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Multispectral control of water bodies for biological diversity with the index of phytoplankton

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Abstract: We performed mathematical modeling population dynamics of phytoplankton in aquatic ecosystems based on interspecific interactions and nutrient pollution and toxic substances. We proposed a method of measuring control multispectral television ecological status of water bodies on the parameters of phytoplankton.

Keywords: Environmental monitoring, controlling, measuring control TV, water, phytoplankton, biosensor

1. INTRODUCTION

Water protection of natural water bodies is the complex system that includes dissolved inorganic and organic matter, suspended particles of different origin, aquatic organisms and so on. When water pollution is being made, it comes the insertion of a matter or energy that changes the functioning of aquatic ecosystems, energy flows, and materials, performance and number of biotech populations. Water pollution and complex human impact on water bodies lead to changes in the concentration of dissolved substances that may exceed the maximum permissible value; changes in the concentrations of suspended particles and the ratio between the volume concentrations of particles of certain types; changes in populations of aquatic organisms in aquatic ecosystems. It leads to the change of the properties of the water body and creates the risk to living resources and ecosystem health.

Many methods have been developed to inspect the current status of water bodies. Monitoring of the water quality with biosensors is increasingly used. The modern devices allow quick and accurate plankton composition (fraction size) analysis and pathogenic toxins detection.

Nowadays, many biosensors already are on the market, however, the apparatus still requires modernization and improvement of the detection quality. In consequence, different measurements techniques are developed at the same time.

One of the integral parameters of water pollution is the volume concentration of particles certain types and relationships between them, which describes the state of aquatic ecosystems. The research of optical-physical parameters of suspended particles could be based on the scattering indicatrix characterizing parameters of the averaged particle environment (when using deep mode) or separate particle parameters (using scanning flow cytometry); besides that, particle parameters may be defined by their images obtained by CCD-camera in the running measuring cell.

Monitoring the state of natural water bodies can be carried out on the basis of indexes of bioindication by phytoplankton [1-3]. The functional role of phytoplankton in the ecosystem - primary level of solar energy conversion, producing of autochthonous organic matter, important self-cleaning agent and photosynthetic water aeration. Phytoplankton is one of the biological indicators of the ecological status of water bodies in accordance with the of the EU Water Framework Directive (WFD) 2000/60 [4] and bioindication systems of water bodies in the USA (Rapid Bioassessment Protocols - RPBs) and the UK (River Invertebrate Prediction and Classification System - RIVPACS) [5]. Phytoplankton algae are mostly unicellular, although there are a lot of colonial and filamentous forms, particularly in fresh water. Chlorophyll *a* is the main pigment, which is located in chloroplasts or similar structures in all photosynthetic organisms (characteristic wavelengths 430 nm, 663 nm). Green algae contain chlorophyll *b* (435 nm, 645 nm). Diatoms and dinoflagellates contain chlorophyll *c* (440 nm, 583 nm, 634 nm). Red algae contain chlorophyll *d*. The chloroplasts are also always available carotenoids, the content of which is estimated based on equivalents beta-carotene (480 nm). Blue-green and red algae contain two types phycobilins (phycocyanin and phycoerythrin) in different ratios. Selection of characteristic wavelengths for the study of phytoplankton samples of water bodies is defined by the spectral dependence of the relative performance of the absorption of phytoplankton pigments [6-14].

2. STATEMENT OF THE PROBLEM

The purpose of the study is the developing of the new methods and means-integrated environmental control parameters of the water pollution, and assessing the impact of anthropogenic and techno-genetic factors. The main task of improving is applying the methods and the development of measuring optical parameters of integrated control of water pollution based on a study of optical-physical parameters of suspended particles of phytoplankton.

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3. MATHEMATICAL MODELING POPULATION DYNAMICS OF PHYTOPLANKTON IN AQUATIC ECOSYSTEMS

In modeling of dynamics population in aqueous media we were using the system of recurrent equations:

$$\begin{cases} N_{i+1}^{(1)} = N_i^{(1)} + \left(r_1 N_i^{(1)} - \frac{r_1}{K_1} \left(N_i^{(1)} \right)^2 + \sum_{j=1}^{n} \gamma_{1j} N_i^{(1)} N_i^{(j)} \right); \\ N_{i+1}^{(2)} = N_i^{(2)} + \left(r_2 N_i^{(2)} - \frac{r_2}{K_2} \left(N_i^{(2)} \right)^2 + \sum_{j=1}^{n} \gamma_{2j} N_i^{(1)} N_i^{(j)} \right); \\ N_{i+1}^{(n)} = N_i^{(n)} + \left(r_n N_i^{(n)} - \frac{r_n}{K_n} \left(N_i^{(n)} \right)^2 + \sum_{j=1}^{n} \gamma_{nj} N_i^{(1)} N_i^{(j)} \right). \end{cases} \quad (1)$$

where N_i - the number of i-th population;

K_i - maximum possible size of the population;

r_i - specific rate of reproduction;

γ_{ij} - factors that account for the interaction of species.

Evaluation of integrated ecological status of water bodies carries out by calculating Simpson and Shannon indices based on the values of the relative number of particles of each species of phytoplankton.

Simpson index (index of dominance):

$$D = \sum_{i=1}^{n} p_i^2 \quad (2)$$

where n – number of phytoplankton species in the sample, which hit the analyzer;

$p_i = N_i / N_\Sigma$ - the relative number of particles phytoplankton i-th species in the study sample;

N_i - the absolute number of particles phytoplankton i-th species in the study sample;

N_Σ - total absolute number of particles of all kinds of phytoplankton in the investigated sample.

Shannon index (index of diversity):

$$H = -\sum_{i=1}^{n} p_i \log_2 p_i \quad (3)$$

With the deterioration of ecological ecosystem water body, such as eutrophication, certain species of phytoplankton begin to rise rapidly; these species begin to dominate the ecosystem gradually displacing other ones. Thus, the relative number of dominant species will increase and approach the unit, which will increase the Simpson index and its approach to unity. In contrast, in the ecosystem water body that has a good ecological status and any of phytoplankton species is not dominant, is balanced ecosystem and the number of certain types is small, which reduces the Simpson index. With the deterioration of ecological ecosystem water body, for example, because of its anthropogenic pollution, the most sensitive species of phytoplankton reduce their numbers and later disappear at all, and are replaced by more resistant to contamination species of phytoplankton, which leads to reducing of the Shannon index. Thus, using Simpson and Shannon indices it is possible to objectively assess the ecological status of the water body using the values of certain types of phytoplankton in the investigated sample.

We can do the modeling of dynamics of phytoplankton for the artificially created environment, which contains three types of phytoplankton; the type of interactions between species - competition.

We introduce the dependence of the parameters of fertility and mortality temperature:

$$f(t) = b \cdot e^{a_1 \left(t - t_{opt}\right)} - d_{opt} e^{a_2 \left(t - t_{opt}\right)} - d_{\max} e^{a_3 \left(t_{\max} - t\right)}, \quad (4)$$

where b - parameter of birth at the optimum temperature that is most favorable for the development of a certain type of phytoplankton,

d_{opt} - parameter of mortality at the optimum temperature that is most favorable for the development of a certain type of phytoplankton,

$d_{\max}$ - parameter of mortality at a temperature higher than the threshold at which begins suppressed permanently developing a certain type of phytoplankton,

a_1, a_2, a_3 - auxiliary coefficients that can be found by the method of approximation based on actual statistics measuring population dynamics of phytoplankton.

Fig. 1 shows the results of simulations to model environment that includes three types of phytoplankton.

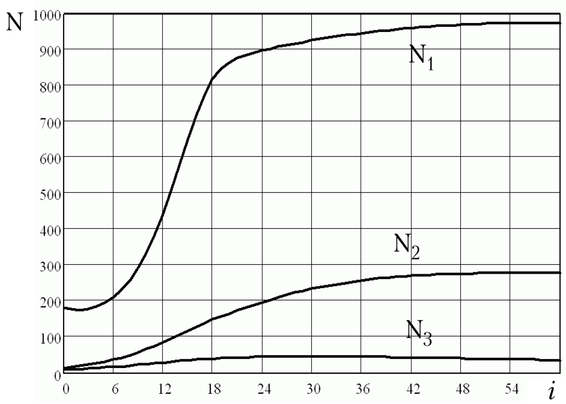

Fig. 1. Modeling phytoplankton population dynamics model for ecosystem protection, contains three types of phytoplankton

As a result, the transition process and the subsequent establishment of equilibrium in the model ecosystem are notable. Next, we analyze changes in Simpson and Shannon indexes that are calculated based on the relative numbers of phytoplankton in the ecosystem water body; the results shown in Fig. 2.

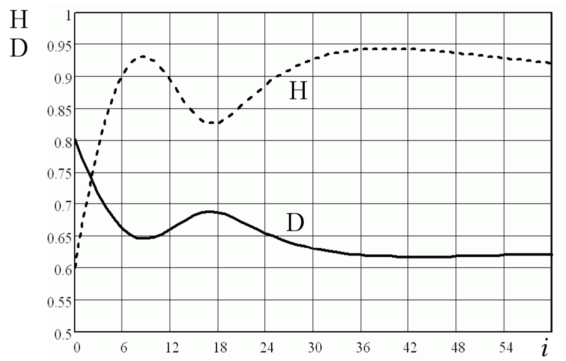

Fig. 2. Modeling changes Simpson index and Shannon ecosystem in the water body as a result of human impacts

4. METHOD OF MEASURING TELEVISION MULTISPECTRAL ENVIRONMENTAL CONTROL OF WATER BODIES FOR THE PARAMETERS OF PHYTOPLANKTON

There is a biosensor technique of water bodies, which includes the definition of the toxicity of the water environment, characterized in that to determine the toxicity of selected samples it is needed to get from the bottom of the reservoir a microphytobenthos samples, examine them, and determine the quality and the number of cells of algae that exist at the bottom. The data are compared with the control data, and the existence of differences in the direction of reducing the number of algae or its absence shows the presence of toxicants in aquatic environment [15]. The disadvantage of this method is the lack of features that can automatically recognize the algae particles. This imperfection makes it difficult to determine the quality of the procedure and the number of cells of algae, which reduces the reliability of monitoring of the ecological state of water bodies.

The closest is the way to identify phytoplankton algae in water samples from water bodies, which includes: the selection of water samples of the water bodies containing phytoplankton algae, mount preparation from each water sample on a slide and placing it under a microscope eyepiece, detection of each instance of phytoplankton algae in the preparations, identifying of each instance of phytoplankton algae due to its belonging to any of phytoplankton algae species, calculation of quantitative indicators characterizing the development of phytoplankton algae in general and their individual development in water system. After placing the mount of the sample under a microscope we shape its video depiction using the camera attached to the microscope optical system. Then we insert this depiction to computers computing environment and identify each instance of phytoplankton algae using a digital processing of the video depiction of the preparation of samples of water. Then for each instance of phytoplankton algae, we count geometric shape features invariant to scaling, rotation and displacement of an instance in the plane of the depiction, and identification of phytoplankton is being made by using an artificial neural network [16, 17]. The disadvantage of this method is that it uses geometric features of the form of microalgae to identify the particles of phytoplankton algae that do not let us accurately determine the species of phytoplankton; the presence of these methods affects the reliability of the environmental monitoring of water facilities.

The basis for the multispectral television method of measurement of ecological control status of water bodies by the phytoplankton parameters is the increase of reliability of environmental control of natural water bodies. The task is being achieved by the way of a multispectral television control measurement of the ecological status of water bodies on the phytoplankton parameters. It consists of the sampling phytoplankton, determining qualitative and quantitative composition of microalgae cells. The data is being compared with the normalized values, flow multispectral TV measuring analysis of continuous action of phytoplankton particles is being made in which the images of the particles, obtained at wavelengths characteristic of phytoplankton pigments using microscope and CCD-TV camera with images from the database particles phytoplankton species in certain specialized processors in real time using the Bayes optimal classifier with resolvers function based on Mahalanobis distance, is being made. Next step is the determination of the absolute and relative numbers of particles of each phytoplankton species that are present in the sample and calculate Simpson and Shannon, which serve as an indicator.

Block diagram of the device (Fig. 3.) on the basis of multispectral television method of measurement of ecological status of water bodies by the phytoplankton parameters that contains: a water sample with particles of phytoplankton 1, pump 2, television CCD-camera 3, microscopes 4, measuring the flow cell 5, drain capacity 6 base the particles phytoplankton 7, specialized processors 8, clarifier 9, block index calculation Simpson and Shannon 10 LED 11.

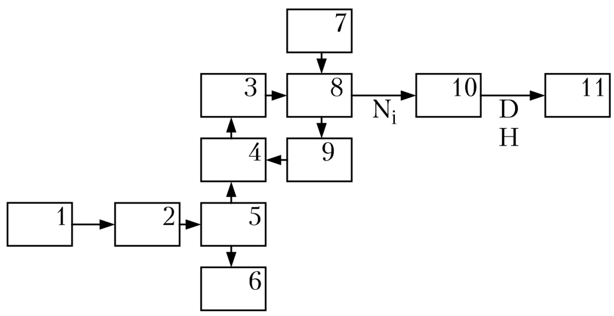

Fig. 3. Block diagram of the device on the basis of multispectral television method of measurement of ecological status of water bodies by the phytoplankton parameters

The method is as follows:

1. The selection of the water sample from a water body is being made. With pump (2) the water with the

phytoplankton, particles are being pumped through the flow measuring cell (5) to draining capacity (6).

2. Using the microscope (4) and CCD-TV camera (3) multispectral TV measuring analysis of continuous action of phytoplankton particles is being made, in which the comparison of the images of the particles, obtained at wavelengths characteristic of phytoplankton pigments, are being made in running measuring cell (5) with images from the database particles of phytoplankton (7) by a specialized processor (8) using Bayes optimal classifier with resolvers function based on Mahalanobis distance. Specialized processor (8) switches the wavelength of the illuminator (9), which provides imaging of particles on the characteristic wavelengths of phytoplankton pigments. Specialized processor (8) calculates the number of particles of every species of phytoplankton that are present in the water body.

3. Calculation block of Simpson and Shannon indexes (10) counts and gives them to the indicator (11). By using a specialized processor (8) it is possible in real time with high accuracy to identify phytoplankton particles, which can reduce the absolute error of determination (N_i) and a relative number $p_i = N_i / N_\Sigma$ of phytoplankton particles of each species that are present in the sample. By using the values of the relative numbers of particles of each species of phytoplankton in the Simpson and Shannon index we can reliably assess the state of the water bodies' ecosystem.

With the deterioration of the ecological status of water body ecosystem, for example, because of a eutrophication, the rapid growth of certain species of phytoplankton begins; those species begin to dominate the ecosystem gradually displacing other water bodies. Thus, the relative number of dominant species p_i will increase and approach the unit, which will increase the Simpson index. In contrast, in the ecosystem of a water body, that has good ecological status none of the species of phytoplankton are not dominant. That system is balanced and the relative value p_i of certain species is small, which reduces the Simpson index.

With the deterioration of the ecological status of water body ecosystem, for example, because of anthropogenic pollution, the most sensitive species of phytoplankton reduce their number, and subsequently disappear. They are replaced by more resistant to contamination species of phytoplankton, which reduces the Shannon index.

5. BIOSENSOR- BASED TECHNOLOGY FOR THE USE IN PHYTOPLANKTON DETECTION

Biosensors are used in medicine, defense, food industry and also wide applied in environmental protection [18]. This modern devices offer alternative or complementary methods of analysis. Biosensor - based technology is also applicable to phytoplankton detection in particular to determine the phytoplankton toxicity. According to worldwide monitoring programs around 4 000 marine plankton type are found and about 97 of this are toxics [19]. Plankton is a food of shellfish, crabs and some fish species. For those creatures the planktonic toxics are not poisonous. It accumulates in their organism. Whereas, when people consumed contaminated see food the intoxication process take place. Depending on the toxin type and accumulated dose, symptoms of poisoning begin to be noticeable. From this reason, measurement plankton toxicity is very important for human health protection.

There are many analytical and biological methods for measuring plankton toxicity. The analytical techniques include: height liquid chromatography (HPLC) coupled with fluorimetric and UV detection, calorimetric immunoassay and liquid chromatography mass spectroscopy (LC-MS). The biological methods are: in vivo assays (performed on mice) and in vitro techniques based on morphological changes in cells. Unfortunately, both biological and analytical techniques are not perfect. In case of applying the methods for accurate measurement the expensive laboratory equipment and highly trained personnel is required. Disadvantages of using the biological methods are ethical issue connected with prolonged suffering animals and technical deficiencies come from lack of sensitivity. Also analytical methods are inconvenience because of lack certificate standards for known analogue toxics groups and contribution of unknown compounds to sample toxicity [20]. Therefore, there is a real need to look for new measurement solutions. Over last decade, new trend in plankton detection is biosensors-based technology. It offers a quick and easy measurement without involving specialized equipment and trained personnel.

Biosensor (according to IUPAC *International Union of Pure Applied Chemistry)* is a self-contained integrated device, which is capable of providing specific quantitative or semi-quantitative analytical information using a biological recognition element (biochemical receptor) which is retained in direct spatial contact with an electrochemical transduction element. The principle of biosensor operation based on signal measuring comes from interaction between the detected molecules (analytes) and selective biosensor receptor layer. The layer is connected to transmitters, where conversion of biological effects on a measurable signal takes place.

Nowadays, biosensors are more often used for phytoplankton detection. An example of biosensor based technology application is yessotoxin [20], saxitoxin [21] and tetrodotoxin [22]. Work is underway on a system providing automatic monitoring of phytoplankton [19]. Biosensor - base technology is developing very dynamically, but still needs improvement in order to increase the accuracy of detection. Therefore, parallel to it, different solutions are developed to measure phytoplankton parameters.

6. THE EXPERIMENTAL RESULTS OF MONITORING OF PHYTOPLANKTON PARTICLE CONCENTRATIONS

According to the results of monitoring of water bodies based on indicators of bioindication by phytoplankton assessed ecological state. Sampling algological material (phytoplankton samples) was carried out in different parts of the river Southern Bug (Ukraine) using the sampler, as well as with the use of filtration and sedimentation methods with membrane filters with a pore diameter of 2 microns. Features of the collection and processing of the material corresponds to the generally accepted approaches the study of phytoplankton. Samples were taken at different locations of the water body at different depths using a sampler to study concentrations of various types of phytoplankton. The analysis of phytoplankton samples showed that the species diversity of algal flora is represented by 242 species. The leading group has algoflora green algae, which are represented by 110 species.

Table 1 - Results of the analysis of species diversity of phytoplankton samples obtained from the areas of a water body with a variety of anthropogenic impacts

Algae group	Sample				
	1	2	3	4	5
blue-green	22	5	8	4	1
euglen.	17	11	6	7	12
diatoms	21	11	16	5	15
green	75	61	33	31	19
other	18	4	4	2	1
total	153	92	65	50	48

The analysis showed that the phytoplankton taken from the river above the town on the river species diversity of specimens (153 species of phytoplankton) is considerably higher than the river area in the central part of the city (92 species), which is a weighty proof of anthropogenic influence on the ecological condition of the river ecosystem.

A feature of polluting chemicals impact on aquatic ecosystem is not only a change of phytoplankton populations in response to these substances, but also competitive interaction between various types of a phytoplankton. Given the sensitivity of different phytoplankton species to chemicals, this leads to a more complex dynamics of phytoplankton particle size of changes in the real multi-species ecosystems.

CONCLUSIONS

In this paper has been improved mathematical model of the dynamics of phytoplankton populations in the aquatic environment through a system of recurrence equations that allowed us to study the impact on the development of phytoplankton concentrations of nutrients and toxic substances. In addition, mathematical models have been suggested to simulate the change ratio of relative populations of phytoplankton in the water during pollution and evaluate integrated pollution characteristics based on changes of the Simpson and Shannon index.

Also, it has been suggested a new multispectral television method of measurement of ecological control status of water bodies by phytoplankton parameters that allows reliably assess the status of the water bodies' ecosystem.

Developed automated control and measurement system for environmental monitoring, which allows real-time monitor the ecological status of water bodies by means of bioindication by phytoplankton and integrated control of pollution of water bodies and nutrient regime toxic compounds that affect the concentration of a certain type of phytoplankton.

The experimental results of monitoring of particle concentrations different species of phytoplankton allow us to estimate of complexes anthropogenic impact on the water bodies.

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