Management of Integrated Ecological-economic Processes in the *Land–Sea* System Maintaining the Marine Environment Quality

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Adaptive model for maintaining the processes in the ecological-economic system connected the "*Land–Sea*" system industrial output, on the one hand, and the contamination level and the marine environment biodiversity index, on the other, is proposed. The paper contains the development of modeling results of such systems obtained using the adaptive method of causes method (the results were published in the 3rd number of this journal, 2015). More complex model of the "*Land*" economic subsystem which had a great number of logical agents of production profitability management is applied. In the "*Sea*" ecologic subsystem a model for monitoring over biochemical processes forming the marine environment biodiversity index is proposed. These processes are: the concentrations of phytoplankton, zooplankton, bioresource, biogenic elements, oxygen, carbon dioxide and detritus. Biodiversity index, along with contamination level, was applied for ecological control of marine environment quality. External impact on the "*Sea*" subsystem is represented by solar radiation, sea upper layer temperature and wind velocity modulus. Being based on analysis of the effect of economic sanctions for pollution upon the processes in marine ecosystem, the model is intended to find a rational balance between the income from marine resources use and the expenditures for preserving marine environment quality. Management agents controlling balance between consumption and reproduction of marine resources are applied in the models of "*Land*" and "*Sea*" subsystems, as well as in the integrated system model. The results of great number of simulation experiments demonstrating the possibility of complex "*Land–Sea*" system management in the modes of rational natural resource use are given. Scenarios of ecological-economic processes arising at transferring industrial production on ecologically clean technologies are constructed, and advantages of such a variant of nature management are shown.

Keywords: ecological-economic model, adaptive balance of causes, scenarios of processes.

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Introduction. Significance of the coastal zone ecological economics increases with the development of marine resources consumption technologies [1 – 4]. As far as the anthropogenic load on the coastal marine environment is constantly increasing, its main quality, along with the biological productivity, becomes its assimilative capacity. In the work [5] the management problem of the coastal zone integral ecological-economic processes, which develops in the model of generalized *Land – Sea* system under conditions of the pollution level control, is considered. The model is constructed by the adaptive balance of causes method and contains management agents, which allow setting the scope of the economic sanctions imposed on the production, depending on the pollution level of the marine environment.

In this work the research had been developed by the usage of more complex models of subsystems within the *Land – Sea* unified system. Integral characteristics of the ecological state of the marine environment became the waste pollution level and biodiversity index. Each of these two indexes is formed under the impact of great number of different factors. But to simplify, it was considered that the level of pollution is determined by the balance of pollution accumulation rate and self-clarification rate of the marine environment as a result of chemical and bacteriological reactions and mixing of water masses, and the index of biodiversity decreases in proportion to the pollution level. The task is to research the environmental management balance in conditions when the economical benefits of production release depends on the costs required for the protection of the marine environment from pollution and the conservation of biodiversity index. Besides, it is necessary to evaluate the economic viability of the *Land* economical subsystem to transfer it to the eco-friendly production technologies.

The structure of the management model for industrial profitability and marine environment ecological state support in the *Land – Sea* system. The model consists of subsystem *Sea*, which represents the marine ecosystem processes (they form an index of biodiversity of the marine environment), and the subsystem *Land*, which describes the economical processes determining the production profitability and pollution level of the marine environment. Both subsystems are combined into a single system by the balance management unit of subsystems *Sea* and *Land* functioning by criteria of marine environment quality preservation.

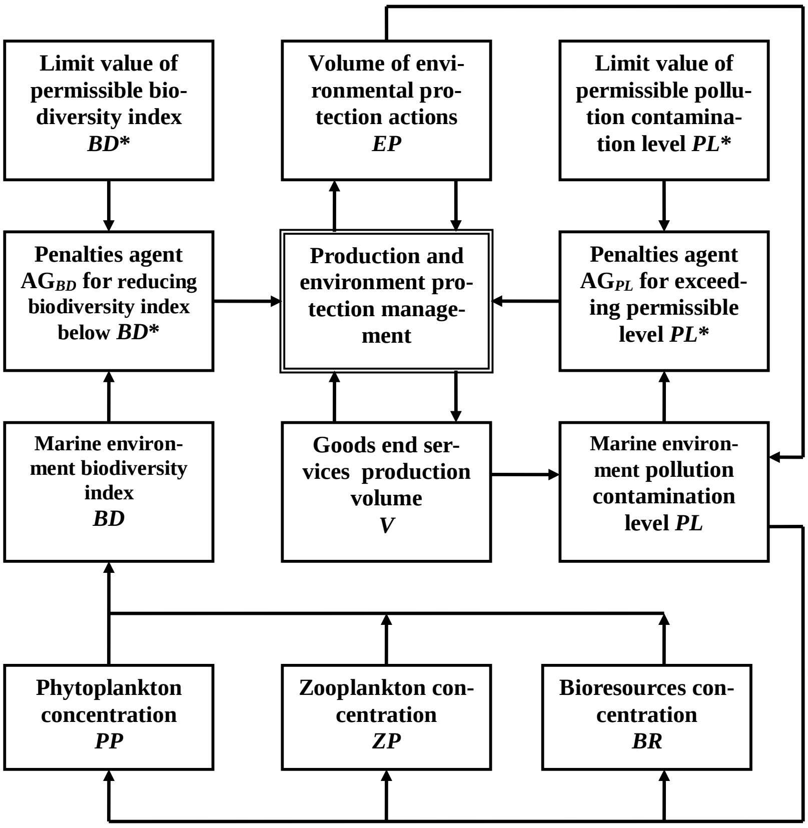


Fig. 1. Conceptual model of ecological-economic production profitability balance management and ecological state of coastal marine environment

For the management unit the conceptual model, which controls ecological-economic production profitability balance and ecological state of coastal marine environment, is proposed. The scheme of this model is depicted in the fig. 1. Production volume *V* causes the pollution of marine environment *PL*, which reduces concentrations of phytoplankton *PP*, zooplankton *ZP* and bioresources *BR*, affecting the biodiversity index *BD*. Environmental management is based on the monitoring of pollution index *PL* and biodiversity index *BD*, for what the exposure limit values of PL^* and BD^* were used. The pollution level monitoring is performed by management agent $AG_{PL,}$ and biodiversity index monitoring – by AG_{BD} agent. In the production and environment protection management units these agents affect the production cost through the pollution tax, which is proportional to *PL* level, and through the penalties for exceeding maximum permissible level of PL^*. Besides, it is imposed a penalty for reducing the biodiversity index *BD* below the minimum permissible level BD^*. Due to the penalties, the fund of environmental protection actions *EP* is formed, and these actions decrease the pollution level and raise biodiversity index of the marine environment. Thus, the chain of stabilizing feedback, which keeps up the ecological-economic environmental balance at the required level, closes.

Conceptual model of ecological subsystem *The Sea.* The model of ecological subsystem *The Sea* links biodiversity index with marine environment pollution level, which happens, mostly, because of domestic and industrial waste inflow from the coastal area. The pollution inflicts a great harm to bioresouces of the sea. In the developed ecosystem model the higher food chain link (phytoplankton – zooplankton – fish (bioresourse)) is related to bioresources. The state of food chain is characterized by concentration values of phytoplankton *PP*, zooplankton *ZP* and bioresources *BR*. Processes, which describe the time changes of these concentrations, are included to the *Sea* subsystem model along with other resources of food chain development: concentration of oxygen *OX*, carbon dioxide *CD* and biogenic elements *BG*. To close the chain of biochemical reactions in marine environment, the process of detritus *DT* formation and its transformation into the biogenic substances, was included to the given model. On the basis of these conclusions the cause-effect relationship system of ecological subsystem *The Sea* (given in the fig. 2) was developed.

The resource limitation agents of substance concentration increase are the important elements of the model. The limitation specifies which type of resources, necessary for the concentration increase, at the moment is available in minimal amount. For example, for the phytoplankton concentration increase it is necessary to have the rise of carbon dioxide *CD* and biogenic substances *BG* concentration, and also to have the increase of solar energy *SR*. The increase of phytoplankton concentration depends on that type of recourses, which concentration is minimal in comparison with the other resources, and it happens because of the constant change of recourse amounts.

That's why four management agents, shown in Fig. 2, are included to the model. AG_{PP} agent limits the phytoplankton concentration increase by solar energy *SR*, carbon dioxide *CD* and biogenic substances *BG*; AG_{ZP} agent limits the zooplankton concentration increase by phytoplankton *PP*, oxygen *OX* and biogenic substances *BG;* AG_{BR} agent limits the bioresource concentration increase by zooplankton *ZP*, oxygen *OX* and biogenic substances *BG*; AG_{BG} agent limits the biogenic substance concentration increase by detritus *DT* and oxygen *OX*.

In marine ecosystem the processes are in the state of constant dynamical balance with external impacts. The main factors of external impacts are solar and atmospheric impact, water mass dynamics and pollutant inflow. To simplify the model we didn’t consider the impact of advection and water mass diffusion at the concentration of the modeling substances. This impact on pollution concentration *PL* (along with chemical-bacteriological reactions) is indirectly considered in function, by which the process of marine environment self-clarification had been modeled.

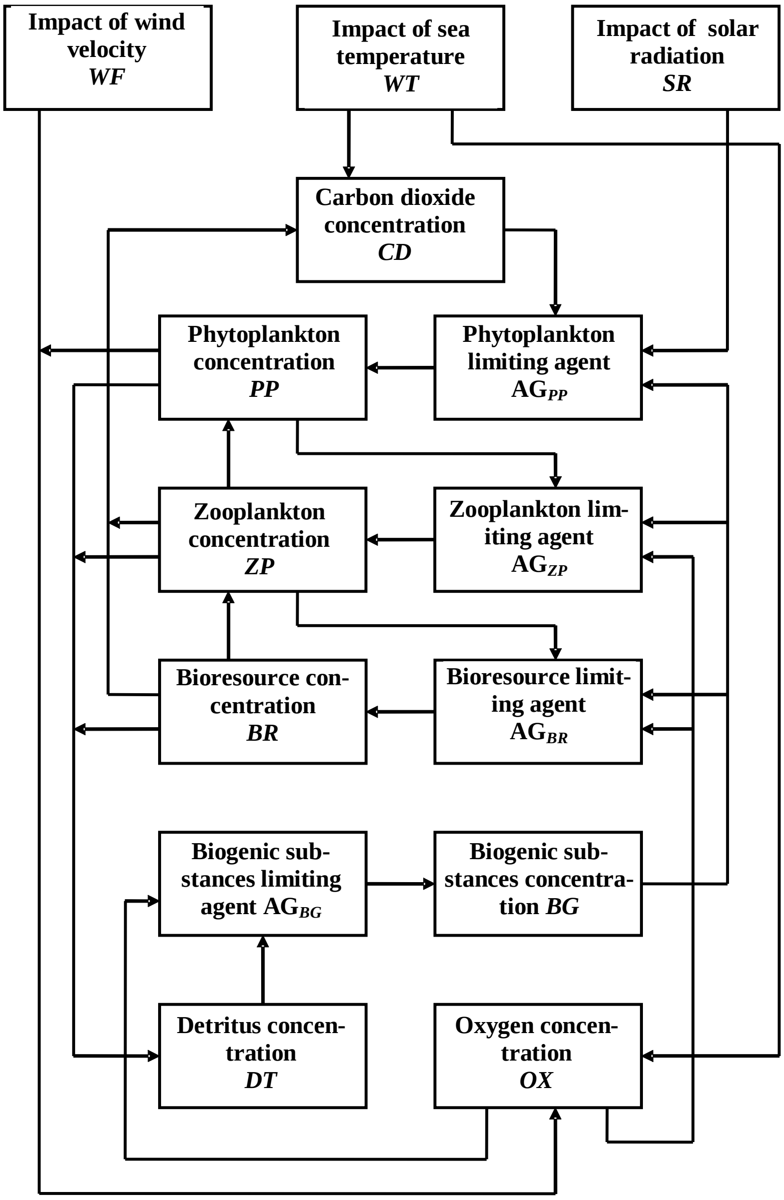


Fig. 2. Conceptual model of ecological subsystem *the Sea*

The external impact on ecosystem is represented by the intensity of solar radiation *SR*, the temperature of the sea upper layer *TW* and the wind velocity module *WF*. It was assumed that the annual temperature variation (average on the volume of the modeled marine environment) affects the concentration of phytoplankton, as well as the concentration of oxygen and carbon dioxide, which decreases with the raise of temperature. It was also accepted that with an increase of wind mixing in the upper layer of the sea the concentration of oxygen also increases.

Conceptual model of economical subsystem *the Land*. The purpose of *the Land* subsystem model constructing is a forecast for scenarios of economic production processes, which affect the pollution levels of the marine environment and biodiversity. Proceeding from such statement of the modeling problem, the most important subsystem processes were selected and a scheme of cause-effect relationships between them is constructed (fig. 3).

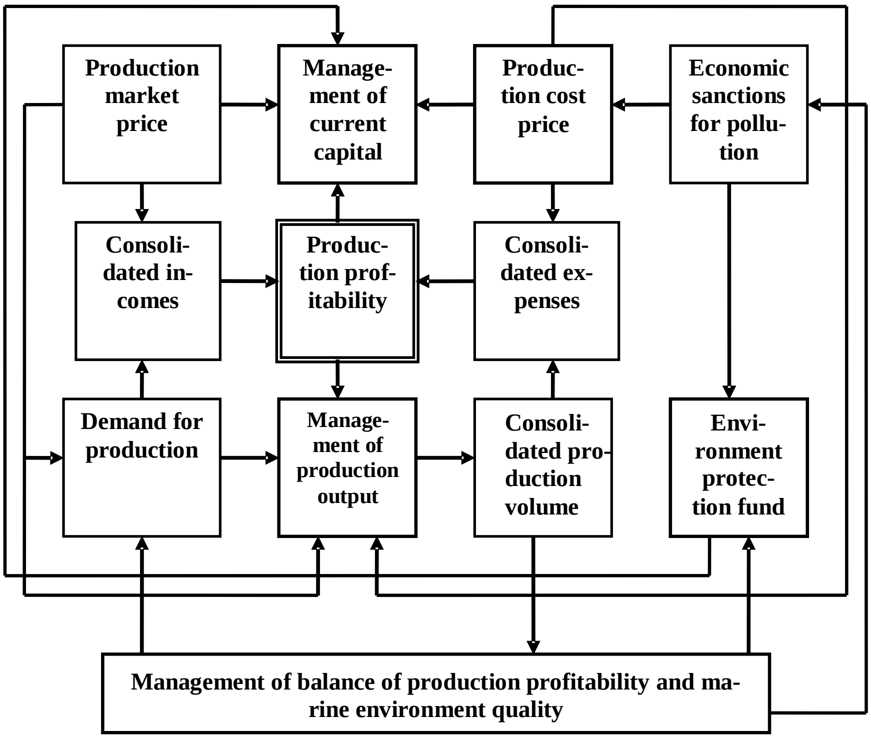


Fig. 3. Conceptual model of economical subsystem *the Land*

In the block of production profitability the consolidated incomes for the appointed period of time are compared with working expenses for the same period of time. Depending on the profitability level the possibility of demand satisfaction on *the Land* subsystem production is estimated and production quota, provided by the existing productive resources, is determined. In the management unit of ecological-economic balance of production profitability and marine environment quality, economical efficiency of production subordinates the marine environment ecological state. Here the penalties for the pollution of the sea by industrial waste are established and governmental nature protection fund is formed.

Specification of *the Land* subsystem conceptual model is performed by information technology of adaptive economical systems *ABC AGENT* model construction, which is described in several works [3 – 6].

The equations of adaptive economical subsystem *the Land*. The main operations of economical system are presented as balance conditions, where the modeling system variable adapts to the algebraic sum of sources (incomes) and outflow (expenses) of different substances (goods, services, resources). These equations are considered in several articles and monographs about the adaptive balance of causes method (*ABC*-method) [3, 6]. That's why we'll just enumerate the main equations for the variables of *the Land* subsystem model. The equations have a module structure and it will be illustrated by the example of equation (1) for the warehouse of manufactured products. Product demand is satisfied by the sale of manufactured products, accumulated in the warehouse, and by the additionally manufactured production. We denote the current amount of ready-for-sale production in the warehouse as H, and assume that it fluctuates around the average value C_H. With continuous production supply and sell the balance equation for function H could be represented as a modular equation of *ABC*-method and the equation for the management agent that restricts the amount of the manufactured production by the warehouse capacity:

$$\frac{dH}{dt} = 2r_H H[C_H - (H - V + S)], \tag{1}$$

$$V - S = IF\{V - S < 0; 0; IF[V - S > 2C_H; 2C_H; V - S]\},$$

where V – the intake of manufactured production to the warehouse, S – its sell, r_H – the relation of specific rate of change H to the value H, and the value $2C_H$ is a warehouse resource capacity. Other equations of economical subsystem are represented in the same way:

– the equation of the resource dynamics H_{1i} of economical subsystem:

$$\frac{dH_{1i}}{dt} = 2r_{H_{1i}} H_{1i}[C_{H_{1i}} - (H_{1i} - V_{1i} + S_{1i})], \qquad (i = 1, 2, \dots, n); \tag{2}$$

– the equation of production current capital H_2:

$$\frac{dH_2}{dt} = 2r_{H_2} H_2[C_{H_2} - (H_2 - I - H_3 + S_2 + S_3)]; \tag{3}$$

– The equation of production investment (loan) dynamics H_3:

$$\frac{dH_3}{dt} = 2r_{H_3} H_3[C_{H_3} - (H_3 - V_3 + S_3)]. \tag{4}$$

In the equation (3) current profit of economical subsystem *the Land* is denoted by I.

The equations of adaptive ecological subsystem *the Sea*. To construct the formal model of subsystem *the Sea* we'll use the designations of ecosystem variables and the scheme of cause-effect relationships shown in the fig. 2. Using the *ABC*-method model equations we obtain the following equation system of marine ecosystem adaptive model:

$$\begin{gathered}
\frac{dPP}{dt} = 2r_{PP}PP\{C_{PP} - [PP + a_{PP/ZP}ZP - AG_{PP}(BG,SR,CD) - a_{PP/TW}TW - a_{PP/WF}WF + \\
+ a_{PP/PL}PL]\}, \\
\frac{dZP}{dt} = 2r_{ZP}ZP\{C_{ZP} - [ZP + a_{ZP/BR}BR - AG_{ZP}(OX,PP,BG) + a_{ZP/PL}PL]\}, \\
\frac{dBR}{dt} = 2r_{BR}BR\{C_{BR} - [BR - AG_{BR}(OX,ZP,BG) + a_{BR/PL}PL]\}, \\
\frac{dOX}{dt} = 2r_{OX}OX\{C_{OX} - [OX + a_{OX/BR}BR + a_{OX/ZP}ZP - a_{OX/PP}PP + a_{OX/BG}BG + \\
+ a_{OX/TW}TW - a_{OX}(WF)]\}, \\
\frac{dCD}{dt} = 2r_{CD}CD\{C_{CD} - [CD - a_{CD/BR}BR - a_{CD/ZP}ZP + a_{CD/PP}PP + a_{CD/TW}TW]\}, \\
\frac{dBG}{dt} = 2r_{BG}BG\{C_{BG} - [BG - AG_{BG}(OX,DT) + a_{BG/PP}PP + a_{BG/ZP}ZP + a_{BG/BR}BR]\}, \\
\frac{dDT}{dt} = 2r_{DT}DT\{C_{DT} - [DT - a_{DT/BR}BR - a_{DT/ZP}ZP - a_{DT/PP}PP + a_{DT/BG}BG + \\
+ a_{DT/OX}OX]\}.
\end{gathered} \tag{5}$$

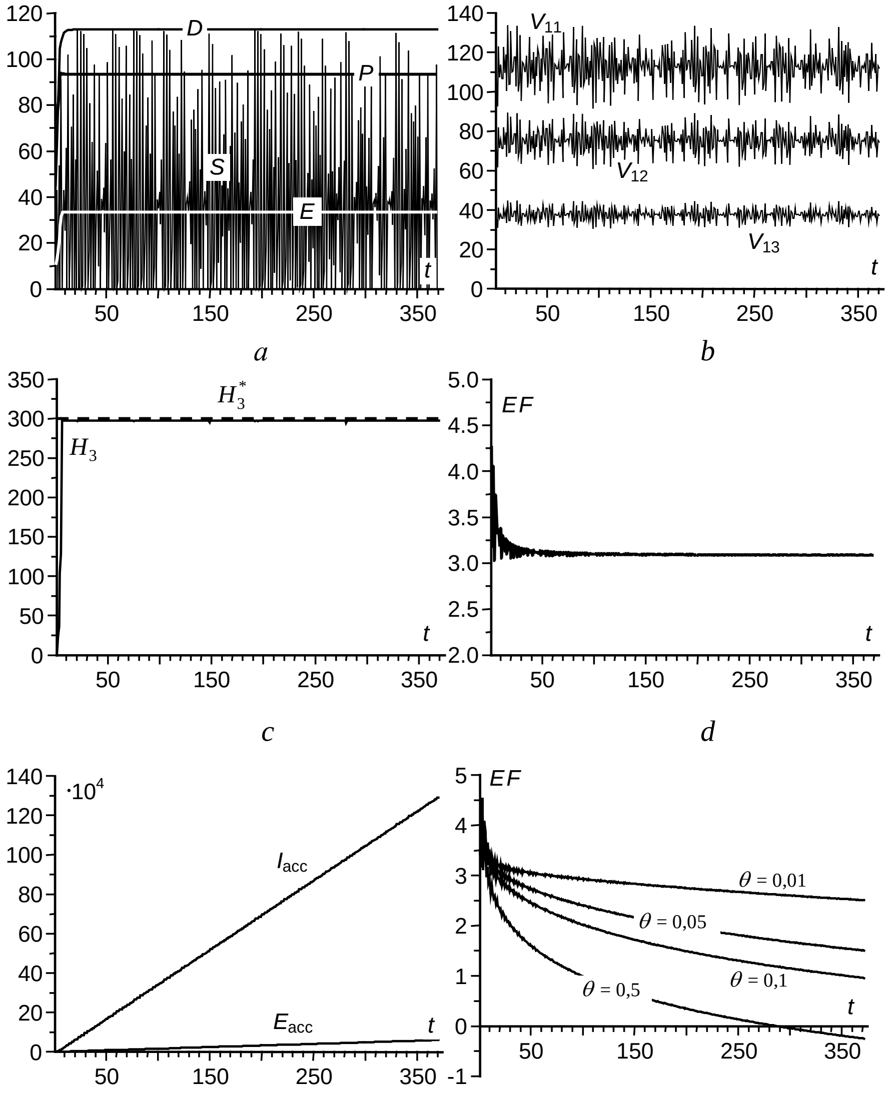
In the equation system (5) the coefficients r_{MN} are the average values of the relations of variable *MN* rate change to the value of this variable, C_{MN} – average value of *MN* variable, $a_{KL/MN}$ – the coefficient of *MN* variable impact on the *KL* variable.

For the resource limiting agents the following expressions are used:

$$\begin{gathered}
AG_{PP}(BG,SR,CD) = IF[M_{PP}(t) = a_{PP/BG}BG(t); a_{PP/BG}BG(t); 0] + \\
+ IF[M_{PP}(t) = a_{PP/SR}SR(t); a_{PP/SR}SR(t); 0] + IF[M_{PP}(t) = a_{PP/CD}CD(t); a_{PP/CD}CD(t); 0], \\
\text{where } M_{PP}(t) = \arg\min[a_{PP/BG}BG(t); a_{PP/SR}SR(t); a_{PP/CD}CD(t)]; \\
AG_{ZP}(OX,PP,BG) = IF[M_{ZP}(t) = a_{ZP/OX}OX(t); a_{ZP/OX}OX(t); 0] + \\
+ IF[M_{ZP}(t) = a_{ZP/PP}PP(t); a_{ZP/PP}PP(t); 0] + IF[M_{ZP}(t) = a_{ZP/BG}BG(t); a_{ZP/BG}BG(t); 0], \\
\text{where } M_{ZP}(t) = \arg\min[a_{ZP/OX}OX(t); a_{ZP/PP}PP(t); a_{ZP/BG}BG(t)]; \\
AG_{BR}(OX,PP,BG) = IF[M_{BR}(t) = a_{BR/OX}OX(t); a_{BR/OX}OX(t); 0] + \\
+ IF[M_{ZP}(t) = a_{BR/ZP}ZP(t); a_{BR/ZP}ZP(t); 0] + IF[M_{BR}(t) = a_{BR/BG}BG(t); a_{BR/BG}BG(t); 0], \\
\text{where } M_{BR}(t) = \arg\min[a_{BR/OX}OX(t); a_{BR/ZP}ZP(t); a_{BR/BG}BG(t)]; \\
AG_{BG}(OX,DT) = IF[M_{BG}(t) = a_{BG/OX}OX(t); a_{BG/OX}OX(t); 0] + \\
+ IF[M_{BG}(t) = a_{BG/DT}DT(t); a_{BG/DT}DT(t); 0], \\
\text{where } M_{BG}(t) = \arg\min[a_{BG/OX}OX(t); a_{BG/DT}DT(t)].
\end{gathered} \tag{6}$$

The coefficients of impact a_{ij} in the model equations could be identified in several ways, considered in the works [3 – 6].

The scenario construction in the economical subsystem *the Land*. The developed economical model shows the dynamics of all *the Land* subsystem processes, described by equations (1) – (4). In the series of numerical experiments the calculations for 370 time steps were performed. All the variables are presented in dimensionless form. The maximally possible production loan is $H_3^* = 300$, and the loan percentage $-\sigma = 0.01H_3^*$. The scenarios of processes obtained under these conditions are shown in fig. 4.



a *b*

c *d*

e *f*

Fig. 4. Scenarios forecasted by economical subsystem *the Land*

To asses the impact of ecological subsystem *the Sea* on the production profitability, during the construction of scenarios, depicted in the fig. 4, *a – ∂*, the impact of environmental taxes and environmental pollution penalties were not considered at first. Horizontal lines in the fig. 4, *a*, depict the constant scenarios of demand D for the subsystem production, the price P and the cost price E of this production. Frequent vertical lines show the values of daily production sale S, which depends on the production support by all kinds of resources. The amount of daily purchased production resources V_{11}, V_{12}, V_{13} are given in the fig. 4, *b*. These amounts depend on the ratio of current assets H_2 and current investment (loans) values H_3, which could be used for the purchase of the missing resources to meet the demand. As it follows from the fig. 4, *c*, production have to constantly invest in the resources purchase a maximum permissible value of accumulated credit H_3^*.

To monitor the production profitability EF, the ratio logarithm of income I_{acc}, accumulated over some period of time t, to the accumulated expenses E_{acc} was used:

$$EF = \ln \frac{1 + I_{\text{acc}}}{e + E_{\text{acc}}}, \quad I_{\text{acc}} = \int_0^t PS(t)dt\,, \; E_{\text{acc}} = \int_0^t EV(t)dt\,. \tag{7}$$

The scenarios of these processes are given in the fig. 4, *d*, *e*. Excluding the environmental penalties for marine pollution, the profitability remained constant.

In a second series of experiments the conditions, under which the economical subsystem should make contributions towards environmental objectives from the current assets in the amount of θH_2, are simulated. The production profitability scenarios are constructed for different percentage of contributions θ. The obtained results are shown in the Fig. 4, *f*. The figure shows the decrease of production profitability with the increasing of environmental sanctions. With significant contributions ($\theta = 0.5$) production becomes unprofitable at 280th step of calculations.

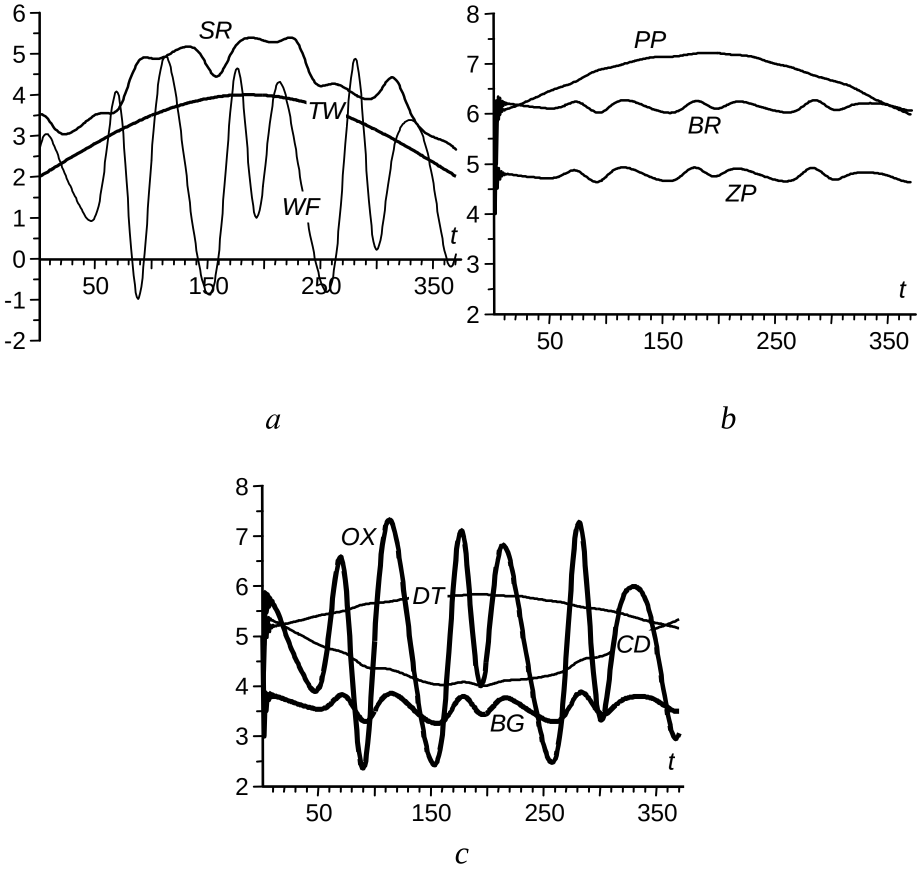
Construction of process scenarios for ecological subsystem *the Sea*. To evaluate the stability and controllability of *ABC*-model (5), (6) the numerical experiments were performed. Model equations were represented in the finite differences and were resolved at (0.370) time interval of iteration steps. The ecosystem variables are written in dimensionless form, and are reduced to the overall variability scale (0.10) by means of linear transformation. The values of several model coefficients are given in the table.

The coefficients of intersystem influences in the ecosystem model

$a_{KL/MN}$	*PP*	*ZP*	*BR*	*OX*	*CD*	*BG*	*DT*
PP	1	– 0.6	–	–	1.5	0.6	–
ZP	0.6	1	– 0.4	0.6	–	0.8	–
BR	–	0.4	1	0.3	–	0.6	–
OX	0.5	– 0.6	– 0.3	1	–	– 0.3	–
CD	– 0.5	0.3	0.2	–	1	–	–
BG	– 0.4	– 0.3	– 0.3	0.7	–	1	0.3
DT	0.4	0.4	0.2	– 0.7	–	– 0.3	1

In the series of experiments features of *the Sea* subsystem model firstly were verified in isolation from *the Land* subsystem. That’s why the effect of pollution inflowing the sea from the shore, was eliminated by equating to zero the coefficients $a_{PP/PL}$, $a_{ZP/PL}$, $a_{BR/PL}$ in the corresponding equations (5).

To assess the effect of climatic and weather conditions on process scenarios, represented by the ecosystem model, the external effects were simulated: solar radiation intensity *SR*, temperature of the sea upper layer *TW* and wind velocity modulus *WF*. The graphs of simulated atmospheric effects and sea temperature are given in Fig. 5, *a*.



a *b*

c

Fig. 5. The external effects (*a*) and the reaction to them of marine ecosystem variables (*b*, *c*) (wind velocity graph *WF* is shifted down at 1)

In the first experiment the resource constraints are removed for the further evaluation of their role in formation of ecosystem process scenarios. Therefore, the logical management agents (6) in the equations (5) are replaced by the influence sums:

$$\begin{aligned} A^*_{PP}(BG,SR,CD) &= a_{PP/BG}BG(t) + a_{PP/SR}SR(t) + a_{PP/CD}CD(t)\,, \\ A^*_{ZP}(OX,PP,BG) &= a_{ZP/OX}OX(t) + a_{ZP/PP}PP(t) + a_{ZP/BG}BG(t)\,, \\ A^*_{BR}(OX,PP,BG) &= a_{BR/OX}OX(t) + a_{BR/ZP}ZP(t) + a_{BR/BG}BG(t)\,, \\ A^*_{BG}(OX,DT) &= a_{BG/OX}OX(t) + a_{BG/DT}DT(t)\,. \end{aligned} \qquad (8)$$

In these conditions by the predetermined intensity of the external effects, the most defined model reaction manifested in those process scenarios, which were directly depended on the near-water wind modulus, annual change of illumination and sea temperature. Significant fluctuations of the oxygen concentration in the upper layer (*OX* curve in the Fig. 5, *c*) and the smoothed annual change of carbon dioxide and detritus concentration (*CD* and *DT* in the Fig. 5, *c*) were represented. Phytoplankton concentration curve (*PP* in the Fig, *b*) is formed mainly due to the annual change of solar radiation (*SR* in the Fig. 5, *a*). Values of zooplankton and bioresource concentrations (*ZP* and *BR* in the Fig. 5 *b*) were affected by minor changes due to the oxygen concentration fluctuations.

In the next experiment the management agents (6) were turned on. The obtained results are shown in the Fig. 6. The resource limiting agents engaging significantly changed the scenarios of ecosystem organisms supplying with the vital resources. As it follows from the figure, management agent scenarios are oriented at minimum values of their arguments. For example, graph values of the phytoplankton limiting by biogenic substances, solar radiation and carbon dioxide (AG_{PP} curve in the Fig. 6, *a*) due to the agent $AG_{PP}(BG, SR, CD)$ correspond to the minimal values of *SR* and *CD* curves. The curve *BG* lays above them, and it means that biogenic substances didn't affect on the phytoplankton concentration.

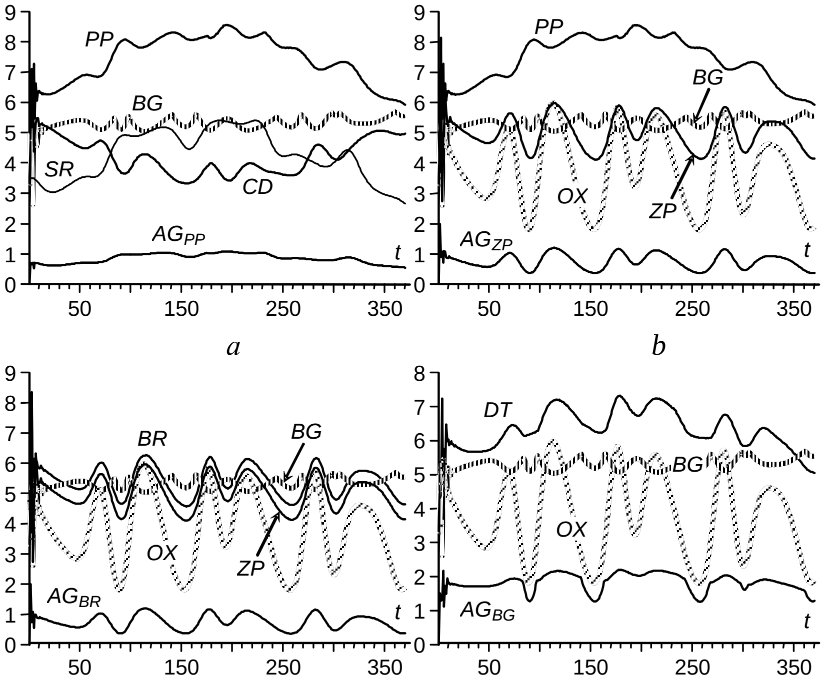


Fig. 6. Functions of resource limiting agents in the model of *the Sea* subsystem and the substance concentrations formed by them: *a* – phytoplankton, *b* – zooplankton, *c* – bioresource, *d* – biogenic elements

The results of these experiments concluded that management agents are really important in the given model of marine subsystem. The model has a relatively high sensitivity to external effects and adequately reproduces a cause-effect relationship between the modeled processes. Therefore, its intersystem influence coefficients (table) were saved when including the subsystem *the Sea* to the general simulation model of ecological-economic processes with economical subsystem *the Land*.

The marine bioresource consumption balance management on the basis of the integrated *Land – Sea* system' model. Consolidation of subsystem *the Land* and *the Sea* models into the integrated system was carried out by management unit of ecological-economic production profitability balance and levels of pollution contamination and marine environment biodiversity. The developed balance management scheme is based on the negative feedback between two subsystems, which operated in the following way. The increase of marine environment pollution concentration *PL* was taken as proportional to the accumulated amounts of selling production S_{acc}. Natural purification of the marine environment occurred due to the turbulent mixing and chemical-bacteriological reactions favored the decrease of concentration. The first of these two factors was considered to be proportional to the pollution level *PL* with a certain coefficient ε, and the second factor – to the amount of money accumulated in the environmental protection action fund *EP*. That's why *ABC*-method modular equation for the pollution concentration has the following form:

$$\frac{dPL}{dt} = 2r_{PL}PL\left[C_{ZP} - \left(PL + a_{PL/EP}EP + \varepsilon PL - a_{PL/S}S_{\text{acc}}\right)\right]. \tag{9}$$

The environmental activities fund *EP* of was formed by the accumulation of contributions *TX* from the economic subsystem profit. To improve the ecological state of the marine environment the environmental tax, proportional to the concentration *PL* value, to which was added an environmental penalty, when the concentration of contaminants got above the maximum permissible value PL^*, was used. The inclusion of environmental penalties and their amount was controlled by the management agent $AG_{TX}(PL, PL^*)$. Therefore, the following equations for *EP* and *TX* values were used:

$$\frac{dEP}{dt} = 2r_{EP}EP[C_{EP} - (EP - a_{EP/TX}TX_{\text{acc}} + F_{EP})], \tag{10}$$

$$\frac{dTX}{dt} = 2r_{TX}TX\{C_{TX} - [TX - a_{TX/PL}PL - AG_{TX}(PL, PL^*)]\}, \tag{11}$$

where F_{EP} – additional investments to the *EP* fund;

$AG_{TX}(PL, PL^*) = IF\{PL < PL^*; 0; a_{TX}[1 - \exp(b_{TX}\tau)]\}$.

To close the feedback loop between the subsystems *the Land* and *the Sea*, biodiversity index of the marine environment *BD* is determined by the concentrations of the aquatic organism main groups – phytoplankton *PP*, zooplankton *ZP* and bioresource *BR*, which sufficiently depend on the marine environment pollution level:

$$\frac{dBD}{dt} = 2r_{BD}BD[C_{BD} - (BD - a_{BD/PP}PP - a_{BD/ZP}ZP - a_{BD/BR}BR)]. \tag{12}$$

Management of the unified *Land –Sea* system was carried out through the dependence of production costs on the pollution sanction level *TX* and the marine environment biodiversity index *BD*:

$$\frac{dE}{dt} = 2r_E E\{C_E - [E - \sum_{i-1}^{3} \rho_i q_i - a_{E/TX} TX - AG_{BD}(BD, BD^*)]\}, \quad (13)$$

where ρ_i –coefficients of resources price impact q_i;

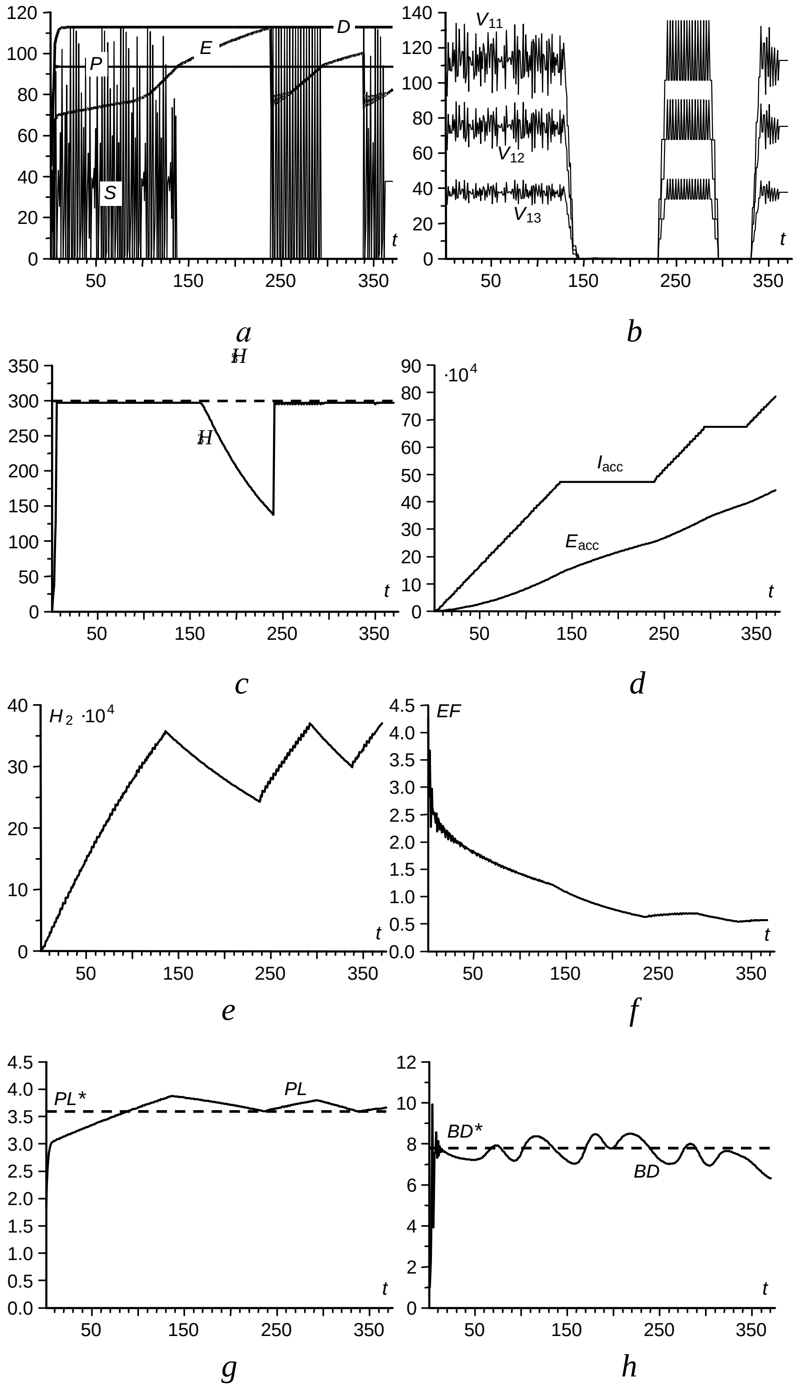
$AG_{BD}(BD, BD^*) = IF\{BD > BD^*; 0; a_{BD}[1 - \exp(b_{BD}\tau)]\}$.

The increase of pollution penalties and decrease of the biodiversity index below the value BD^* increased production costs and decreased the production profitability.

It should be noticed that the unified *Land –Sea* model (1 – 13) describes the ecological-economic development processes in detail. In this model the environmental management of the marine environment is performed not only by the pollution level criterion, but also by the biodiversity index. Using the unified model a series of numerical experiments was carried out. The results of one experiment are summarized in Fig. 7.

At the beginning of the experiment almost continuous production sell *S* under the constant demand *D* and the market value *P* (Fig. 7, *a*) was observed. At the same time increased the pollution concentration in the sea (Fig. 7, *f*). Biodiversity index have been fluctuated around the maximum permissible value BD^* = 8 (Fig. 7, *g*). So, the major impact on the production cost was provided by the pollution level. Production cost increased rapidly and at the 130th time step it became equal to the product price and it was the cause of the first stop of the production (Fig. 7, *a*). The subsystem *Land*, which got necessary types of resources using the maximal loan amounts (Fig. 7, *c*) also stopped that purchases (Fig. 7, *b*).

The suspension of production had been lasted until the 239th step. After the suspension of production the pollution level reduced due to the processes of marine environment self-purification and also because of environmental action fund. The velocity of marine environment pollution concentration decrease determined in this experiment has provided its fall to the value PL^* = 3.7 at the 239th step of experiment, when the sanction agent $AG_{TX}(PL, PL^*)$ in the equation (11) abruptly reduced the production cost and production management agents resumed the production (Fig 7, *a*). During the suspension of production period the growth of accumulated incomes stopped (Fig. 7, *d*) and took place a partial repayment of accumulated loans (Fig 7, *c*) from the available current assets. Thus, the current assets reduced (Fig. 7, *e*) and the accumulated expenses kept growing (Fig. 7, *d*). By this fact could be explained the decrease of total production profitability (Fig. 7, *h*).



a *b*

c *d*

e *f*

g *h*

Fig. 7. The results of the ecological-economic process scenario management on the criterion of the marine environment pollution level *PL*

Since the resumption of production at the 239th step the above-mentioned pollution level management cycle repeated again. Thus, during the entire experiment the pollution level didn't exceed the upper limit of permissible values $PL < 4.0$ and tended to decrease (Fig. 7, *f*). The total profitability remained positive and had a tendency to stabilization.

The scenarios given in Fig. 7, were obtained during the experiment, when it was set the problem to find such a marine pollution sanction value at which the permissible pollution level could reach the value PL^* = = 3.6, but should not exceed the value $PL = 4.0$. During the calculations it was determined that to provide these conditions the contribution from the current assets of *the Land* subsystem to the environmental actions fund should make about one percent ($\theta = 0.01$).

Thus, the ecological scenarios *PL*, *BD* and also economical scenario of profitability *EF*, forecasted by the unified the *Land –Sea* model, allowed us to find the necessary environmental balance. The numerical experiments showed that there are different variants of the *Land –Sea* model usage to find this balance.

Production volumes of the *Land* subsystem and, consequently, the pollution level affected the biodiversity index by the concentration values of phytoplankton, zooplankton and bioresource in accordance with the equation (12). The permissible value of biodiversity index lower bound $BD^* = 7.8$ was found and it was set the problem to determine the necessary amount of pollution sanctions at which the *BD* index stay above this bound. The numerical experiment was performed with the same *Land – Sea* model parameter values as in the above-mentioned case. Scenarios of ecological-economic processes obtained during this experiment are shown in the Fig. 8.

Due to the use of $AG_{BD}(BD, BD^*)$ management agent in the equation for production cost (13), the production cost curve *E* (Fig. 8, *a*) became more variable than in the first experiment (Fig. 7, *a*). Now it was affected by two management agents: $AG_{TX}(PL, PL^*)$ – through the equation (11) and $AG_{BD}(BD, BD^*)$ – through the equation (13). As a result, the sanction amounts affecting the production cost increased, and the production cost scenario stopped the production for 5 times, whereby the pollution level *PL* (Fig. 8, *f*) and biodiversity index *BD* (Fig. 8, *g*) were kept near the maximum permissible values. With the parameters of the *Land – Sea* system model management, which were used in these calculations, total production profitability decreased (Fig. 8, *h*). Negative tendencies were observed in the scenarios of ecological processes – the phytoplankton, zooplankton and bioresource concentrations decreased.

To improve the ecological state of the marine environment the size of the sanctions imposed on the economic subsystem should be increased at the cost of further reducing of the total production profitability. As an alternative variant it was considered the changing of production itself – transferring to the eco-friendly technologies. But the transferring to such technologies requires a significant investment.

The production should allocate certain funds to the special fund of new environmental technologies *EP*, which eliminate or significantly reduce the pollution level.

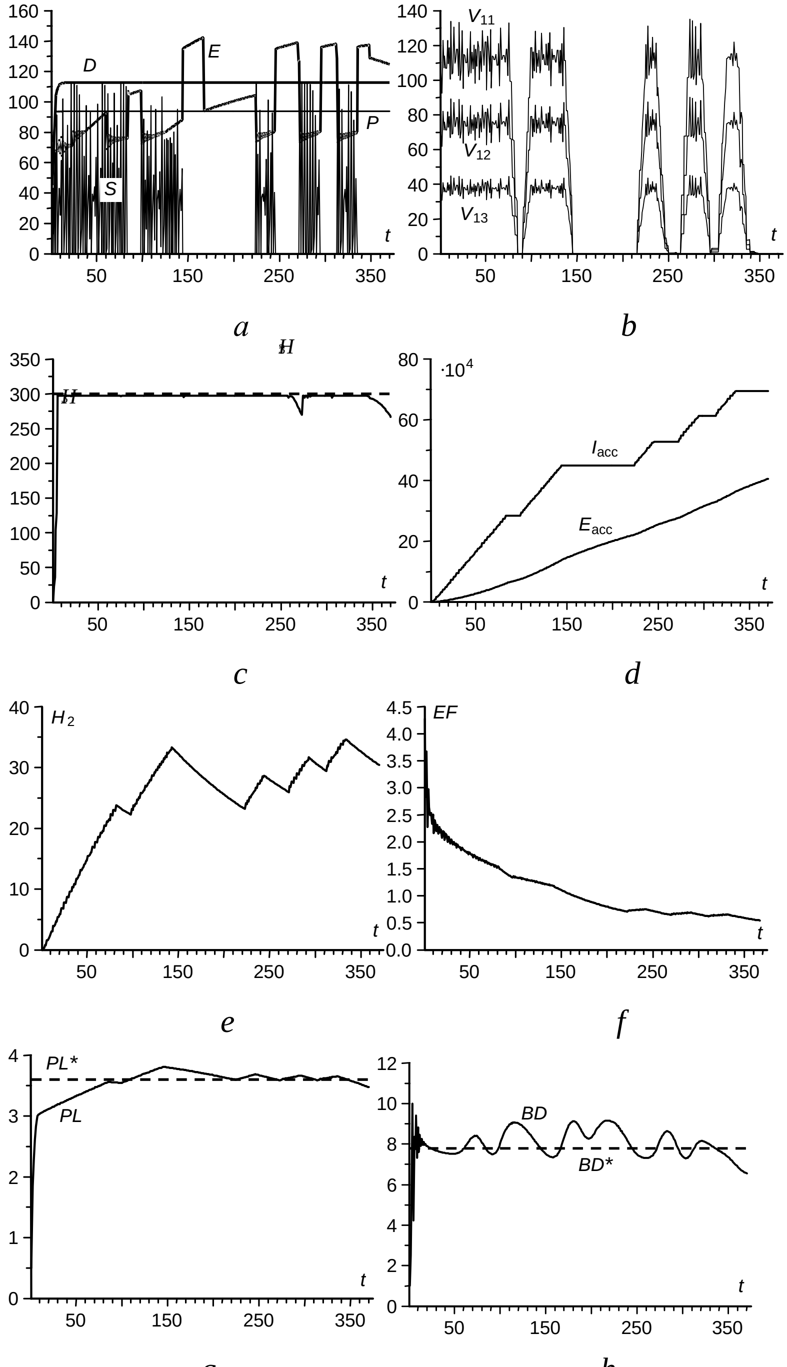


Fig. 8. The scenario management results of ecological-economic processes by the pollution level criterion *PL* and the marine environment biodiversity index *BD*

To test the effectiveness of the production transferring to eco-friendly technologies, the following experiment was performed. In the model of ecological-economic system *Land – Sea* the fund of environmental activities *EP* was simulated, which accumulated funds from the marine environment pollution penalties. In addition, a certain part of current assets was regularly allotted to this fund (*e.g.* $0.001H_2$). For the comparability of the modeling results the model parameters remained the same with the exception of the fact that now in the equation for pollution level (9) the impact of *EP* fund was considered and the equation for *EP* took the following form:

$$\frac{dEP}{dt} = 2r_{EP}EP\{C_{EP} - [EP - (a_{EP/TX}TX + a_{EP/H_2}H_2)_{\text{acc}}]\}. \tag{14}$$

The scenarios of ecological-economic processes in the *Land – Sea* model, obtained by the simulation of production transferring to the eco-friendly technologies, are given in the Fig. 9. As it follows from the Fig. 9, *f* in the initial period of the experiment (up to 90th time step) an increase of pollution concentration occurred and the production cost increased (Fig. 9, *a*) due to economic sanctions (Fig. 9, *e*). At that period we haven't enough funds for introduction of new technologies (Fig. 9, *c*). So, after the 90th step occurred a momentary stop of production (Fig. 9, *a*). But since that period of time the funds accumulated in the fund of environmental activities began to exceed the total amount of economic sanctions, as the summand $a_{EP/H_2}H_2$ in the equation (14) tended to sustainable growth and the summand $a_{EP/TX}TX$ rapidly decreased, following the pollution level curve (Fig. 9, *f*). As a result, the amount of accumulated means of environmental activity fund rapidly increased.

According to the idea of simulation experiment the increase of the fund means allowed us to transfer the production to the eco-friendly technologies. The graph of total production profitability is indicative (Fig. 9, *h*). In the initial period of time before the transfer to the new technologies the same profitability drop as in the experiment without transferring to the new technologies was observed (Fig. 8, *h*). But after the 90th step of time calculations the total profitability graph at first stopped the decrease and then a tendency of growth was acquired.

The effectiveness of production transfer to the eco-friendly technologies became obvious when we compare the graphs of accumulated incomes and accumulated expenses of the experiment without a transfer to eco-friendly technologies (Fig. 8, *h*) with the same graphs in another experiment (Fig. 9, *d*). By the end of the experiment the accumulated expenses were almost equal: E_{acc} = $405 \cdot 10^3$ c.u. – without transferring to the new technologies and E_{acc} = $414 \cdot 10^3$ c.u. – with the transferring. But the accumulated incomes in the experiment with the transition to the new technologies appeared to be essentially higher. Their amount was I_{acc} = = $1.25 \cdot 10^6$ c.u., whereas without transition to the new technologies they amounted $I_{\text{acc}} = 0.41 \cdot 10^6$ c.u.

Thus, the simulation experiment allowed us to quantify the economic benefits of the production transferring to the eco-friendly technologies. The decrease of marine environment pollution level by the end of experiment almost to zero positively impacted on the marine environment ecological state.

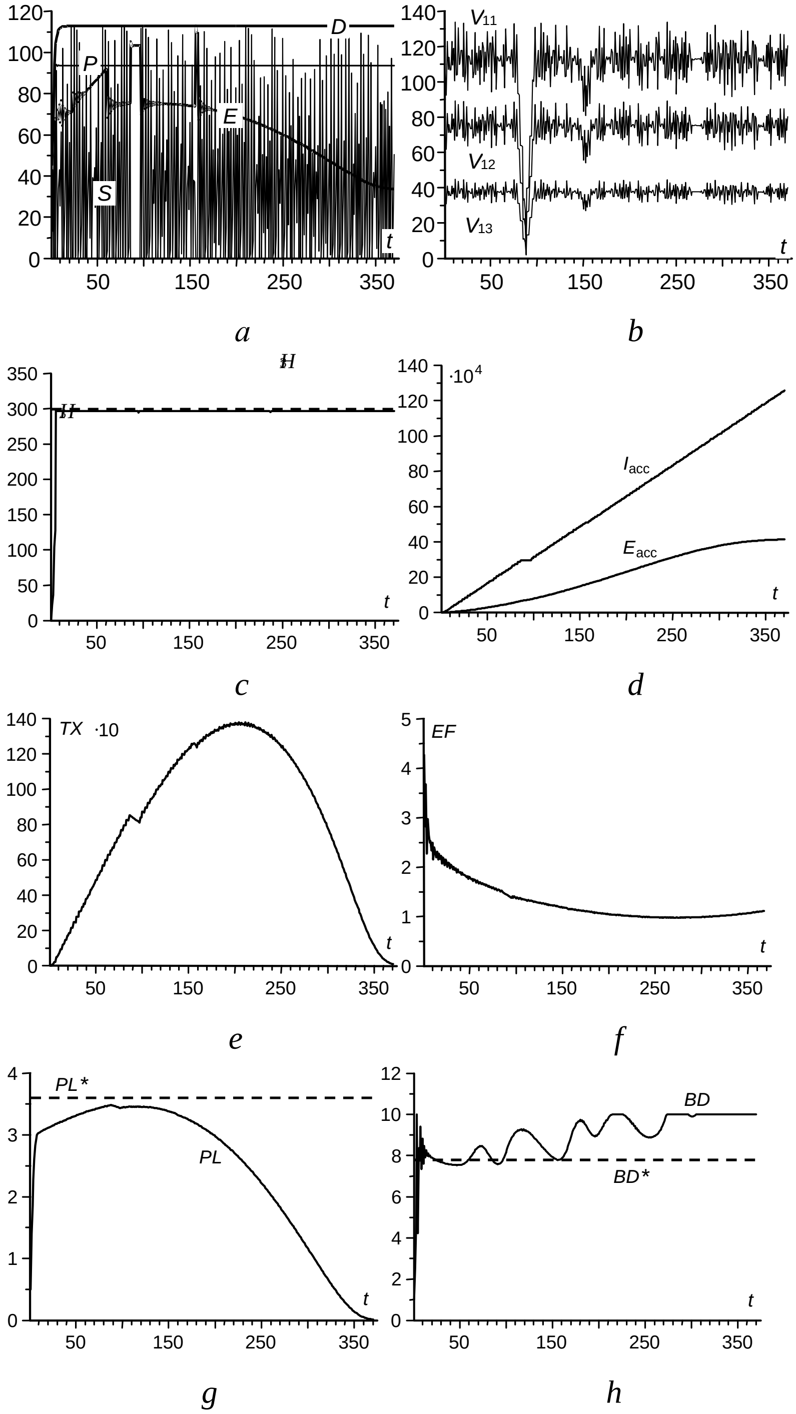
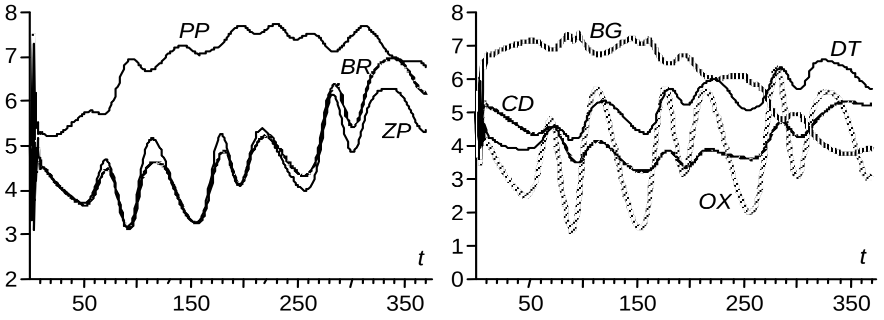


Fig. 9. Scenarios of ecological-economic processes in *the Land – the Sea* system during the production transfer to the eco-friendly technologies

The concentrations of phytoplankton and zooplankton increased and emerged a tendency of bioresource concentration growth, which in the end of the experiment was weakened by the seasonal factors (Fig. 10, *a*). In this regard the concentration of biogenic substances decreased and the detritus concentration increased (Fig. 10, *b*). The consequence of the new technologies transferring was an abrupt decrease of pollution level (Fig. 9, *f*) and a significant increase of biodiversity index (Fig. 9, *g*), which reached its maximum value conditioned upon the given marine environment resource capacity by this parameter $2C_{BD} = 10$.



a *b*

Fig. 10. Scenarios of ecological processes during the production transferring on the eco-friendly technologies

Conclusion. The simulation experiments performed applying the *Land – Sea* model confirmed the applicability of ecological-economic system adaptive models for the finding of marine resources consumption and reproduction rational management. The production transferring on the resource-saving technologies is more profitable, because the investments for eco-friendly technologies introduction lead to the reduction of penalties and production suspensions for the ecological reasons, and consequently increase the production efficiency.

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