplankton biomasses were registered in the numerical experiments with simulation of the biogenic elements inflow from the Karelian and Central groups of the rivers. The average annual concentrations of total nitrogen and phosphorus in river water are maximal in these groups of rivers.

The numerical experiments with simulation of anthropogenic inflow of the biogenic elements have given the following conclusions. In all the numerical experiments, there were two blooms of the phytoplankton – spring-summer and summer-autumn ones. In all cases, the first spring-summer bloom is greater than the summer-autumn one for diatomic and blue-green algae. The group of rest algae shows inverse picture. The increase of the biogenic elements inflow influences at the beginning of the spring-summer bloom of the diatomic algae. The increase of the biogenic elements inflow leads to increase of primary production of the all phytoplankton groups. There is growth of the zooplankton biomass during periods of its maximum values without change of the peaks time. At increasing of the biogenic elements inflow there is decrease of dissolved oxygen concentration during summer and autumn due to the oxygen consumption for molding of the defunct organic matter [11].

The numerical experiments with simulation of toxic substance inflow have given the following conclusions. The toxic substance inflow leads to decrease of the phyto- and zooplankton biomasses. The benchmark numerical experiment with absence of anthropogenic impacts and the numerical experiment with minimal inflow of the toxic substance according to the intra-annual dynamics of chrome in the Smolyachkov stream shows very close dynamics of the model components. The experiment with minimal toxic matter inflow shows decreases of maximum biomasses of the plankton groups. Increase of the toxic substance in inflowing river water in three and five time leads to significant decrease of the plankton for the year, and peaks of the plankton blooms are essentially lower in comparison with the ones in the benchmark experiment. All the numerical experiments show evident spring peak of diatomic algae bloom. However, the autumn peak does not evident. The spring-summer peak of blue-green algae and other groups of the phytoplankton is below than the summer-autumn one. The spring-summer peak of the zooplankton biomass development is greater than the summer-autumn one. The toxic substance makes the feature more evident. Increase of the toxic substance concentration in three and five times the summer-autumn peak disappears [12].

The numerical experiments with joint simulation of anthropogenic eutrophication and toxic substance inflow have given the following conclusions. The toxic substance inflow leads to decrease of the phytoplankton biomass. Diatomic algae is most sensitive to the increase of the biogenic elements. The increase in three times leads to increase of the diatomic algae maximum summer biomass at 47%. The increase of the biogenic elements inflow accelerates the beginning of the spring-summer bloom of the diatomic algae. Additional inflow of the biogenic elements neutralizes the toxic substance negative influence upon the primary production [13].

The numerical experiments have given the following conclusions about the toxic substance distribution within the trophic net. In the experiments with simulation of the toxic substance inflow, there are insignificant decrease of the diatomic algae biomass with disappearing of the autumn bloom. Toxic pollution of the ecosystem leads to increase biomasses of the blue-green algae and other groups of the phytoplankton except diatomic algae. The maximum accumulation of the toxic matter in the phytoplankton organisms shows the experiment with the maximum concentration of the inflowing toxic substance. The toxicant inflow suppresses the autumn peaks of the phyto- and zooplankton. The phytivorous zooplankton and bacteria plankton shows the maximum average annual concentrations of the toxic substance in the ecosystem organisms. All the components of the biota except two-year age predatory fishes show increase of the average annual concentration of the toxic substance in the organisms at increase of the toxic substance inflow in the ecosystem. The two-year age predatory fishes show the minimal average annual concentration of the toxicant at its maxima inflow into the ecosystem [14].

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