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Prognostication of Water Quality and Condition of Ecosystems in Siberian Reservoirs and Yenisei River: Biophysical Approach *

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Abstract : *An avenue to integrate theoretical, experimental and field research methods to forecast water quality in water bodies for different scenarios of water management is proposed. Exploration of the laws of organization, stability and controllability of laboratory "ideal" water microbial communities (model ecosystems) is the basis to build the following biophysical research chain: to formalize with primary field information a conceptual block-diagram of a water ecosystem →to real chemical and other density-dependent and population- growth-controlling factors → to find our limiting factors for natural ecosystems → to conduct experiments with isolated chemical factors and hydrobionts to derive kinetic dependencies and quantitative parameters → to transfer regularities of operation and kinetic dependencies to the natural ecosystem → retrospective verification of the model on the base of available field and derived theoretical-experimental data → prognostic calculations for the scenario. Efficiency of the approach is demonstrated in microalgal "blooming" models for Krasnoyarsk and Kantat reservoirs and in prognostication of radioecological state of great Yenisei river: 1) radionuclide distribution in the Yenisei's bottom sediment is nonuniform - "spotty"; 2) it is theoretically shown, that due to biological interactions and trophical radioniclide migration there is "spotive" type of space radionuclide distribution. The research is to make use of the novel methods of ecological biophysics: Monitoring: spectral analysis of surface waters (algal pigments), fluorescent techniques to evaluate productivity and condition of algae; rapid bioassays for water toxicity (bioluminescence, chemotaxis techniques). Kinetic experiments: microcosms on evaluating self-purification rates; special cultivators to evaluate the rates of growth of hydrobionts and radioactive engulfing, nutrition spectra; methods of finding growth limiting factors. Models: application of Bellman Principle to optimizing the river water use; theory and peculiarities of microbiological decomposition of pollutants in the river ecosystem. The composition of Prognostication Simulation Model is the next: 1) hydrodynamical unit to calculate 2-dimensional space-time rate of stream on any depth; 2) hydrophysical unit to calculate: water temperature and level of solar radiation inside the water body; 3) ecosystem unit to calculate dynamic of concentration of phytoplankton, zooplankton, bacteria, major chemical matters and pollutants in water, content pollutants inside of hydrobiont's cells and dynamic of bentos; 4) radioecological unit to forecast the dynamic of radionuclides in the water body and bottom, their hydrobiont's concentration; 5) database. Reservoirs and river models are provided by monitoring and kinetic experiments data.*

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1. Introduction: biophysical approach and its components

Increasingly growing consumption of water will soon make fresh water one of the key natural resources limiting development of civilization as rigorously as the sources of energy. The interests of water users are generally contradictory. Common for them is the act they pollute water objects, essentially intervene into an ecosystem introducing adverse changes. To be able to forecast ecological consequences of water user's activities, to satisfy their requirements to optimum are the pressing problems of the present day encompassed by the "stable development" concept adopted by the UN. Simulation modeling with mathematical simulation model of an object, phenomenon, process is one of powerful and integrative means facilitating solution of problems of this kind.

Generally (the most common technique) construction of mathematical model of ecosystems rests on the following chain: to formalize a conceptual block-diagram of a water ecosystem → to identify parameters by field data → to verify adequacy of a model by retrospective data → to calculated by project scenarios.

This method is not acceptable for forecasting water ecosystems of non-existent water objects or objects for which field data is unavailable yet. What is more, the heuristic value of such an approach is low, since the identified constants are local and are not applicable for other ecosystems.

The biophysical way to create ecosystem models is based on: 1) acquisition of preliminary evidence about laws of stability and controllability of the constitution of "ideal" (model) communities; 2) exploration of the laws of action and dynamics of limiting factors – tools to control the composition of communities; 3) experimental kinetic dependencies of growth rates, mortality, respiration on identified limiting factors; and 4) using this knowledge in ecosystem models.

1.1 Laws of "ideal" communities

1.1.1 Criterion of coexistence of mixed populations

An "ideal" community is considered to mean a set of populations whose population dynamics (growth) is determined by certain chemical factors of the medium, depending in their turn on the density of these populations (density-dependent growth-control factors (DDGCF)). A part of these factors may ingress the system from outside and/or form by the biotic turnover. The medium is assumed to be sufficiently homogenous. Satisfying these conditions are, for example, a community of microorganisms developing in a continuous cultivation system, on the assumption that mixing is ideal. The hydrological component in forming the community is, at this, reduced to nil; ecological mechanisms of ecosystem stability are considered only.

To find out the general condition linking the number of coexisting species in a community and the number of chemical DDGCF of the environment consider a mixed microbial culture without predators. It is convenient to start theoretical analysis of interacting populations with a model (Degermendzhy, 1981) describing population dynamics of m species in an open system of a chemostat type (Degermendzhy *et al*, 1979). It was proved the possible number of steadily coexisting species (m) does not exceed the number of DDGCF independent factors (*n*) determined by the densities (X) of these species, (i.e. $m \leqslant n$). Varying the inputs of these factors the population composition of community can be controlled. Data available in literature and our own data about the mechanism of stable coexistence of experimental mixed cultures of microorganisms (up to 9 coexistent populations) prove validity of the above given criterion of coexistence ($m \leqslant n$) (Degermendzhy *et al.*, 1989).

1.1.2 Complication of balance of factors

Complication in the balance of factors does not, in principle, afford to estimate the values of factors with the number of species larger than the number of DDGCF, i.e. the earlier proved "forbiddeness" on excessive number of coexistent species is still in force.

1.1.3 Mixed culture with predators

The principal statement for this system: possible number of predator species (*k*) coexisting in equilibrium does not exceed the number of prey (*m*) species which, in its turn is not more than the sum of number of predators and the number DDGCF (*n*), i.e. $k \leqslant m \leqslant (k+n)$.

1.1.4 Spatial inhomogeneity

Space heterogeneity can be an additional factor of species diversity. In this case it is the system of associated chemostats with controlled channel for interchange of populations and the medium that can be a model of spatial inhomogeneity. Coexistence of, for example, two species with one limiting factor in such a model has been theoretically shown to be possible for fairly small intensity of exchange flows only (Degermendzhy, 1986). Hence, the cause of coexistence of species in well mixed water bodies is to be in existence of DDGCF discussed in 1.1.1.

1.1.5 Effect of autostabilization of chemical DDGCF

The essence of the effect is independence of the steady (average) level of chemical DDGCF in an ecosystem of the input flows' level of these vary factors. Alongside with this there is a correlation between the populations' biomass and input concentration of the factors limiting their growth (Degermendzhy *et al.*, 1979). Hence, there should be no correlation dependence between the background value of the DDGCF and the biomass magnitude of this population.

Analysis of the effect of independence of DDGCF on input flow intensity in biological systems of most different kind (from laboratory batch and continuous to natural) allows to conclude that the autostabilization phenomenon is a common feature of developing biological systems. The essence of this phenomenon does not change with the nature of the DDGCF, provided the following conditions hold: the factor is density-dependent, i.e. variation of the level of this factor correlates with the population density and the factor, as it is controls the growth rate of this population.

2. Prognostication Models

Necessity of mathematical simulation of ecological processes is at present beyond question. Many versions of mathematical models distinct in a number of features are available (Strashkraba and Gnauk, 1989). We prefer dynamic chamber models taking into consideration essential mechanisms of interaction of hydrobionts with nutrition elements and other environment factors. Dynamic models are advantageous over statistical, based on approximation of time series in their basis of physical (chemical, biological) regularities, and, consequently, are able to predict earlier unavailable situations, arising, for example, in construction of a new water body.

2.1 System and nomenclature

Prognostication Simulation Model (PSM) is designed to conduct simulation experiments with a mathematical model of a water ecosystem of reservoirs. The composition of PSM is the next (Fig.1): 1) hydrodynamical unit to calculate 2-dimensional space-time rate of stream on any depth (as a function of morphometry, friction, wind, slopes, flow, tributaries); 2) hydrophysical unit to calculate: water temperature and level of solar radiation inside the water body (as a function of outside solar radiation, light consumption and scattering by hydrobionts (microalgae) and particles, sedimentation et cetera); 3) ecosystem unit to calculate dynamic of concentration of phytoplankton, zooplankton, bacteria, major chemical matters and pollutants in water, content pollutants inside of hydrobiont's cells (as a function of population interactions, specialty of turnover of matter, industry pollutions, DDGCF, hydrodynamical and hydrophysical conditions, transfer of bottom sediments); 4) radioecological unit to forecast the dynamic of radionuclides in the water body and bottom, their hydrobiont's concentration (as a function of results of ecological, hydrophysical and hydrodynamical units); and 5) database. Before calculations the water body is divided into the 3 layers along of depth. The each layer is divided into a number of sections-chambers (in accordance with the map of chambers) concentrations of substances and organisms in each is assumed to be distributed uniformly.

PSM is designed to carry out simulation experiments using mathematical models of aquatic ecosystems (lakes, artificial reservoirs, bays). The simulation experiment allows a number of water management problems in a given region to be solved. The mathematical model also allows: 1) the dynamic of water ecosystem components (chlorofill concentration, blue-green alges, green alges, zooplankton, bacteria, radionuclide composition, etc., a lot of organic and unorganic substances) to be calculated; 2) estimation of the influence antropogenic and hydrometeorological environmental conditions on space-temporal dynamics of ecosystem and water quality and its sensitivity; 3) adequacy check for some real water ecosystem. It also provides for the on - site ecological assessment of various projects by responsible agencies and scientific laboratories, elucidation of hydrochemical, hydrophysical situation and repercussions of different water-use regimes.

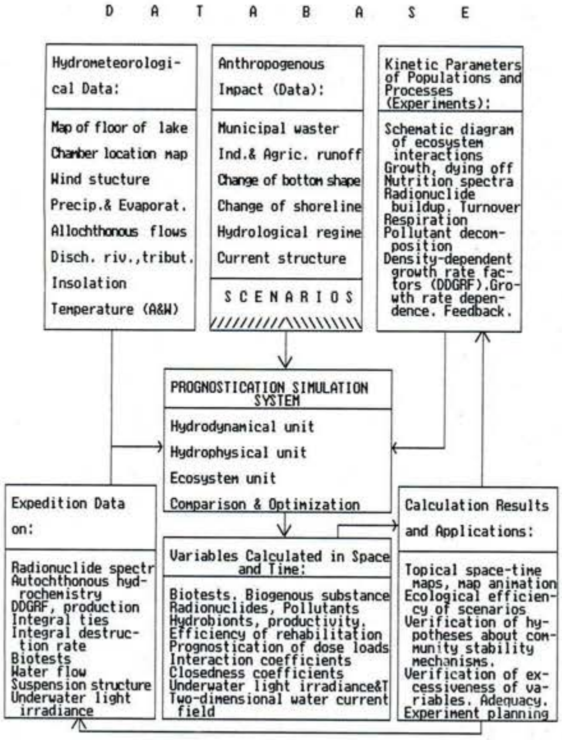

Fig. 1 Composition of prognostication simulation model

Adaptation of a system to a new water body is considered to mean bathymetric charting, zoning, setting appropriate input series and plotting hydrometeorological data.

Ecological model block describes ecosystem processes in the water mass and is constructed by the data of specific studies or by literature data combined with the hypotheses advanced.

Block of input time series contains information about known external parameters for a given scenario of ecosystem dynamics calculation and is a local bank of space-time parameters.

Time series, initial conditions and model parameters are provisionally formed and stored by auxiliary programs - databases. The dialogue operation of these programs requires little user skill.

The water quality is considered to mean the condition vector which is a list of indexed components that are the coordinates of a point - water body condition - in a multidimensional space of signs.

Model components or components of condition vector are hydrological, hydrobiological, hydrochemical dependent variables whose dynamics is calculated in the model. Derivative of components are the left-side parts of respective differential equations comprising the model in accordance with ecosystem skeleton diagram.

Parameters are external as related to the model variables affecting dynamics of components, but independent of them. Examples: air temperature, precipitation, amount and chemical composition of run-offs in the water body.

The system also involves constants - kinetic characteristics of physical, chemical and biological processes, reflecting accounting for relations between components, components and parameters. Thus, prognosis is calculation of condition vector for certain scenarios of water management.

The above said formed the basis of development of water quality prognostication models for the most "blooming" area of Krasnoyarsk reservoir - the Syda bay and the Kantat river reservoir within the limits of Zheleznogorsk city (Krasnoyarsk-26).

3. Siberian Reservoirs

3.1 Krasnoyarsk Reservoir

The Yenissey (600 $km^3 \cdot a^{-1}$) is the first water way of the Russia. Its waters are consumed by several large users: industry, agriculture, communal facilities, etc. Tremendous water resources are used by hydroenergy. Krasnoyarsk and Sayano-Shushennskaya Hydroelectric power stations are among the most powerful in the world.

3.1. 1 Reservoir characteristics

Krasnoyarsk reservoir is a deep seasonal slow-flow water body with predominantly seasonally controlled flow. Diversified use of the reservoir tends to hydroenergy. The water surface area is 2000 km^2, volume: 73.3 km^3, length about 390 km, average width: 5-6 km, greatest width about 15 km, average depth: 37 m, maximum depth: 105 m. Annual mean discharge at the dam discharge line 80-90 $km^3 \cdot a^{-1}$. The reservoir is noted for highly variable water-surface elevation: from 243 m to 225 m, i.e. the range of 18 m. The reservoir is 35 years old.

Hydrobiology of the reservoir is characterized by intensive "blooming" of blue-green microalgae up to 1.4-3.3 $g \cdot m^{-3}$ in dry weight. This process is most intensive in Syda bay, located in the lower reach of the upper part of the reservoir - the largest in the reservoir (30-35 km long, 4-5 km wide, up to 40 m deep) (Fig. 2).

Thus, in 1979-1980 *Aphanizomenon flos-aquae* blue-green algae developed most (68-105 billion cells$\cdot m^{-3}$). Dominating in mass among the diatomaceous algae are *Melosira granulata* (0.34 $g \cdot m^{-3}$) and *Fragilaria crotonensis* (0.31 $g \cdot m^{-3}$) producing about 75% of phytoplankton biomass. Phytocenoses had high densities in this area in 1981-1983 (*Aphanizomenon flos-aquae* ~ up to 3.3 $g \cdot m^{-3}$).

Development of Syda bay water ecosystem model representative of the general development trend of Krasnoyarsk reservoir ecosystem is beneficial for elucidating the mechanisms of "blooming" and makes possible to evaluate efficiency of simulation system to be used for other water objects.

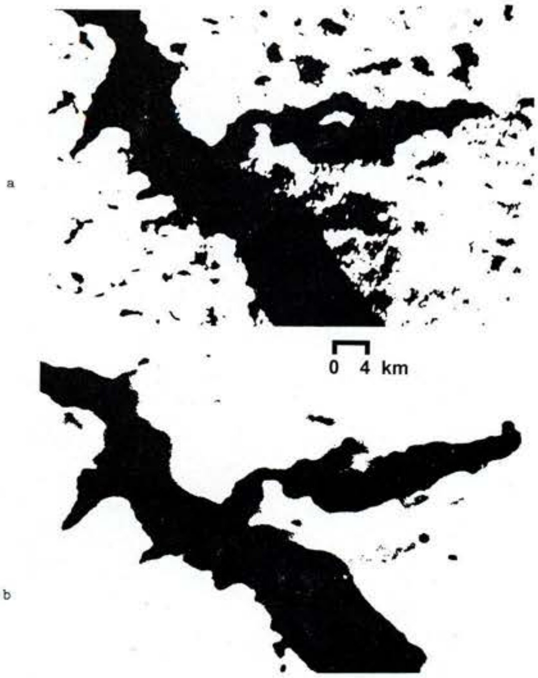

Fig.2 Space images of Krasnoyarsk reservoir Syda bay water area
(a:1985-07-04; b:1985-08-06)

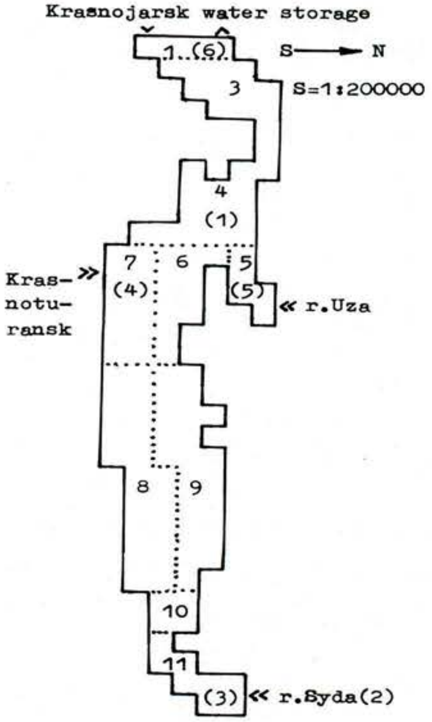

Fig.3 Chart: chamber arrangement boundaries (...), numbers without brackets - chambers, numbers in brackets - sites of Syda bay area, 1985-07-30

3.1.2 Experiments on measurement of kinetic characteristics

Experiments were conducted after field information retrieved from station (Fig. 3) as a result of expedition research in 1984-1986 has been analyzed. An attempt was made to test theoretical results about weak correlation of the limiting factor background level - DDGCF - with the limited biomass level.

Results of biosurvey are given in Fig. 4. The range of variability of input concentration of phosphorus corresponding to observed chlorophyll variation ($\Delta C_{\text{chl}} \approx 50$ mg·l^{-1}) was 16 mg l^{-1}. The range of phosphorus background concentration variation is estimated at 1.6 mg l^{-1}, i.e. 10 times less than the input variability. This fact was a good enough reason for experimental verification of the limiting effect of phosphorus which yielded dependence of specific growth rate of *Aphanizomenon flos-aquae* blue-green algae on mineral phosphorus concentration $\mu_{\text{b-ga}}(\mu_{\text{b-ga}}^{\max}, \text{P})$ (Fig. 5). The nature of dependence of maximum specific growth rate on temperature and illuminance $\mu_{\text{b-ga}}^{\max}(t^0, E)$ (Fig. 6) is taken from literary evidence (Gentile and Maloney, 1969).

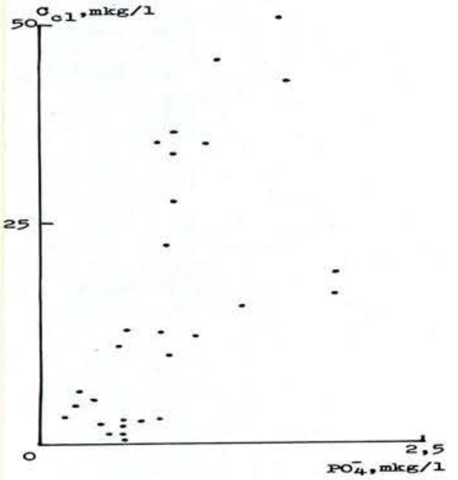

Fig.4 Field data of combined observation of chlorophyll a and phosphorus concentration from 1984-08-24 in Syda bay, Station 1

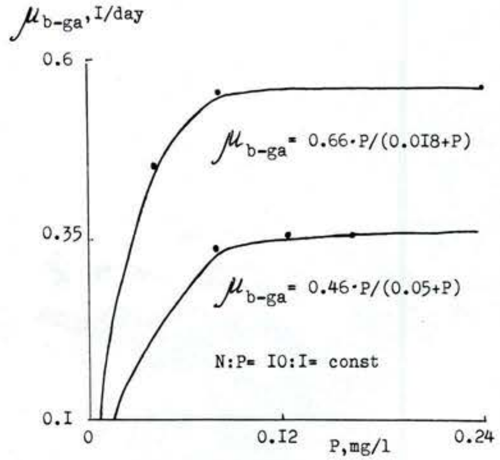

Fig.5 Specific *Aphanizomenon f.-a.* growth rate vs limitative phosphorus concentration (t= 20 C)

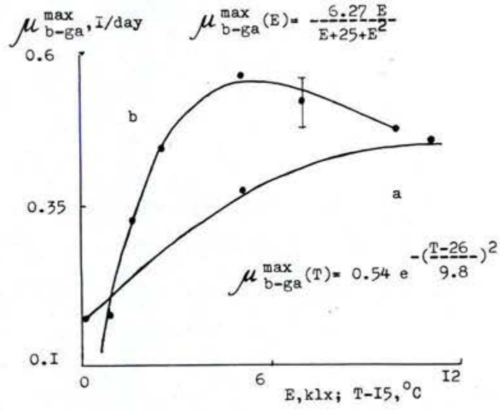

Fig.6 Maximum specific *Aphanizomenon f.-a.* growth rate vs a - temperature, b – PAR (t=20 ℃); (Gentile and Malony,1969)

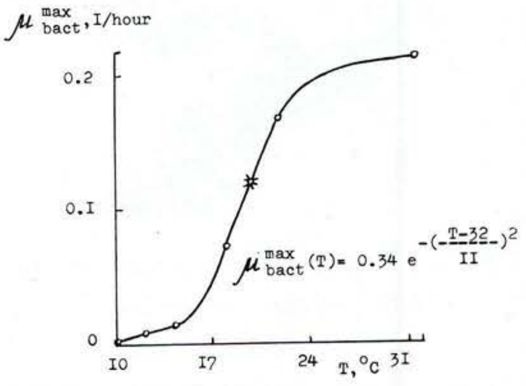

Fig.7 Maximum specific growth rate ($\mu^{\max}$) of mixed bacterial culture vs temperature

Obtained were: $\mu_{\text{bact}}(\mu_{\text{bact}}^{\max}$, DOM) - specific growth rate of aggregate bacterioplankton vs. concentration of dissolved organic matter (DOM) (Fig. 1) and $\mu_{\text{bact}}^{\max}$ - dependence of maximum specific growth rate of bacterioplankton on temperature (Fig. 7).

In addition to dependencies of specific growth rates on the limiting factors with account for specificity of type specific growth rate, it is possible to estimate theoretically and experimentally the "force" and "type" of intra- and interpopulation interactions. The criterion is the nature of variability of growth acceleration of "accepting" population in response to deviation of the biomass level (ΔX) of the "donor" species (Degermendzhy and Adamovich, 1984; Adamovich *et al.*, 1987). Experimentally, for example, to estimate the effect of bacteria on themselves, B_{bb} (at $\Delta X = 1$ g m^{-3}) this value is calculated by formula:

$$B_{bb} = \ln \frac{X_f^e X_i^c}{X_f^c X_i^e} / [(\Delta t)^2 (X_i^e - X_f^c)]$$

where the lower index - final (f) or initial (i) time, the upper is experiment (e) or control (c). For station 1 during 1986-09-01, $B_{bb} = -(0.072 \pm 0.021)$ h^{-2}.

3.1.3 Ecological forecast experience

Field data on ecosystem components and derived experimental characteristics formed the basis to create an ecosystem model (block-diagram in Fig. 8). Characteristics of diatomaceous algae (μ_{da}, μ_{da}^{max}) were taken from literature (Tilman, 1986). The model was built into a PSM for personal computers.

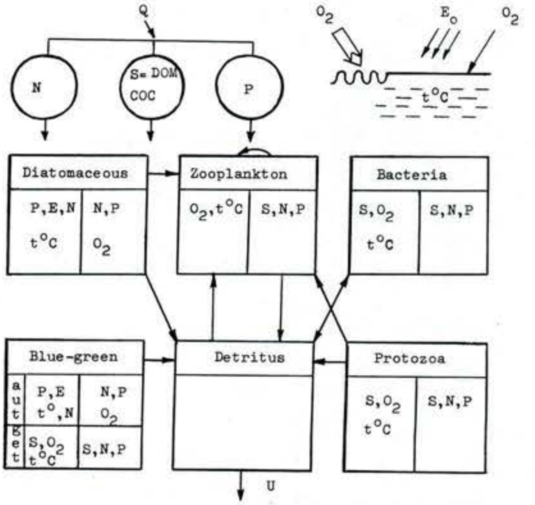

Fig.8. Syda bay ecosystem skeleton diagram. Rectangular blocs: left - substances consumed and growth conditions, right - substances emitted. Arrows show trophic limiting connections. Q - substance flow; N - nitrogen; S - dissolved organic matter; P - phosphorus; O_2 - oxygen; E_0 - PAR; t - temperature; u - sedimentation rate; aut. - "autotrophic" growth component; het. - "heterotrophic" growth component.

Polyvariant calculations with account of input hydrological, meteorological (Fig. 9) and other information were done for the following scenario versions (Fig. 10): 1) to estimate effect of hydrology only on distribution of abiotic components, the ecological model is not involved; 2) the ecological model takes into consideration bacterioplankton only, simulated by organic matter, no other biotic components; 3) taken into consideration are the following components: diatomaceous and blue-green algae, bacteria, Protozoa, organic matter, nitrogen, phosphorus, biotic turnover of the matter is absent; 4) the same as in version 3, biotic turnover inclusive (theoretically involved (Fishtein *et al.*, 1983; Gubanov *et al* , 1984)); 5) the same as version 3, μ_{da} is increased, zooplankton inclusive; 6) the same as version 5, biotic turnover inclusive; 7) the same as version 6, μ_{da} is increased; 8) the same as version 3, including biotic turnover and zooplankton cannibalism, μ_{da} is somewhat reduced.

Analysis of hydrological calculations (version 1) shows that in one season on the average simulation results beyond the "blooming" ranges are close to observed in quality and for some chamber in quantity. This conclusion is most true for chambers 5 and 11 strongly affected by tributaries - high flow (Fig. 10, 11).

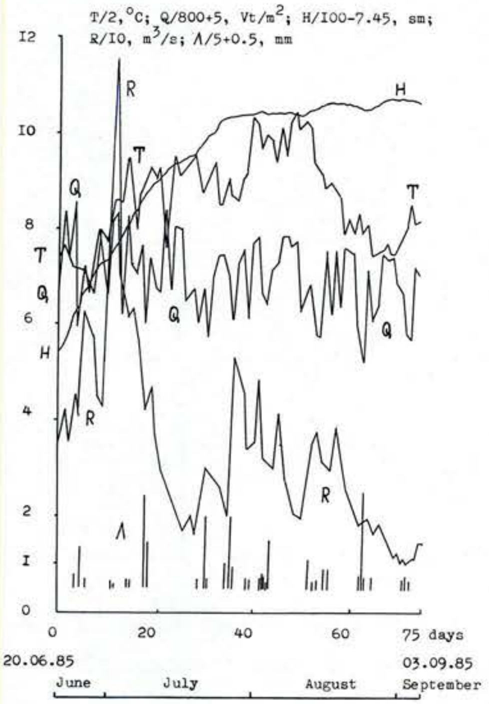

Fig.9 Hydrological and meteorological data. Lebyazhye settlement: H - Krasnoyarsk reservoir level (elevation over head pond zero level site), L - precipitation; Khakasskaya metėo station: Q - total daily solar radiation; Syda-Otrok post (chamber 11, station N2): R - discharge of the Syda river; T - mean daily temperature of water

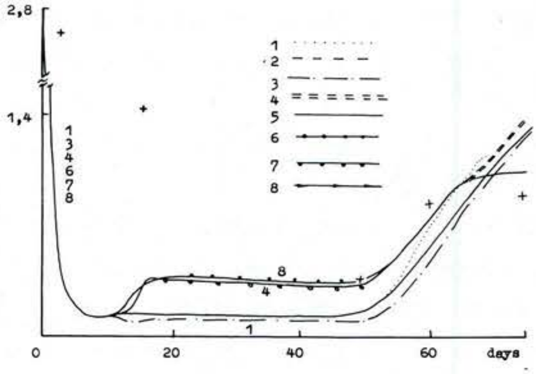

Fig.10. Total mineral nitrogen dynamics; chamber 11 (+ - field data)

Dynamics of aggregate bacterioplankton (Fig.2) represents variation of growth limiting organic matter flow into chambers. Where this flow reduces the dying off process prevails and bacterioplankton density decreases (chambers 4 and 7 devoid of large flows of organic matter, in particular). Hence follows a very important conclusion that income of allochtone organic matter only is not sufficient for estimated dynamics of bacterioplankton adequate to observations, this requires formation of additional autochtonous substance. This was a good reason to complicate successively the model of the ecosystem (to introduce into the model biotic turnover of the matter and processes and components forming it).

For the ecosystem with account of matter turnover dwell upon dynamics of biological components only, since dynamics of hydrochemical components depends only slightly on the ecosystem version.

In quantity estimated dynamics of diatomaceous algae is close to the field data for flow areas, in quality - to chamber 7 on version 8 calculation basis. Without impact of zooplankton the density of diatomaceous algae reaches very high values. Hence, zooplankton growth kinetics, the spectrum of its nutrition play a considerable role in "blooming" dynamics" (autumn, in particular) of diatomaceous algae.

Calculated dynamics for the blue-green algae (Fig.11) is less adequate to observation than for the diatomaceous, even though the phase of autumn outbreak is well predicted for version 7 and version 8.

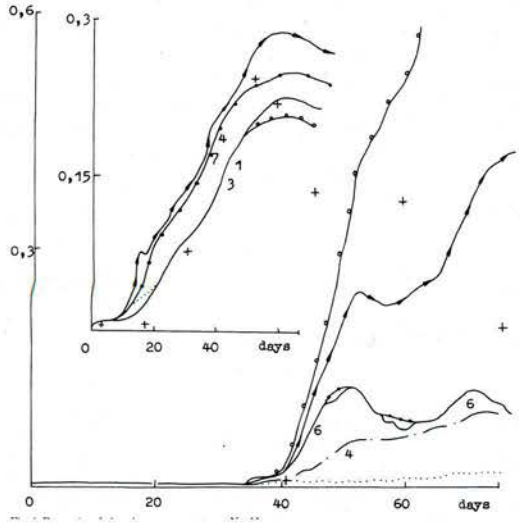

Fig.11. Mineral phosphorus and blue-green algae (right) dynamics;
chamber 11

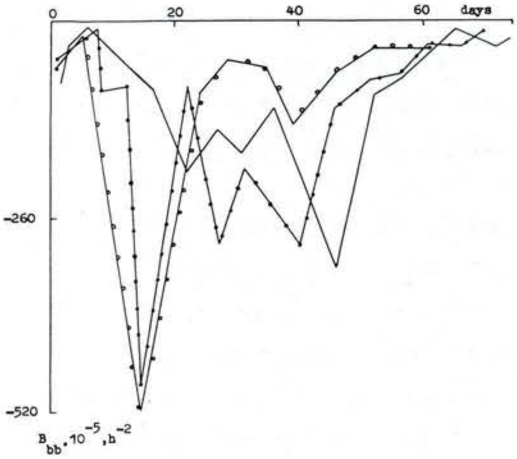

Fig.12. Estimated seasonal dynamics of bacterial regulation feedback (B_{bb})
at $\Delta X_b = 1$ g m^{-3}; chamber 11

Calculation of theoretical dynamics of seasonal changes of the feedback coefficient of bacterioplankton (B_{bb}) for some versions of ecosystem with account of dynamics of chemical oxidation decomposition (COD) - permanganate, temperature, etc. is given in Fig. 12. These versions show intraseasonal aggravation of negative feedback and bacterioplankton regulation to $B_{bb} = -0.005$ h^{-2}. When COD level limiting bacteria matched the observed one, the level of $B_{bb} \approx -0.004$ h^{-2} (Fig. 12, beginning and end of season). The natural level of B_{bb} is about -0.07 h^{-2}, i.e. in magnitude an order more than calculated theoretically. The feedback sign coincides with the theoretical. Thus, the natural "force" of feedback in bacterioplankton regulation is considerably higher than that theoretically found calling for further search of growth regulators.

Introduced parameters of B_{ij} are a basically new additional criterion for verification of model ideas and acquisition of new knowledge about characteristics of intraecosystem relations.

3.1.4 Conclusions

Computations show that:

1) the seasonal trend in hydrochemical components' dynamics can be accounted for hydrology only, without resort to biological processes;

2) hydrology only is not sufficient to explain dynamics of biological components: account of ecosystem processes is required;

3) a simplest "bacteria-organic matter" model reveals that bacterioplankton is hardly sustained by allocation inflow of organic matter only: additional production of organic matter, such as by

phototrophs is required; average seasonal concentration of COD in the water body is found to depend slightly on organic load (autostabilization effect);

4) "blooming" of diatomaceous algae can be accounted for the combination of biogenous load and their relationship with zooplankton;

5) intensity and the moment of beginning of "blooming" development of blue-green algae is well predicted by the model taking into account elevated eutrophication of the bay by mineral phosphorus; the mechanism of decay of "blooming" call for experimental elucidation.

3.2 Kantat Reservoir

3.2.1 Water body parameters

The man-made water body of recreation purpose on the Kantat - a small river is within the city limits. The volume of the reservoir is about 0.01 km^3, water surface area 3 km^2, length 3 km, maximum width 2 km, average depth 3.5 m, maximum depth 7 m. The reservoir is 32 years old.

In recent years negative phenomena observed in the reservoir revealed in changing color and decreasing transparency of water, its deteriorating taste, strong obnoxious odor, etc. Preliminary field studies (Krasnoyarsk State University, 1989-1990) showed these negative phenomena, the detrimental condition of the reservoir to be due to excessive development of algae - "blooming" of the water body. The grade of water quality in Kantat reservoir during "blooming" ranged from moderately to highly contaminated.

One of the signs demonstrating that the level "blooming" in the Kantat reservoir is up to critical is mass domination not of *Aphanizomenon* blue-green alga only but also of other species: *Anabaena* and *Microcystis*. Our laboratory studies show that the species of *Anabaena* and *Microcystis* genera generally dominate at higher concentrations of biogenous elements of nitrogen and phosphorus than those optimum for *Aphanizomenon*. This is indicative of the fact that the biogenous load of these elements in the water body is not constant but increasingly grows. Algal "blooming" (blue-green, first) demonstrates strong eutrophication of the water body due to large income of biogenous elements into it (phosphorus and nitrogen, first). The biogenous elements may income with the river feeding the water body, rainfall runoffs, atmospheric precipitation, etc. (external load). Eutrophication makes disturb balance flows of organic matter and oxygen used for its oxidation, resulting in recovering conditions and biogenes buried in sludge sediments intensively get into water increasing internal biogenous load.

In this connection a series of measure were proposed to reduce external and internal biogenous loads. Among them the principal were: 1) to divert or purify rainfall runoffs, 2) to a accelerate water exchange, 3) to remove sludge sedimentation and bottom deepening. It is the goal of ecological-mathematical prognostication modeling to choose specific and optimum action or rank these measures (taking into account ecological consequences).

3.2.2 Field and experimental evidence

Field observations and experimental work were done in the reservoir with 5 chambers - 4 surface and one bottom - which took samples - 3 stations in each chamber (Fig. 13).

In the summer survey seasons of 1989-1992 we studied dynamics of organic (COD, phenols, petroleum products, synthetic surfactants) and mineral (Cu, Zn, K, Na, Fe, etc.) components. The substances analyzed involved, in addition to water, the reservoir bottom: bottom cone experiments were conducted to study exchange processes (phosphorus and nitrogen) between the bottom sediments and adjacent water mass (Fig. 14). Under investigation was the chemical composition of rainfall runoffs and of the Kantat river. Figure 15 gives dynamics of mineral phosphorus (PO_4) by field chambers of the water body and the contents of these components in the Kantat river and in rainfall runoffs N5 and N7.

Among the biological components under investigation were zoo- and phyto- and bacterio-plankton. Figure 16 shows dynamics of chlorophyll "a" by field chambers in 1991. It is like for another chamber 2-5.

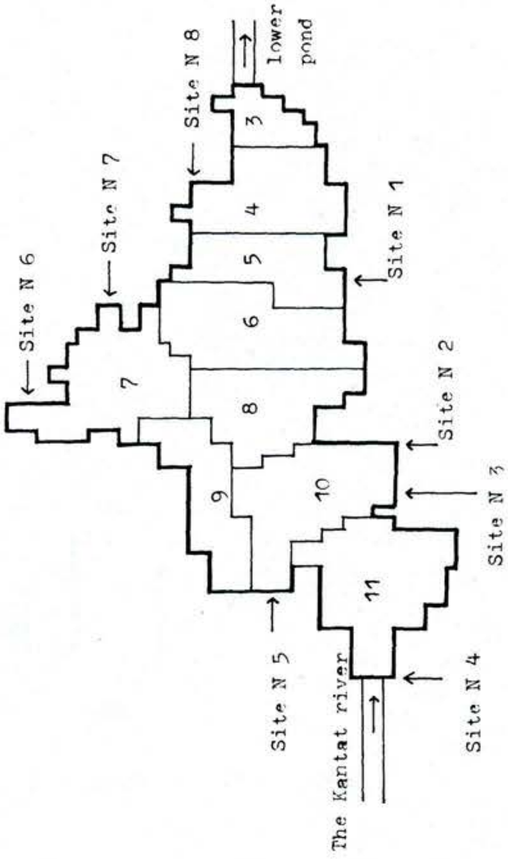

Fig.13 Chart-diagram of the Kantat river reservoir

3.2.3 Model calculations

For computer studies the Kantat river water body was divided into 11 model chambers: 1st - dummy chamber, 2nd - bottom chamber and 9 surface chambers (Fig. 13).

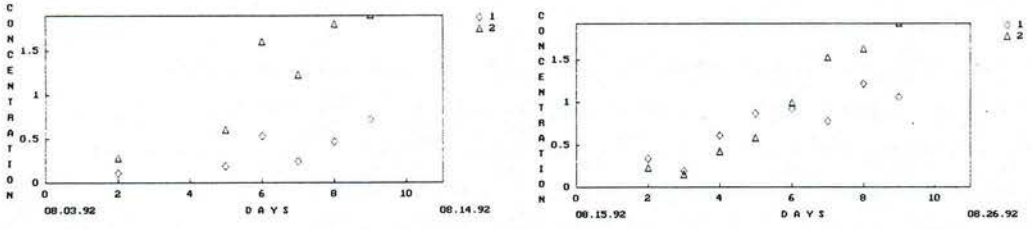

Fig.14 Dynamics of mineral phosphorus emission from bottom sediment. Experiments with bottom cones 1 and 2. a) - first experiment; b) - second experiment.

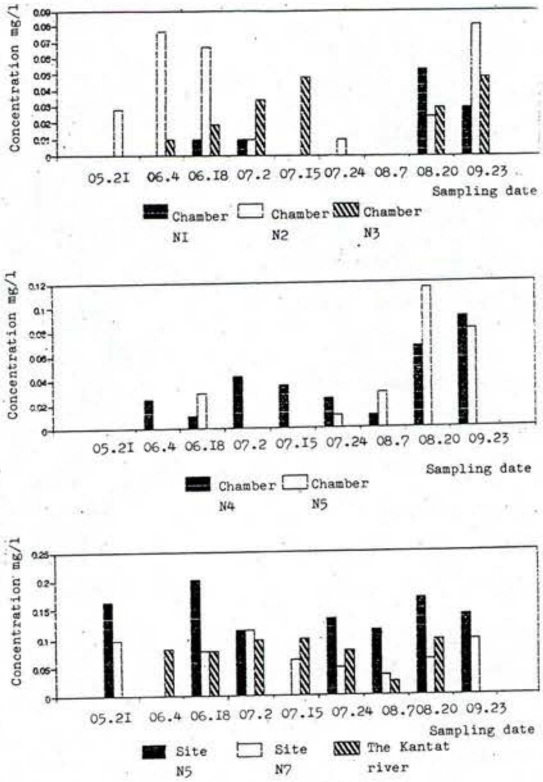

Fig.15 Mineral phosphorus. The Kantat river reservoir, 1992

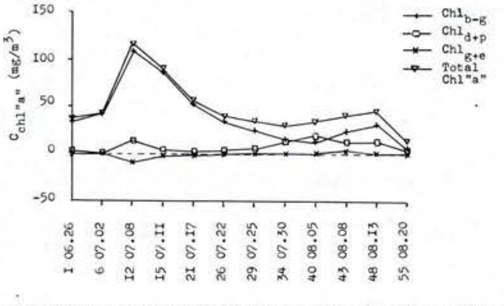

Fig.16 Chlorophyll "a" dynamics in chamber 1 (a)

The gleaned field evidence formed the basis to propose a structure for a mathematical model describing operation of the water body as an ecosystem (block-diagram in Fig. 17). The model involves 2 algal species (blue-green and, conditionally, fodder), 1 integral species of reducers (bacteria), zooplankton. The model takes into account processes of growth, respiration, dying off of biotic components, organic matter decomposition, utilization of biogenous elements, possible limiting (illuminance, temperature, phosphors, nitrogen, oxygen, organic matter) and inhibiting (Fe, illuminance, temperature) factors. The hydrological model has adjusted and coefficients necessary for its operation have been identified. Adjustment was made by measurements of water level with water discharge in the Kantat river 1 000-10 000 $m^3 \cdot h^{-1}$(modal 3 000-3 600 $m^3 \cdot h^{-1}$).

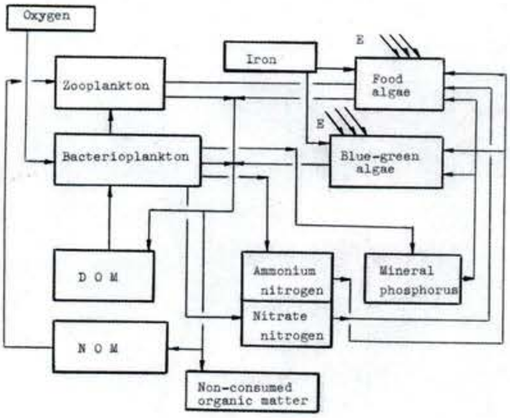

Fig.17 The Kantat river reservoir ecosystem skeleton diagram. Arrows show energy and substance flows. E: light flow; DOM: dissolved organic matter; NOM: non-dissolved organic matter

Methods of deriving kinetic dependencies were analogous to those for Krasnoyarsk reservoir. Lacking coefficients were identified and ecological model was verified by phytoplankton, and by the blue-green algae on the whole which were dominant species and a marker of the reservoir condition, on the one hand, and the reason of its poor condition - on the other hand.

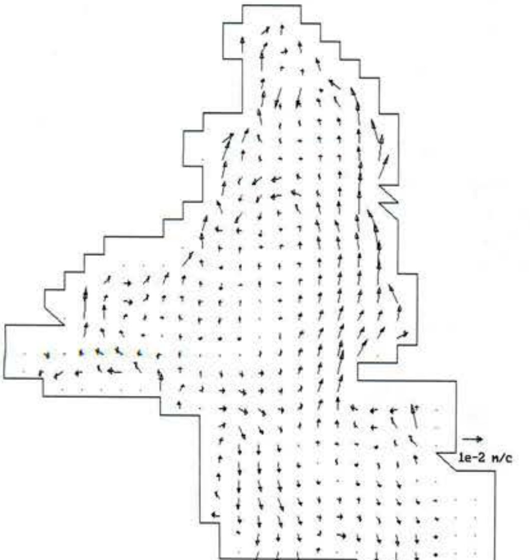

Fig. 18. Calculated map of flow speed structure for Kantat reservoir. Wind speed: 1 m s^{-1} (direction is "from N6 to N2"), depth: 1 m

3.2.3.1 Computer calculations of the scenario

The model evaluates development of phytoplankton as a mass phenomenon. The base versions are considered to mean the most matching the field data, dynamics of blue-green algae growth, in particular. Under consideration was the behavior of the ecosystem (dynamics of its components) depending on the kind and magnitude of the load on it. Results of calculations are illustrated with the example of the 6th model chamber as the central chamber of the water body (for field observation - chamber 3).

Figure 18 demonstrates one of the lot of the calculated maps of structure of speed of flow for Kantat reservoir. Figure 19 gives dynamics of three base versions. Figure 20-22 demonstrate some elements of adjusting the ecomodel to field data for base versions. The load on ecosystem with rainfall runoffs and the Kantat River is assumed, at this, to be constant, continuous and be calculated on average estimation basis. Initial (spring, start) condition (IC) is somewhat more than the average. Bottom is assumed to be not a continuous source of biogenes , but supplies them (is "on") at low concentration of O_2 in the near bottom layer. When the content of O_2 in the bottom chamber is low, the organic matter is accumulating. Biogenes of bottom sediments getting involved into the turnover the "blooming" level of the blue-green algae is, at this, rather high (Fig. 22).

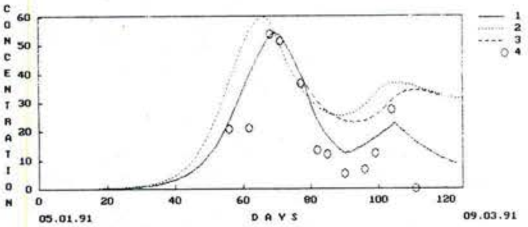

Fig.19 Estimated (base version) and field dynamics of blue-green algae in the 6-th model(3-rd field) surface chamber. O: from here on field data

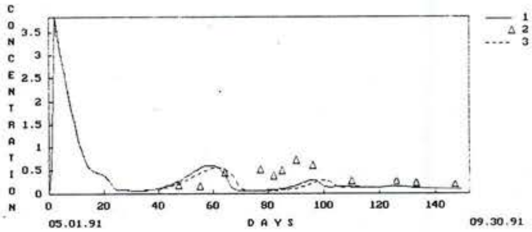

Fig.20. Estimated and field dynamics of bacterioplankton in the 6-th model (3-rd field) surface chamber

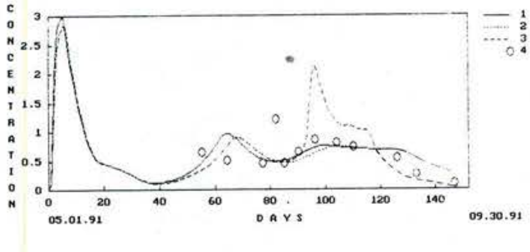

Fig.21 Estimated and field dynamics of bacterioplankton in the 6-th model (2-nd field) surface chamber

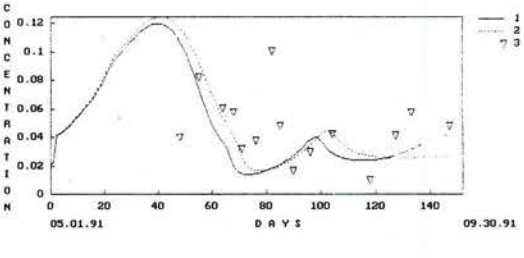

Fig.22 Estimated and field dynamics of mineral phosphorus (PO_4) in the 6-th model (3-rd field) surface chamber

Figure 23 shows versions with variable flow rate. From this follows that elimination of the chemical components in the Kantat River discharge reduces the level of "blooming" by 15 %-20%. Sheer volume increase of the discharge (1.5 times) without reduced concentration of pollutants in it yield no positive effect while cleaner inflow makes development of the blue-green somewhat reduce. Good positive effect can be observed when the water level in the water body lowers.

From Fig. 24 it follows that decreasing level of IC makes decrease the peak of "blooming" by

20-25 per cent and shifts its development for the second half of summer. Lack of inflow of biogenes from the bottom decreases the level of phytoplankton development by about 70 % (Fig. 25). The analog of this situation is when the bottom processes are blocked by aeration of the water mass. Reduced biogenous load with the rainfall runoffs has no marked effect.

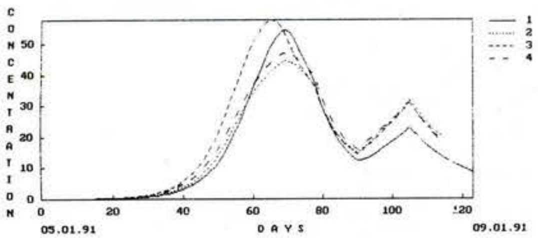

Fig.23 Estimated dynamics of blue-green algae the 6-th chamber for 1) one of the base versions and as related to it; 2) the Kantat river without contaminating components (pristine water); 3) discharge volume of Kantat river increased 1.5 in base contamination; 4) as a version of 3, contamination in the Kantat river reduced 1.5 times.

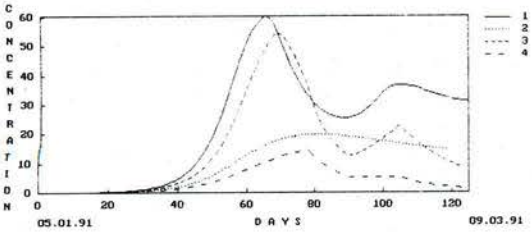

Fig.24 Estimated dynamics of blue-green algae the 6-th chamber

1, 2 - base versions;

3 - considerable decrease of initial conditions.

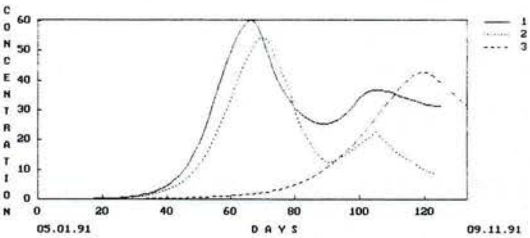

Fig.25 Estimated dynamics of blue-green algae in the 6-th chamber for 1, 2 - base versions and 3, 4 - lack of exchange of mineral phosphorus between bottom sediment and water mass (respectively).

3.2.4 Conclusions

Based on the analysis of the averaged data and computer calculations, we could draw four conclusions, i.e.:

(1) The contribution of contaminants coming with runoffs into eutrophication of the water body is not great, not more than 5 % of the total effect, at least. The effect of rainfall runoffs can be taken into account and is necessary for larger times, since they make a certain contribution into bottom sediment formation.

(2) The water body eutrophication is substantially affected by the Kantat river discharge and IC; assuming IC to be of the same order as the concentration of the corresponding components in spring-summer period for the water body on the whole. The contribution of the Kantat River and IC into eutrophication is approximately identical and is about 15 %-20 %-25 % of the total effect. IC forming early spring, hence dependent on a number of physical processes providing for formation of the water body during spring may substantially vary changing the contributions of

other sources of contamination.

(3) The increasing flow rate of the Kantat River under the same conditions of its contamination yields no positive effect. Therefore to create an upstream reservoir to control discharge of the Kantat river, provided the contamination is similar to that of the downstream reservoir, will not considerably reduce "blooming" in the downstream reservoir. The water in the upstream reservoir must be sufficiently clean. The increase of flow rate of the reservoir by lowering the water level may be efficient, this, however, may result in decreasing depth of the water body, which is unlikely to be desirable.

(4) The income of pollutants of the Kantat river, rainfall runoffs and of IC do not on the whole provide for the necessary level of "blooming" over the reservoir. The largest contribution into water body eutrophication (50 %-70 %) is by the bottom processes. We should note here that the bottom takes part in forming the spring starting conditions (such as spring upending of the water masses, ascending of bottom burials, etc.), which reveals another hidden feature — in a vigorous spring the IC may be rather high (considerable) and enhance eutrophication of the reservoir increasing the "blooming" of the algae. "Elimination" of the bottom, as a source of eutrophication of the water body can be done my aeration of the water mass.

5 Yenisei River Ecosystem

5.1 Theory and software of ecological-economical optimization of river water use

Before long rational management of nature will be based on regional ecological-economical models. We consider a model of rational water use for a large river basin. This model (when related to a specific river) enables the administration of the region to choose an optimum strategy in ecological policy with the enterprises-users and provides a possibility to evaluate the cost of different projects in "ecological" terms. This part of paper considers a system formed by a river (or its basin) and industrial enterprises. This poses the question of optimal distribution of costs with the sum total fixed between enterprises-water users to purify the river waters to standards required by technologies and purification of waste waters taking into consideration the self-purification ability of the river. Appropriate formalization made possible to specify the target function and to reduce the N-dimensional non-linear optimization problem to a sequence of N one-dimensional optimizations. When implementing this system into practice ("relating" the model to a specific river) the ecological situation can be improved without additional expenses - by re-allotting means spent to purify water between different enterprises. This means that some enterprises should be subsidized from the local budget. Respective expenses of the regional budget should be covered by increased taxation of other enterprises which benefited from improved ecological condition of the river reducing their expenses for preliminary purification of water (or increased their profit, speaking about the "natural" type enterprises). This part of work is of interest for experts in ecological-economical simulation, decision-makers.

However acute is the ecological situation with the water ecosystems today it is impossible to eliminate discharge of all contaminants completely; it is realistic to put only the question of reducing the pollution level. It is customary to assume that research should, at this, place primary emphasis on finding new "wasteless" technologies and more up-do-date means of water purification. Supporting this approach we should note that ecological situation can be improved with technologies available - by more sound management of water use. By sound water use we mean reasonable compromise between industrial necessities and ecological needs, i.e. when the enterprise makes optimum use of the self-purification capabilities of the ecosystem thus reducing the costs for purification of water with fixed upper limit of pollution, or - which is more important - to reduce water contamination with the cost amount fixed.

Note that water can be used rationally only within the framework of a region - and the concept of rational water use cannot be applied to an individual enterprise. It is an easy matter to illustrate this assertion with an example. Assume a pulp-and- paper mill to be located in the upper stream of the river while a fishery - downstream. For the pulp-and-paper mill it is not profitable to purify the wastes (or to purify it as little as possible); this, however, will decrease the profit (or increase expenses) of the downstream enterprise and the region on the whole is a loser.

Below we consider a model of rational water use for a large river basin. This model (when related to a specific river) enables the administration of the region to choose an optimum strategy in ecological policy with the enterprises-users and provides a possibility to evaluate the cost of different projects in "ecological" terms.

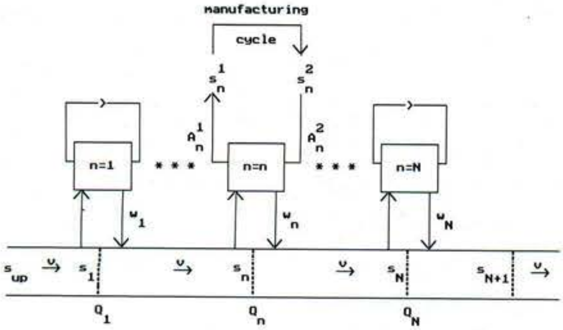

Fig.26 Location of drafts and discharge points of individual enterprises (*n=1,...,N*) on a linear section of the river (single contaminant case)

5.1.1 Base model

Let's formulate basic provisions of the model with the example of a linear part of a river (Gitelson *et al*, 1993) with enterprises-users along its banks (Fig. 26) and with a condition of only one contaminant present.

Denote contaminant concentration by s; s_n means concentration immediately before the n-th site. Each enterprise bears expenses for preliminary purification of water (before the manufacturing cycle) and waste water treatment. Assume for the sake of simplicity the volumes of draft to be equal to effluents (denoted by V_n) in a time unit and much less than the river discharge at the hydrometric section of the n-th site: $V_n << Q_n$. Specify the degree of purification by purification depth value A which is defined in a regular way as $A=\ln(s_{in}/s_{ex})$ where s_{in} is the input concentration of the water treatment facility, while s_{ex} at its output ($s_{in} \geq s_{ex}$; $A=0$ represents no purification).

Obviously, the cost of purification of a volume unit depends on the purification degree. Denote this dependence by $P(A)$ – a monotonously increasing function of A. Specific form of the function depends on the specific type of the treatment facility (Vavilin and Vasiliev, 1981). Den by $s^1{}_n$ the technological standard for water quality (the level of water purification to be attained (or changed) before the manufacturing cycle), by $s^2{}_n$ - contamination of the waste water coming to the treatment facility and, after this – after decreasing the concentration to w_n –into the river. Then the total cost of water purification for the region will be

$$P = \sum_{n=1}^{N} V_n \left[P_{\mathrm{n}}^1 \left(A_{\mathrm{n}}^1 \right) + P_{\mathrm{n}}^2 \left(A_{\mathrm{n}}^2 \right) \right], A_n^1 = \ln \left(s_n / s_n^1 \right), A_n^2 = \ln \left(s_n^2 / w_n \right). \tag{1}$$

These formulas should be added relation

$$s_{n+1} = C_{n,n+1} \left[s_n \left(Q_n - V_{\mathrm{n}} \right) + V_n w_n \right] / Q_n , \tag{2}$$

taking into account the fact that the waste waters of the n-th enterprise are "diluted" by the water of the river and are partially self-purified while running to the n+1 site. The value of self-purification coefficient $C_{n,n=1}$ is determined by several factors: microbial activity, water temperature, distance between the sites, pattern and rate of flow, number of clean tributaries flowing into this reach and so on.

Finding w_n from (2) and substituting it in $A^2{}_n$ (1), have that the total costs for the regions P are function N+1 of independent variables s_n and the problem of regional water management is formulated in a simple way:

$$P = P(s_1, s_2, s_3, \ldots, s_N, s_{N+1}) \Rightarrow \min. \tag{3}$$

5.1.2 Solution

Let $F_n(s_{n+1})$ be an optimum solution of the model for a subsystem of n first enterprises under the condition that the value of contaminant concentration before the (n+1)-th site (i.e. after n-th site) is s_{n+1}. Then the optimum solution for the subsystem of n+1 enterprises under the condition that the concentration before the (n+2)-th site is s_{n+2} is determined by relation

$$F_{n+1}(s_{n+2}) = \min[F_n(s_{n+1}) + f_{n+1}(s_{n+1}, s_{n+2})], s_{n+1} \tag{4}$$

where $f_{n+1}(s_{n+1}, s_{n+2})$ are the expenses of the (n+1)-th enterprise to purify water:

$$f_{n+1}(s_{n+1}, s_{n+2}) = V_{n+1}[P^1{}_{n+1}(A^1{}_{n+1}) + + P^2{}_{n+1}(A^2{}_{n+1})] \tag{5}$$

and the variable w_{n+1} in (8) is expressed by formula (2) through the values of variables s_{n+1}, s_{n+2}:

$$w_{n+1} = [s_{n+2} Q_{n+1} / (C_{n+1,n+2} V_{n+1})] - s_{n+1}(Q_{n+1} / V_{n+1} - 1).$$

Taking into account that $F_0(s_1)=0$ ($s_1 \equiv s_{\mathrm{up}}$ is set by the background concentration at the uppermost hydrometric section, Fig.26) and iterating relation (4) we can find solution of the problem as a function of system parameters and concentration value s_{N+1} at a certain downstream control hydrometric section. The described method is easily programmed and presents no difficulty for modern computers.

It is convenient to present the solution of the task graphically in the form of "optimum routes" (i.e. the values $s^*{}_n$ yielding the minimum of the target function P^*). Corresponding to each route, at this, is a certain value $F_N(s_{N+1}) \equiv P^*(s_{N+1}) = P(s^*{}_1 \equiv s_{up}, s^*{}_2, \ldots, s^*{}_N, s_{N+1})$. We should once more emphasize that the total costs for the region P^* are now a function of the background concentration $(s^*_{1} \equiv s_{\mathrm{up}})$ at the uppermost hydrometric section and contamination s_{N+1} at the control hydrometric section only.

It is not difficult to extend this model more optionally, such as: a) the case when the river has tributaries with enterprises-users; b) direct economical damage due to river pollution for the population and enterprises of "natural character" like fish factories; c) effect of ecological condition of the river on the costs related to water use; d) case of several contaminants; and so on.

5.1.3 Conclusion

In the foregoing we considered the key moments of the rational water use system. When implementing this system into practice ("relating" the model to a specific river) the ecological situation can be improved without additional expenses – by re-allotting means spent to purify water between different enterprises. This means that some enterprises should be subsidized from the local budget. Respective expenses of the regional budget should be covered by increased taxation of other enterprises which benefited from improved ecological condition of the river reducing their expenses for preliminary purification of water (or increased their profit, speaking about the "natural" type enterprises). We should note that since the optimum expenses over the region depend on the background concentration s (upstream the 1st enterprise, Fig.26), when taking into account the "paradoxical" effect of the relationship between the "downstream" concentration with the "upstream" one, the optimum expenses may be lower for the scenarios with higher upstream background contaminant concentration s.

The primary value of the model is, however, in its feasibility to be used as a working instrument to work out the policy of nature protection. This model allows to forecast quantitatively negative consequences of construction of new enterprises and positive consequences of putting into operation new treatment facilities. In the latter case calculating specifically the "optimum" path it is expedient to "ascribe" each enterprise all basic types of treatment facilities, even if this enterprise has none. In this case after the optimization process we have the "ideal" path that minimizes all expenses for purification within the framework of technologies available. Comparing this ideal situation to the real one makes possible reveal "bottlenecks", i.e. to point out where additional treatment facilities should be built first and their type. What's more calculation of this planned situation (i.e. taking into account scheduled projects) makes possible to define the recoupment period of construction of these treatment facilities.

To verify and check the theory and model it is necessary to find an experimental "testing range" and a special program of regional acquisition of ecological-economical (radioecological) information and observation in the course of experiment.

5.2 Mathematical theory of new ecological mechanism of formation of spatial distribution of radionuclides in river ecosystem

This part of work has been brought about by the radioecological situation that occurred on the Yenissei river. The Mining Chemical Works (MCW of the Ministry of Nuclear Power Industry of the Russia) have been discharging radionuclide contaminated wastewaters into the river for more than thirty years and formed "radioactive bottom". Radionuclide distribution is nonuniform-mutlipeak (Fig. 27).

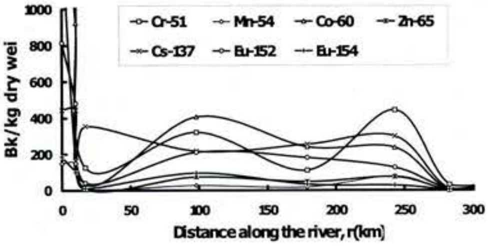

Fig.27 Distribution of radionuclides along the Yenisei river
from radioactive waste discharge site (Nosov *et al.*, 1993).

Non-uniformity may be due to different reasons. Different soil types are known to have different sorption capacity both with respect to biogenes and to radioisotopes. Heterogeneous distribution of radionuclides over the river bottom may be also conditioned by the hydrological factors. It can be ruled out that nonuniform distribution of radionuclides in the water and bottom sediments of the river is due to purely biotic interrelations between components of the river system. This work deals with theoretical analysis of the role of interpopulation interactions in forming nonuniform distribution of radioisotopes in the river ecosystem. The model is targeted to estimate the radioecological situation on the Yenissei river.

5.2.1 Mathematical model

The role the hydrobionts play in the processes of concentrating radionuclides from the water medium is well known. Higher growth rates and specific body surface make phytoplankton and zooplankton crucial for this process. To move along the trophic chains is the principal migration pathway for the radionuclides in the fresh-water ecosystems. By desorption the organisms lose adsorbed from the water radioisotopes faster than those arriving by the trophic chain (Carisco *et al.*, 1992). That's why mathematical simulation of the process of active transport of radionuclides along the components of the "water-phytoplankton-zooplankton-sediments" river system is of great interest.

Hydrodynamic characteristics of rivers are calculated by the one-dimensional Saint-Venan equations. Dynamics of all components of the ecosystem and radionuclides is described with a system of the 11-th partial derivative equation. *L* is the biogenic element (most frequently this is phosphorus) limited phytoplankton growth, *R* is the radioisotope (cesium, for example), *S* is the stable analog (potassium), *P* is the phytoplankton, *Z* is the zooplankton, *D* is the sediment. R_1, R_2, R_3 are the part of radionuclides in the phytoplankton, zooplankton and the sludge respectevly, S_3 is the part of the stable analog in the sluge. H_3 is the coefficient of conversion of sludge concentration measured in $mg \cdot m^{-2}$ to dry sludge biomass. The necessity to calculate this coefficient stems from the fact that the chemical composition of the sludge varies with the dominance of phyto- or zooplankton in it.

5.2.2 Results

Numerical experiments with the mathematical model find out two main types of the model system behavior in dependence on a depth of the phytoplankton growth limitation.

(1) *Phosphorus-limited system.* With high phosphorus limitation system the all components have monotonous dynamics(Fig.28). The nature of the curves of spatial distribution of radionuclides in water, phytoplankton, zooplankton and sediments is analogous to those of phyto-, zooplankton and sludge. The limiting biogenuos element determines the maximal concentration of the phytoplankton biomass and the other components corollary.

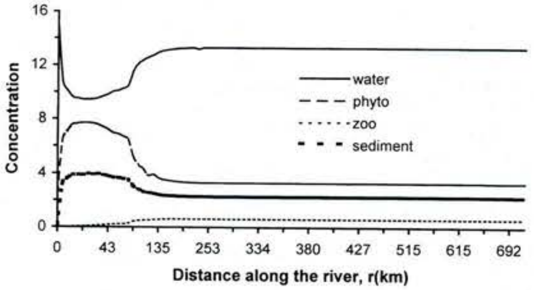

Fig. 28 Phosphorus-limited system.

Estimated spatial distribution of radionuclides in the different model components

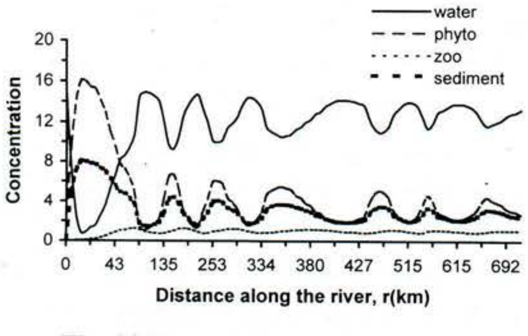

Fig. 29 Phosphorus-unlimited system.

Estimated spatial distribution of radionuclides in the model components.

(2) *Phosphorus-unlimited system.* At the site of discharge of radionuclides (beginning of the river segment under investigation) the river receives sufficient quantity of the limiting biogenous element (conditionally phosphorus) and the stable analog (potassium), i.e. phytoplankton growth is not limited by the biogenous elements. The system is assumed not to form deadlock substances. In this case the behavior of the ecosystem is determined by interrelations of "predator-prey" type between the phytoplankton and the zooplankton (Fig. 29). All components of the system undergo fluctuations determined by interrelations between the phytoplankton and zooplankton. At the moment of increase the phytoplankton intensively consumes biogenous elements, radionuclides -

their concentration in the water decreases. The stationary distribution along the river all of these components is of fluctuative nature.

5.2.3 Conclusion

So, experiments with the mathematical model demonstrate that when phytoplankton growth is not limited by biogenous elements the river system generates longitudinal oscillations (standing waves) of all components of the system, which may determine heterogeneity of spatial distribution of radionuclides in water and bottom sediment. The temporal population oscillations produced by the interpopulation interaction of the predator-prey type in the terrestrial ecosystems transform into the spatial population oscillations (standing waves) in the river ecosystems.

6. Summary

This work is to demonstrate a novel unconventional trend in developing prognostication simulation models for water ecosystems based on experimental biophysical research methods. The conventional (traditional) approach to developing such models at the verification stage rests, generally, on long series of field observations. This is hardly acceptable for water objects scantily known or nonexistent in nature making alternative ways of constructing simulation models adequate to natural systems a priority.

Investigation of ecosystems by biophysical methods made possible to delineate the scope of important ecological problems that may be solved by laboratory experimental methods independent of field observations. These are, first, the issues related to the principles of organization of aqueous communities in some "ideal", but physically controlled conditions.

Theoretically it was shown that: 1) in homogenous environment in a steady-state community the number of coexistent species does not exceed the number of DDGCF, independent of their physical, chemical or biological nature, 2) the threshold of heterogeneous environment from which the coexistence criterion comes into force is low in exchange flow rates. Development of theory of communities taking into account the uniting effect of chemical factors made naturally refine the measure of interaction between the species. Rather than the criterion based on variations in growth rate (Odum, 1975) a more adequate - criterion of growth acceleration - is proposed.

Another series of problems that an be considered in laboratory systems - a special feature of the density factors responsible for growth regulation of monocultures and coexistence of species in a community is the autostabilization effect, i.e. independence of steady-state background levels of these factors on their inflows. As opposed to modifying (density-independent) or nonlimiting factors, whose level follows changes of external conditions one-to-one, the value of the autostabilized component varies less. This fact can help more rapidly find really limiting factors in cultivation systems and in natural ecosystems.

Levels (concentration values) of metabolic factors (as density-dependent), responsible for interaction of populations within one trophic level must particularly, remain almost invariable under various perturbations of inflows. Experimental verification of this ascertion would promote wider use of autostabilization effect in ecological research and in finding specific coexistence factors, in particular. In response to the objection that presence of large number of connections in real ecosystems would deny isolation of the few factors which are limiting, we can note: the factors to be studied first are the autostabilized components.

Cite the statement of E. Odum on this subject: "Main attention should be drawn to the factors 'functionally vital' for the organism at the main stages of its life cycle". A beginning ecologist should be aware the analysis of the environment should be aimed not to compile a long uncritical list of "factors"; the goal is much more important: to reveal by means of observation, analysis and experiment "functionally vital" factors and find out how these factors affect individuals, populations and communities" (Odum, 1975, p. 145). It is this class of factors that the autostabilized factors belong to.

The criterion of coexistence and the autostabilization effect complement each other. Thus, in a mixture of species the DDGCF provide for coexistence of the species, while the reverse effect of community on the factors is based on autostabilization of the latter. Variation of input concentrations of DDGCF controls the species composition of the community.

On the whole, the biophysical methods of research formed the basis to put forward an approach to forecast water quality in any water object (water bodies, water courses), an approach which we call "biophysical", from theoretical elaboration through laboratory experiments to mathematical models. It has been tested on Siberian reservoirs: Krasnoyarsk and Kantat. This work developed within its framework a simulation system to forecast water quality in small-flow water bodies; the system has been developed for IBM PC AT type computers and written in PASCAL; three versions of the system are available: stationary model, parametric model and time-series model.

Further work on ecological models for estimating water object condition and water quality in them is to integrate (conjugate) them with economic models making possible to assess the damage due to the negative condition of the water object, expenditures to improve it according to this or that rehabilitation scenario, expenses to maintain ecologically optimal water management scenario, etc.

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