Original article

Effect of Intra-Annual Dynamics of Ecosystem Components on Ecological Risk: Model Assessments

N. V. Solovjova

P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia
e-mail: soloceanic@yandex.ru

Abstract
The article proposes a model for assessing ecological risk taking into account the intra-annual dynamics of the main components of the ecosystem. Based on model calculations, ecological risk assessments are given for variations in the intra-annual state of low-productive ecosystems of the Arctic shelf and the effect of technogenic stressors. The proposed approach combines ecological risk models and observational data. The calculations made it possible to obtain model estimates of the intra-annual dynamics of ecological risk and permissible impacts on ecosystems from stressors in the conditions of development of Arctic shelf resources. The obtained preliminary results of calculations allowed us to identify areas of increased risk and take into account the different degree of requirements for the exclusion of type 1 and 2 errors due to the specifics of ecological safety tasks. An important practical result of the development of the risk assessment methodology is the identification of time intervals of impacts at which a dangerous situation is hidden by external well-being (type 2 error). The conducted modelling studies allow reallocating safety expenditures throughout the year so as to reduce risks during hazardous periods of offshore resource development and exclude cost overruns during relatively safe times. In other words, it is possible to resolve environmental and economic contradictions in risk management.

Keywords: ecological risk model, probability of acceptable impacts, Arctic shelf, ecosystem, mathematical modelling, phytoplankton biomass, anthropogenic impact

Acknowledgements: This work was prepared under state assignment no. 0128-2021-0004. The author expresses gratitude to the heads of the laboratories of P. P. Shirshov Institute of Oceanology of the Russian Academy of Sciences, in particular to V. A. Silkin, Dr. Sci. (Biol.), for discussing the directions of modeling environmental risk, M. V. Flint, Academician of the Russian Academy of Sciences, for organizing expedition work in the Arctic seas, and E. E. Sovga, Dr. Sci. (Geogr.) (MHI RAS), for assistance and support with submission of the work to *Environmental Safety of Coastal and Shelf Zones of Sea* journal.

For citation: Solovjova, N.V., 2023. Effect of Intra-Annual Dynamics of Ecosystem Components on Ecological Risk: Model Assessments. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 86–97.

Влияние внутригодовой динамики компонентов экосистемы на экологический риск: модельные оценки

Н. В. Соловьева

Институт океанологии имени П. П. Ширшова РАН, Москва, Россия
e-mail: soloceanic@yandex.ru

Аннотация

Предложена модель оценки экологического риска с учетом внутригодовой динамики основных компонентов экосистемы. На основе модельных расчетов даны оценки экологического риска при вариациях внутригодового состояния низкопродуктивных экосистем арктического шельфа и действии техногенных стрессоров. Проведенные расчеты позволили получить модельные оценки внутригодовой динамики экологического риска и допустимого воздействия на экосистемы со стороны стрессоров в условиях освоения ресурсов арктического шельфа. Полученные предварительные результаты расчетов позволили выделить области повышенного риска и учесть различную степень требований к исключению ошибок 1-го и 2-го рода, обусловленных спецификой задач экологической безопасности. Важным практическим результатом разработки методики оценок риска является выявление временны́х интервалов воздействий, при которых опасная ситуация скрыта внешним благополучием (ошибка 2-го рода). Проведенные модельные исследования открывают возможность перераспределять экономические затраты на безопасность в течение года так, чтобы снизить риски в опасные периоды разработки морских ресурсов и исключить перерасход средств в относительно безопасное время. Другими словами, можно снизить эколого-экономические противоречия в управлении риском.

Ключевые слова: модель экологического риска, вероятность допустимых воздействий, арктический шельф, экосистема, математическое моделирование, биомасса фитопланктона, антропогенное воздействие

Благодарности: работа подготовлена в рамках государственного задания № 0128-2021-0004. Автор выражает благодарность руководителям лабораторий Института океанологии им. П. П. Ширшова РАН, в частности доктору биологических наук В. А. Силкину, за обсуждение направлений моделирования экологического риска, академику Российской академии наук М. В. Флинту за организацию экспедиционных работ в морях Арктики и доктору географических наук Е. Е. Совге (МГИ РАН) за помощь и поддержку работы при представлении в журнал «Экологическая безопасность прибрежной и шельфовой зон моря».

Для цитирования: *Соловьева Н. В.* Влияние внутригодовой динамики компонентов экосистемы на экологический риск: модельные оценки // Экологическая безопасность прибрежной и шельфовой зон моря. 2023. № 3. С. 86–97. EDN JKDPNP.

Introduction

The relevance of ecological risk assessments as integral characteristics of the state of marine ecosystems is determined not only by the wide range and rate of change in parameters, but also by the presence of processes of various genesis in oceanologically contrasting water areas. Intensive development of marine resources causes the effect of technogenic stressors on natural processes of various origins: hydrophysical, hydrochemical, hydrobiological, geological. In this case, there is a need for an integral quantitative assessment of the state of marine ecosystems under such conditions. It is not possible to obtain a reliable risk assessment within a single discipline. The very concept of ecological risk requires interdisciplinary approaches as an integral characteristic of the state of the ecosystem. In this case, contradictions can arise in combining the requirements of each of the disciplines separately. Thus, in the practice of developing shelf resources, economic and ecological requirements are directed differently.

When making business decisions, as a rule, economic indicators come to the fore, which is reflected in the main accepted form of ecological risk assessment, which comes down to assessing the following product: *event probability* × *damage*. In this case, priority is given to the economic component [1] and leads to a decrease in the importance of assessing the ecological component in projects aimed at the development of shelf resources.

For the Arctic shelf, the task of calculating the dynamics of ecological risk is especially relevant in connection with increasing climate change and the prospective development of the mineral and biological resources of the region. In this sense, understanding the dynamics of marine ecosystems in the context of global changes [2] makes it possible to calculate risks [1–7]. Existing approaches to ecological risk assessments can take into account a combination of stressors of different nature and the diversity of responses of marine ecosystems to external effect [4]. For the Arctic marine ecosystems, risk assessment methods ERA [4] in combination with the dynamic object-oriented Bayesian network DOOBN [8] and DBN [9] are known. To assess the risk of oil spills in the Arctic, models have been developed taking into account the toxicity of biotransformation [10].

The analysis of current situation with risk assessments shows that to increase the efficiency and relevance of methods, the most preferable way is to combine different approaches. Ecological risk assessment using system models at various levels of ecosystem organization is an evolutionary step in maintaining ecological safety. However, it is not enough to take into account the cumulative effect of stressors under static conditions only. It is necessary to combine the dynamics of stressors with the dynamics of ecosystem functioning. In order to advance in this direction, this article proposes an approach based on the synthesis of probabilistic risk models and field observation data.

The purpose of the research was to obtain model assessments of the influence of the intra-annual dynamics of ecosystem components (in particular, phytoplankton) on the dynamics of ecological risk under the influence of technogenic stressors. Observational data on phytoplankton biomass in low-productive ecosystems of the Arctic shelf were used for the modelling.

Materials and methods

For model studies of intra-annual risk variations in low-productive ecosystems of the Arctic shelf, observational data on seasonal variations in phytoplankton biomass in the Kara, Laptev, East Siberian Seas and main waters of the Chukchi Sea were used [11–21]. The low productivity of ecosystems in these water areas is stipulated by strong density stratification due to the intense desalination of the surface 5–12-meter water layer effected by the river flow into the marginal Arctic seas [12, 13]. Seasonal convection on the Arctic shelf for the most part does not overcome the stability of density stratification [21], and the process of enrichment of the photic layer with nutrients does not occur [12, 13]. This natural barrier is not weakened by such modern climate changes as an increase in the ice-free period and warming of the surface layer of water [13, 21]. Such features determine the low level of productivity and effect the ecological risk under the influence of stressors in the conditions of shelf resource development.

The ecological risk is regarded as the probability of death of a biological system (in particular, a population) under conditions of anthropogenic impact during a fixed period of impacts from stressors. The impact of technogenic stressors and their multiple combinations is reflected in the natural intra-annual dynamics of ecosystems with periods of outbreaks and declines in the biomass of ecosystem components.

The risk-based ecological safety criterion has the following form [22] $K = \{y \le y_p\}$, where y – ecological risk; y_p – permissible risk.

At $y \le y_p$, a decision is made on ecological safety, at $y > y_p$ – on ecological danger [22]. It is impossible to obtain the exact value of ecological risk y in principle. It is possible to obtain only upper $\overline{y}$ and lower $\underline{y}$ risk assessments ($\underline{y} \le y \le \overline{y}$). The value of permissible ecological risk lies in the interval between upper $\overline{y}$ and lower $\underline{y}$ assessments. For the criterion of ecological safety, the upper estimates $\overline{K} = \{\overline{y} \lesseqgtr y_p\}$ will be used.

We will take into account L stressors ($i = \overline{1,L}$) that have a negative impact on the ecosystem functioning under natural conditions. Let us assume that the stressors can take k states ($k = \overline{1,K}$). Such states include, for example, normal operating conditions and emergency events in the operation of technical means effecting the ecosystem. In accordance with Boole's inequalities, $\max\limits_i y_i = y_l \le y \le y_h = \sum_{i=1}^{L} y_i$, where y_i – risk from the i-th stressor [23, 24]. Ecosystem components (biomass of populations of organisms) can experience rises and falls during the year: M – number of periods of rise and fall during the year ($m = \overline{1,M}$). Observational data give maximum values of population biomass on rises $N_{\max}$ and falls N_{cr}. We will take into account the imposition of the effects of technogenic stressors on the natural dynamics of the ecosystem, for example, by modelling the impact of a technical resource development system in the *k*-th state on the aggregated component of the ecosystem (phytoplankton) with seasonal variations in its biomass.

In the general case, for intra-annual risk depending on time we have the following relations [5–7, 23, 24]

$$y_k(t) \le \sum_{k=1}^{K} q_k \sum_{m=1}^{M} p_{km} y_{km} = \sum_{k=1}^{K} q_k \sum_{m=1}^{M} \left(p_{am} y_{am} + p'_{am}\, y'_{am} \right)_k = \sum_{k=1}^{K} q_k y_a(t),$$

$$y_a(t) \le \frac{1 - \overline{Ev}(t) / N_{\max}}{\left(1 - N_{cr} / N_{\max}\right)^2}, \qquad (1)$$

$$p_{am} = \frac{t_m}{t},\ p'_{am} = \frac{t'_m}{t},\ \sum\nolimits_{m=1}^{M} \left(t_m + t'_m\right) = t,$$

$$\sum\nolimits_{m=1}^{M} \left(p_{am} + p'_{am}\right) = 1, \quad \sum\nolimits_{k=1}^{K} q_k = 1,$$

where y_i – risk from a separate *i*-th impact from stressors (a technical object); q_k – probability of the *k*-th state of a technical object; p_{mk} – conditional probability of the *m*-th state of the ecosystem at the *k*-th state of the technical system; y_{imk} – conditional risk from a separate *i*-th impact factor for the *k*-th state of a technical object, and the *m*-th state of the ecosystem; $\overline{Ev}(t)$ – mathematical expectation of the population biomass value; $y_k(t)$ – intra-annual biosystem risk at the *k*-th state of a technical object; p_{am} – probability of a biosystem being in the *m*-th intra-annual state of biomass rise; y_{am} – risk at biomass rise; y'_{am} – risk at biomass fall; $\overline{y}_a$ – ecological risk throughout the year; y_{km} – biosystem risk probability at the *k*-th state of a technical object and the *m*-th state of the biosystem; t_m – duration of biomass rise; t'_m – duration of biomass fall. Formula (1) is used for the normal distribution of a random variable.

The model of intra-annual risk variations (1) makes it possible to move on to the assessment of the dynamics of the probability of acceptable impacts from stressors on the ecosystem. This hierarchy of actions reflects the priority of the environmental component in the development of marine resources [21]. For the case where the permissible probability of impacts depends on time *Q*(t), the ecoscreening equations [23, 24] were expanded to the following form [7]

$$Q(t) = \begin{cases} 1 \ \text{for} \ y_k(t) \le y_d, \\ \dfrac{y_d}{y_k(t)} \ \text{for} \ y_d < y_k(t) < 1, \\ y_d \ \text{for} \ y_k(t) = 1, \end{cases} \qquad (2)$$

where $Q(t)$ – maximum permissible probability of anthropogenic impact on the ecosystem; $y_k(t)$ is determined by equations (1); y_d – maximum permissible risk for the ecosystem under various requirements for maintaining environmental quality.

The probability of the state of technical systems (accident, normal operating conditions, degree, and modes of impact) taken into account in the technical operation project, also represents the input data for the risk model. Approximate acceptable risks of the impact of stressors on marine ecosystems were used for the calculations (Table).

According to data [25], the range of probability values of acceptable ecological risk for various types and stages of technological activity on the shelf ranges from 10^{-7} to 10^{-1}. To calculate $Q(t)$, values y_d were selected that correspond to increased ($y_d = 10^{-5}$), average ($y_d = 10^{-4}$), and insignificant ($y_d = 10^{-3}$) requirements for the ecosystem quality. Probability q_k of the technical system being at the k-th state (we assume $k = 3$) was chosen from the range from 10^{-3} to 10^{-1} (Table). Probability values of low $q_1 = 10^{-3}$, average $q_2 = 10^{-2}$, and high $q_3 = 10^{-1}$event frequency were chosen (Table).

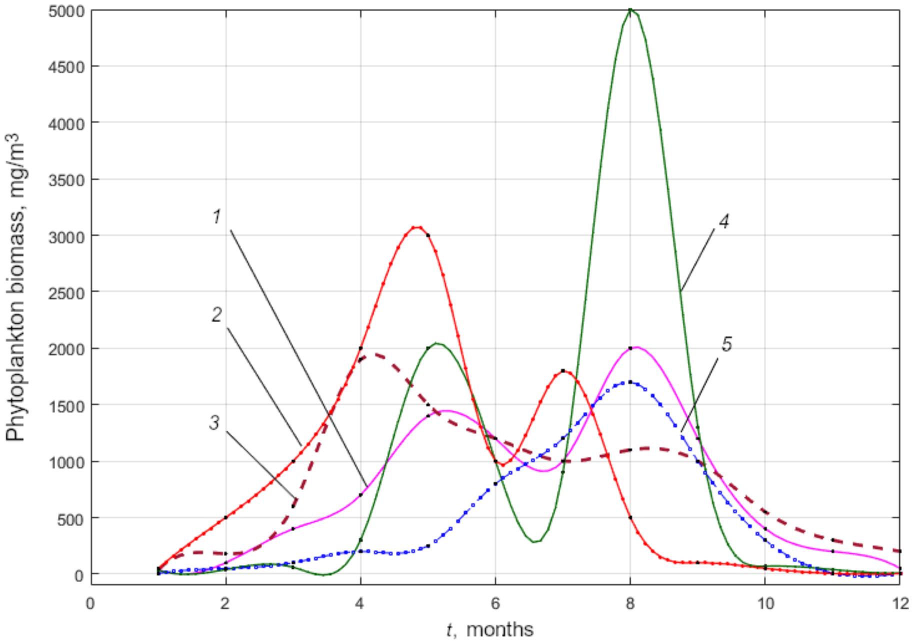
The proposed method takes into account the ecosystem aggregated components. The efficiency of the method is confirmed by the results of calculating the risk for the aggregated component of the initial link of the food chain – phytoplankton.

Acceptable risks of stressors on marine ecosystems at the main stages of oil and gas resources development [25]

Type of anthropogenic impact on ecosystems	Impact scale		Estimated permissible risk
	Spatial	Temporal	
Seismic exploration	Local	Temporary	10^{-1}
Exploratory well drilling	Topical	Short-term	10^{-7}
Field operations from single platforms	Local	Temporary	10^{-5}
Regional field work	Regional	Long-term	10^{-2}
Construction of platforms, pipelines, etc.	Topical	Temporary	10^{-5}–10^{-7}
Operation of pipelines in accident-free mode	Regional	Long-term	10^{-5}
Tanker shipping in accident-free mode	Sub-regional	Temporary	10^{-7}

Generalization of the method to the case of all main components of the ecosystem will reveal the most vulnerable link in the food chain, which will determine the risk for the entire ecosystem. Model relations (1)–(2) generalized to the case of J populations make it possible to determine acceptable values of the probability of impacts from stressors in relation to the j-th population of the ecosystem. If the existence of all J populations is equally important to us, then the reliability of technical systems affecting the ecosystem should be subject to the requirement of an acceptable annual probability of accident $Q(t)$, satisfying the following condition $Q(t) = \min\limits_{j} Q(t)_j$ [22, 23].

Observations of phytoplankton biomass are used as input data to the risk model. Summarizing observation data on the seasonal variation of phytoplankton biomass in the Kara, White, Laptev, East Siberian, and Chukchi Seas [11–20], we chose values $N_{\max}$, N_{cr}, p_{am}, p'_{am}, $\overline{Ev}(t)$ as input parameters of the risk model. The results of ecosystem modelling can also be used to obtain input data for the risk model [26, 27]. But with little knowledge of the seasonal dynamics of biomass of the main components of the Arctic shelf ecosystems, especially in connection with new climate changes, ecosystem modelling is still difficult.



F i g . 1 . The annual course of phytoplankton biomass according to gener-alized observations of freezing waters (*1*) [28]; the Barents, White and Chukchi Seas (*2*) [29]; non-freezing waters (*3*) [30]; the coastal part of the Kara Sea (*4*) [30]; the Kara, Laptev, East Siberian Seas (*5*) [11–20]

Dynamics of phytoplankton biomass in highly productive ecosystems with two maxima (the Barents, Bering, Chukchi (Barrow Canyon) [12, 13], White Seas, estuarine and slope frontal zones) and low-productive (the main water area of the Kara and Chukchi Seas, Laptev, East Siberian Seas [11–20]) vary greatly (Fig. 1). No spring phytoplankton blooms in a significant part of low-productive areas (the Kara Sea) confirmed by expeditionary observations [11–20], are stipulated by stable density stratification. Based on the above expeditionary observations, the following values were selected for a low-productive ecosystem: $N_{\max} = 1.7 \cdot 10^3$ mg/m^3, $N_{cr} = 10$ mg/m^3, $p_{am} = t_m/t = 1/6$, and $\overline{Ev}(t)$ (curve *5* in Fig. 1) as input values to risk model (1).

Calculation results

Calculation according to model (1)–(2) showed that intra-annual variations in ecological risk y_k (Fig. 2, *a*) ranged from 0 to 0.8. Calculated permissible impact probability values $Q(t)$ from 0 to 0.2 correspond to the specified probabilities of impacts from stressors (Fig. 2, *b*). This is typical throughout almost the entire year except for the phytoplankton biomass peak (Fig. 2). Only at the phytoplankton biomass peak (Fig. 2, *b*), an impact probability of 80 to 100 % can be assumed for a low-productive ecosystem.

The performed calculations confirm the initial assumption about the influence of the intra-annual dynamics of ecosystem components on the intra-annual dynamics of risk. Confirmation of such an influence results in adjustments to static matrix risk assessment methods.

The results obtained made it possible to calculate the dependence of the permissible probability of impact on the ecosystem on the ecological risk $Q(y_k)$ in the range of values $q_k = 10^{-5}$–10^{-1} and $y_d = 10^{-5}$–10^{-3} (Fig. 3). The calculation revealed areas of increased danger and relative safety (Fig. 3) under various combinations of impacts and the required environmental quality.

An important practical result of the conducted research can be considered the emerging opportunity to identify type 1 and 2 errors. The peculiarity of environmental problems in the presence of type 1 and 2 errors is associated with different severity of the consequences if they persist. The concepts of errors are taken from statistical theory, and type 1 error means mistaking a safe situation for a dangerous one, while type 2 error corresponds to the fact that a dangerous situation is hidden by external well-being [21–23]. In the case of type 1 error, excessive reinsurance associated with a false alarm is not as dangerous, although it involves unreasonable costs, as type 2 error. Model calculations (Fig. 3) revealed such areas. Analysis of all combinations of impacts and environmental quality requirements possible in practice will make it possible to determine the areas of such errors. In its turn, this will allow reallocating environmental safety expenditures throughout the year in order to minimize costs. In other words, harmonization of environmental and economic requirements for the safe development of shelf resources is achieved.

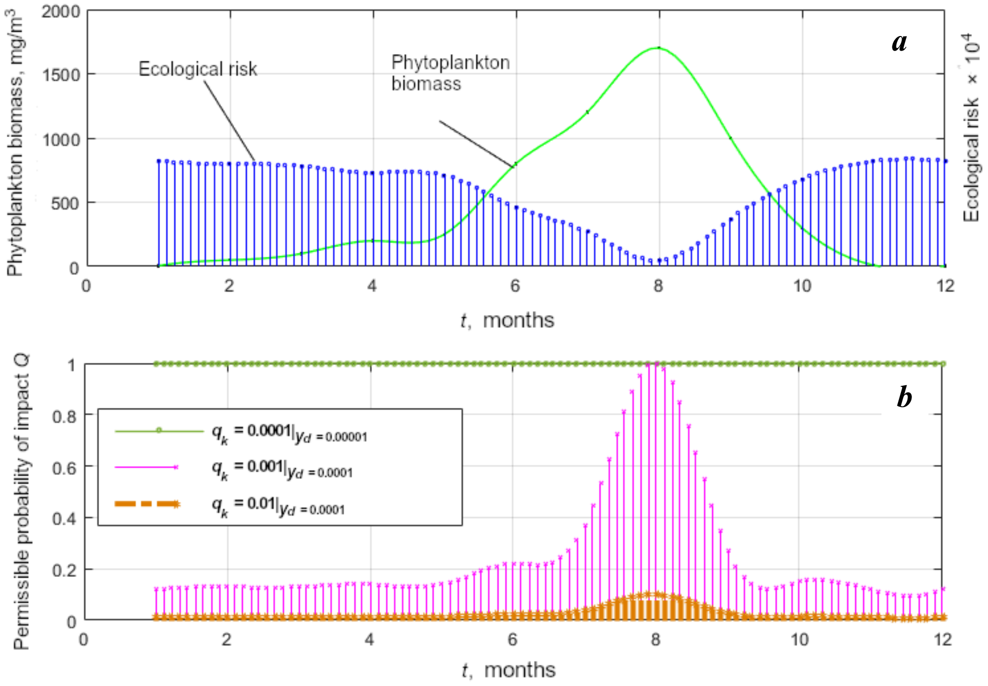


Fig. 2. Generalized annual course of phytoplankton biomass in low-productive ecosystems of the Arctic according to observations [11–20] and model intra-annual variations of ecological risk values (*a*) and the annual course of the permissible probability of impacts $Q(t)$ from stressors in the range of values $q_k = 10^{-5}–10^{-2}$; $y_d = 10^{-4}–10^{-3}$ (*b*)

Increasing the accuracy of ecological risk assessments requires the use of large volumes of data on processes of different nature: physical, chemical, biological, geological, technogenic. In our case, part of the data used on the components of ecosystems, on stressors of technogenic and natural origin relates to parameters that undergo quick changes in the water layer. This part of the data satisfies the *3V* requirements characteristic of *BigData* [31], which will make it possible to link the proposed risk assessment approach with *BigData* technologies in the future. The synthesis of *BigData* modelling and technologies is stipulated by the need to analyze quickly all possible combinations of stressors of different nature with a large number of parameters and to impose impacts on the spatiotemporal natural dynamics of the ecosystem in real time [31]. In this sense, remote sensing data is of great importance, providing information on the oceanological parameters of the marine environment, including hydrobiological ones, in particular the concentration of chlorophyll a [25, 26].

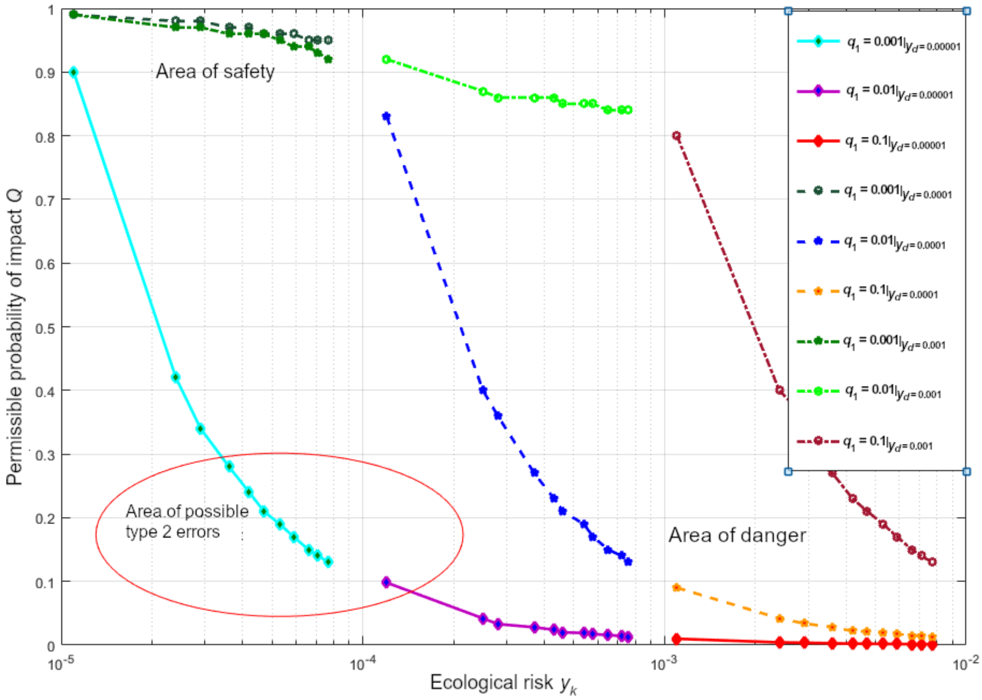


Fig. 3. Calculation of the dependence of the permissible probability of impact on the ecosystem on the environmental risk $Q(y_k)$ at values $q_k = 10^{-5}$–10^{-1} and $y_d = 10^{-5}$–10^{-3}

Conclusions

In this work, the influence of seasonal dynamics of ecosystem components on ecological risk intra-annual variations is confirmed by model calculations. The results obtained are one of the stages in creating a quantitative method for calculating risk, taking into account not only the parameters of stressors, but also intra-annual variations in the state of the ecosystem under natural operating conditions. An important result of the research was the calculation of the dependence of the permissible probability of impact on the ecosystem on ecological risk $Q(y_k)$, which made it possible to identify the areas of type 1 and 2 errors.

Improvement of the assessment of ecological risk requires expanding data on stressors of technogenic origin. The influence of various modes of technological processes, degree, frequency, and time of impacts of technical systems and human economic activities in the shelf waters must be taken into account in the dynamics of both technogenic processes and the ecosystem itself. Expanding the range and content of risk model input data will make it possible to bring the proposed method closer to *BigData* technologies.

Preliminary calculations of intra-annual risk variations presented in this paper, performed in accordance with the proposed methods in order to identify dangerous situations, showed the efficiency of the approach and the possibility of extending the calculations to marine ecosystems of various water areas.

REFERENCES

1. Fath, B.D., Asmus, H., Asmus, R., Baird, D., Borrett, S.R., de Jonge, V.N., Ludovisi, A., Niquil, N., Scharler, U.M. [et al.], 2019. Ecological Network Analysis Metrics: The Need for an Entire Ecosystem Approach in Management and Policy. *Ocean and Coastal Management,* 174, pp. 1–14. doi:10.1016/j.ocecoaman.2019.03.007
2. Elliott, M., Borja, A. and Cormier, R., 2020. Activity-Footprints, Pressures-Footprints and Effects-Footprints – Walking the Pathway to Determining and Managing Human Impacts in the Sea. *Marine Pollution Bulletin*, 155, 111201. doi:10.1016/j.marpolbul.2020.111201
3. Elliott, M., Cutts, N.D. and Trono, A., 2014. A Typology of Marine and Estuarine Hazards and Risks as Vectors of Change: A Review for Vulnerable Coasts and their Management. *Ocean and Coastal Management*, 93, pp. 88–99. doi:10.1016/j.ocecoaman.2014.03.014
4. Chen, S., Chen, B. and Fath, B.D., 2013. Ecological Risk Assessment on the System Scale: A Review of State-of-the-Art Models Future Perspectives. *Ecological Modelling*, 250, pp. 25–33. doi:10.1016/j.ecolmodel.2012.10.015
5. Solovjova, N.V., 2019. Ecological Risk Modelling in Developing Resources of Ecosystems Characterized by Varying Vulnerability Levels. *Ecological Modelling*, 406, pp. 60–72. doi:10.1016/j.ecolmodel.2019.05.015
6. Solovjova, N.V., 2020. Risk Assessment Simulation for Shelf Ecosystems Based on the Ecoscreening and Dynamic Methods Synthesis. *Estuarine, Coastal and Shelf Science,* 243, 106881. doi:10.1016/j.ecss.2020.106881
7. Solovjova, N.V., 2021. Ecological Risk Simulation Assessment in Marine Ecosystems of the Arctic shelf. *Marine Pollution Bulletin*, 169, 112577. doi:10.1016/j.marpolbul.2021.112577
8. Sajid, Z., Khan, F. and Veitch, B., 2020. Dynamic Ecological Risk Modeling of Hydrocarbon Release Scenarios in Arctic Waters. *Marine Pollution Bulletin*, 153, 111001. doi:10.1016/j.marpolbul.2020.111001
9. Arzaghi, E., Abbassi, R., Garaniya, V., Binns, J. and Khan, F., 2018. An Ecological Risk Assessment Model for Arctic Oil Spills from a Subsea Pipeline. *Marine Pollution Bulletin*, 135, pp. 1117–1127. doi:10.1016/j.marpolbul.2018.08.030
10. Fahd, F., Veitch, B. and Khan, F., 2019. Arctic Marine Fish 'Biotransformation Toxicity' Model for Ecological Risk Assessment. *Marine Pollution Bulletin*, 142, pp. 408–418. doi:10.1016/j.marpolbul.2019.03.039
11. Silkin, V., Pautova, L., Giordano, M., Kravchishina, M. and Artemiev, V., 2020. Interannual Variability of *Emiliania huxleyi* Blooms in the Barents Sea: *In Situ* Data 2014–2018. *Marine Pollution Bulletin*, 158, 111392. doi:10.1016/j.marpolbul.2020.111392
12. Flint, M.V., Poyarkov, S.G., Rimsky-Korsakov, N.A., 2016. Ecosystems of the Russian Arctic-2015 (63rd Cruise of the Research Vessel Akademik Mstislav Keldysh"). *Oceanology*, 56, pp. 459–461. doi:10.1134/S0001437016030061
13. Flint, M.V., Poyarkov, S.G. and Rymsky-Korsakov, N.A., 2018. Ecosystems of the Siberian Arctic Seas-2017 (Cruise 69 of the R/V *Akademik Mstislav Keldysh*). *Oceanology*, 58, pp. 315–318. doi:10.1134/S0001437018020042
14. Sukhanova, I.N., Flint, M.V., Druzhkova, E.I., Sazhin, A.F. and Sergeeva, V.M., 2015. Phytoplankton in the Northwestern Kara Sea. *Oceanology*, 55, pp. 547–560. https://doi.org/10.1134/S0001437015040141
15. Sukhanova, I.N., Flint, M.V., Pautova, L.A., Stockwell, D.A., Grebmeier, J.M. and Sergeeva, V.M., 2009. Phytoplankton of the Western Arctic in the Spring and Summer of 2002: Structure and Seasonal Changes. *Deep Sea Research Part II: Topical Studies in Oceanography*, 56(17), pp. 1223–1236. doi:10.1016/j.dsr2.2008.12.030
16. Matishov, G.G., Dzhenyuk, S.L. and Moiseev, D.V., 2017. Climate and Large Marine Ecosystems of the Arctic. *Herald of the Russian Academy of Sciences*, 87, pp. 30–39. doi:10.1134/S1019331617010087

17. Makarevich, P.R. and Oleinik, A.A., 2009. Structure of the Annual Cycle of Phytoplankton Community Evolution in the Ob-Yenisei shoal of the Kara Sea. *Doklady Earth Sciences*, 426, pp. 669–671. doi:10.1134/S1028334X09040357
18. Mosharov, S.A., Demidov, A.B. and Simakova, U.V., 2016. Peculiarities of the Primary Production Process in the Kara Sea at the End of the Vegetation Season. *Oceanology*, 56, pp. 84–94. https://doi.org/10.1134/S0001437016010100
19. Demidov, A.B., Kopelevich, O.V., Mosharov, S.A., Sheberstov, S.V. and Vazyulya, S.V., 2017. Modelling Kara Sea Phytoplankton Primary Production: Development and Skill Assessment of Regional Algorithms. *Journal of Sea Research*, 125, pp. 1–17. doi:10.1016/j.seares.2017.05.004
20. Demidov, A.B., Mosharov, S.A. and Makkaveev, P.N., 2014. Patterns of the Kara Sea Primary Production in Autumn: Biotic and Abiotic Forcing of Subsurface Layer. *Journal of Marine Systems*, 132, pp. 130–149. doi:10.1016/j.jmarsys.2014.01.014
21. Fleishman, B.S., 2008. *Fundamentals of Systemology*. New York: Lulu, 184 p.
22. Fleishman, B.S., 1984. Contribution to the Theory of Adaptation with Application to Ecology. *Ecological Modelling*, 26(1–2), pp. 21–31. doi:10.1016/0304-3800(84)90090-5
23. Fleishman, B.S., 1991. Hyperbolic Law of Reliability and its Logarithmic Effects in Ecology. *Ecological Modelling*, 55(1–2), pp. 75–88. doi:10.1016/0304-3800(91)90066-A
24. Patin, S.A., 2017. *Oil and Continental Shelf Ecology. Vol. 1: Offshore Oil and Gas Industry: Actual Situation, Prospects, Factors of Impact*. Moscow: VNIRO Publishing, 326 p. (in Russian).
25. Belyaev, V.I., 1987. [*Marine System Modelling*]. Kiev: Naukova Dumka, 201 p. (in Russian).
26. Belyaev, V.I. and Konduforova, N.V., 1990. [*Mathematical Modelling of Shelf Ecological Systems*]. Kiev: Naukova Dumka, 240 p. (in Russian).
27. Flint, M.V., 2015. [Bioresources of the Russian Arctic Seas: Changes Influenced by Climate and Anthropogenic Factors, Ecosystem Basis of Protection]. In: N. P. Laverov, V. I. Vasiliev and A. A. Makosko, eds., 2015. [*Scientific and Technical Issues of Arctic Exploration*]. Moscow: Nauka, pp. 55–71 (in Russian).
28. Druzhkova, E.I. and Makarevich, P.R., 2008. Annual Cycle of nanophytoplankton in Coastal Waters of the Barents Sea. *Biology Bulletin*, 35(4), pp. 428–435. doi:10.1134/S106235900804016X
29. Ilyash, L.V., Ratkova, T.N., Radchenko, I.G. and Zhitina, L.S., 2012. [Phytoplankton of the White Sea]. In: A. P. Lisitsin, ed., 2012. [*System of the White Sea. Vol. 2. Water Column and Atmosphere, Cryoshpere, River Runoff, and Biosphere Interacting with it*]. Moscow: Nauchny Mir, 605–639 (in Russian).
30. Makarevich, P.R. and Larionov, V.V., 2011. Annual Cycle of the Planktonic Phytocenosis in the Ob-Enisei Shallow Zone of the Kara Sea. *Russian Journal of Marine Biology*, 37(1), pp. 3–8. doi:10.1134/S1063074011010093
31. Gvishiani, A.D., Lobkovsky, L.I. and Solovjova, N.V., 2022. Prospects for Synthesizing Ecological Risk Models and Big Data Technologies for Marine Ecosystems. *Fizika Zemli*, (4), pp. 101–112. doi:10.31857/S0002333722040044 (in Russian).

Submitted 29.05.2023; accepted after review 07.06.2023;
revised 28.06.2023; published 25.09.2023

About the author:

Natalia V. Solovjova, Chief Research Associate, P.P. Shirshov Institute of Oceanology, RAS (36 Nakhimovskiy Ave., Moscow, Russia, 117997), Dr.Sci. (Phys.-Math.), **ORCID ID: 0000-0002-4268-7790, ResearcherID: AAZ-2398-2020, Scopus Author ID: 6507375823**, *soloceanic@yandex.ru*

The author has read and approved the final manuscript.