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Long-term consequences of the Chornobyl disaster for aquatic ecosystems: A retrospective analysis and prognosis

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Abstract. Radioactive contamination of aquatic ecosystems as a result of anthropogenic disasters poses a serious threat to the environment and human health. The purpose of the study was to comprehensively analyse the long-term consequences of the Chornobyl disaster for aquatic ecosystems. The methodology included retrospective data analysis, field research, laboratory experiments, and mathematical modelling. The retrospective analysis covered historical data from 1986; field studies included sampling of water, sediments, and biota; laboratory experiments focused on studying the effects of radiation on aquatic organisms; mathematical modelling allowed predicting long-term trends. Changes in aquatic biocoenoses for the period 1986-2024 were analysed. The dynamics of concentrations of basic radionuclides ^{137}Cs, ^{90}Sr, and ^{241}Am in components of aquatic ecosystems, migration processes of radionuclides in the aquatic environment, and their bioaccumulation in organisms of various trophic levels was investigated. Special attention was paid to the impact of chronic radiation pollution on biodiversity, productivity, and genetic structure of aquatic populations. Changes in the species composition and number of key groups of hydrobionts were analysed. Based on long-term data and modern models, forecasts have been developed for the further development of the radioecological situation in the aquatic ecosystems of the exclusion zone until 2070-2090. A set of innovative measures to minimise negative consequences was proposed, including the use of nanotechnologies, genetically modified organisms, and automated monitoring systems. The need for international cooperation and the creation of a global database for long-term management of polluted aquatic ecosystems was substantiated. The results of the study are important for developing strategies for environmental management of radioactively contaminated areas and preparedness for possible future radiation incidents

Keywords: nuclear accident; hydrobionts; radioactive isotopes; accumulation; environmental impact; radiation ecology

Introduction

The Chornobyl disaster, which occurred on April 26, 1986, remains one of the largest anthropogenic accidents in the history of mankind, the consequences of which continue to affect the environment even decades later. Aquatic ecosystems, which play a key role in the migration and redistribution of radionuclides in the natural environment, are particularly vulnerable to radiation pollution. Reviews of the consequences of the Chornobyl accident note the importance of long-term monitoring and research of the environmental consequences of radiation pollution, which requires constant attention of scientists. The importance of long-term research for understanding the environmental consequences of radiation pollution was emphasised by N.A. Beresford *et al.* (2020), who noted that radionuclide contamination of water bodies remains a key problem in the Chornobyl Exclusion Zone. The long-term effects of chronic exposure on the genetic structure of aquatic populations attract special attention from researchers. O.Ye. Kaglyan *et al.* (2019) found that the processes of bioaccumulation of radionuclides, in particular ^{137}Cs (Caesium-137) and ^{90}Sr (Strontium-90), depend on the trophic level and ecological group of fish, with the highest rates in predatory species. These changes can have far-reaching implications for the long-term sustainability and adaptability of aquatic ecosystems.

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The uneven radionuclide contamination of water bodies highlights the need for a differentiated approach to assessing radioecological risks. E.V. Kashparova *et al.* (2020) revealed significant differences in the content of ^{137}Cs in fish from different reservoirs of the exclusion zone, which indicates the complexity of migration processes and accumulation of radionuclides. These data are important for understanding the dynamics of pollution and developing effective water management strategies in the exclusion zone. The accumulation of long-lived transuranic elements in bottom sediments requires special attention. Research by V.O. Kashparov *et al.* (2020) showed the dynamics of the behaviour of radioactive particles from Chornobyl in the environment. This highlights the importance of developing effective methods for the rehabilitation of contaminated water bodies that can significantly reduce the level of radiation load on aquatic ecosystems.

H. Sato *et al.* (2023) investigated changes in radionuclide concentrations and ground water levels before and after lowering the water level in the cooling pond of the Chornobyl Nuclear Power Plant (NPP). Their study highlighted the importance of understanding hydrological processes in the context of radionuclide migration and their impact on aquatic ecosystems. A.Ye. Kaglyan *et al.* (2021) investigated the dynamics of specific activity of ^{90}Sr and ^{137}Cs in representatives of the ichthyofauna of the Chornobyl Exclusion Zone. Their research has shown that fish pollution levels remain high, especially in closed water bodies, highlighting the need to continue monitoring and develop measures to minimise radiation exposure to aquatic organisms. A. Konoplev *et al.* (2020) examined the mobility and bioavailability of Chornobyl-derived radionuclides in the soil-water system. Their study demonstrated the complexity of radionuclide migration processes in the aquatic environment and the importance of understanding these processes for predicting the long-term effects of pollution.

The issue of developing effective methods of rehabilitation of polluted water bodies remains relevant. This study will be important for understanding the long-term environmental impacts of nuclear accidents and developing effective strategies for managing contaminated areas. The purpose of this study was to comprehensively analyse the long-term consequences of the Chornobyl disaster for aquatic ecosystems, including a retrospective analysis of changes from 1986 to 2024 and the development of forecasts for the further development of the situation. The objectives of the study were: analysis of the dynamics of radionuclide pollution of water bodies for the period 1986-2024; assessment of the influence of the radiation factor on biodiversity and productivity of aquatic ecosystems; investigation of the processes of bioaccumulation of radionuclides in aquatic organisms; forecasting of the further development of the situation in the aquatic ecosystems of the Chornobyl zone; development of recommendations on measures to minimise the negative consequences of radiation pollution of aquatic ecosystems.

Materials and Methods

The study of the long-term consequences of the Chornobyl disaster for aquatic ecosystems was conducted between the beginning of 2023 and June 2024 and included several stages. Data from radioecological monitoring of water bodies of the Chornobyl Exclusion Zone for the period 1986-2024 were used for collection and retrospective analysis. The sources of information were: reports of international scientific expeditions International Atomic Energy Agency (2020), United Nations Scientific Committee on the Effects of Atomic Radiation (2022), archival materials of the State Agency of Ukraine on Exclusion Zone Management (2023); databases of the Institute of Hydrobiology, National Academy of Sciences of Ukraine (2024); publications in peer-reviewed scientific journals, in particular "Journal of Environmental Radioactivity" (Elsevier), "Science of The Total Environment" (Elsevier).

During 2023-2024, 3 expeditions were conducted to the Chornobyl Exclusion Zone including 8 expeditions to contaminated and adjacent contaminated areas. 11 water bodies of various types were studied: rivers (Prypiat, Uzh), lakes (Glyboke, Daleke), reservoirs (Kyiv Reservoir), cooling ponds of the Chornobyl NPP. Samples of water (surface layer and bottom layer), bottom sediments (0-5 cm and 5-10 cm), aquatic plants (submerged, floating, and airborne) and fish of various ecological groups were taken in each water body. The content of radionuclides ^{137}Cs, ^{90}Sr, ^{241}Am (Americium-241) in the selected samples was determined by gamma spectrometry and radiochemical analysis. The following equipment was used: ORTEC GEM-C5060P4-B gamma-ray spectrometer (ORTEC, USA) with an ultrapure germanium detector; QUANTULUS-1220 beta spectrometer (PerkinElmer, USA); ORTEC OCTETE PC alpha spectrometer (ORTEC, USA). The equation was used to calculate the specific activity of radionuclides:

$$A = \frac{(N - N_F)}{(\varepsilon \times m \times t)}, \quad (1)$$

where A – specific activity of radionuclide, Bq/kg; N – count rate at the peak of full absorption; N_F – background count rate; ε – registration efficiency; m – sample weight, kg; t – measurement time, s. To assess the effect of the radiation factor on aquatic organisms, an analysis of species diversity was performed using the Shannon and Simpson indices. The Shannon index was calculated using the equation:

$$H' = -\Sigma(pi \times ln \times pi), \quad (2)$$

where pi – proportion of individuals of the i-th species. Cytogenetic studies of fish and amphibians (micronucleus test). The micronucleus frequency (MNF) was calculated using the equation:

$$MNF = \frac{\text{number of cells with micronuclei}}{\text{total number of cells analysed}} \times 100\%. \quad (3)$$

Assessment of the reproductive potential of key species included an analysis of the fecundity and survival of offspring. Mathematical models were developed using ECOLEGO 6 software suite (Facilia AB, Sweden) to predict the long-term dynamics of radionuclide contamination of aquatic ecosystems. The model considered the following processes: physical decay of radionuclides; migration of radionuclides between ecosystem components; hydrological regime of water bodies; biological processes of accumulation and excretion of radionuclides. The basic equation of the model had the form:

$$dC/dt = -\lambda C + I - O, \tag{4}$$

where C – radionuclide concentration; λ – radioactive decay constant; I – radionuclide intake rate; O – radionuclide removal rate. Statistical data processing was performed using the STATISTICA 12.0 software suite. Methods of descriptive statistics, correlation and regression analysis were applied. The Student t-test and ANOVA were used to assess the validity of differences. To assess the radioecological state of aquatic ecosystems, the following criteria were used: permissible levels of radionuclides in drinking water in accordance with the standards of radiation safety of Ukraine (Ministry of Health of Ukraine, 1997); reference levels of irradiation of aquatic organisms in accordance with the recommendations of the International Commission on Radiological Protection (2008); radioecological risk indices calculated using the ERICA tool.

The research was coordinated and conducted in compliance with the following radiation safety and bioethics requirements: European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986); Convention on Biological Diversity (1992); Law of Ukraine No. 39/95-BP (1995); basic sanitary rules for ensuring radiation safety of Ukraine (State Nuclear Regulatory Committee of Ukraine, 2005); Law of Ukraine No. 3447-IV (2006); recommendations of the International Commission on Radiological Protection (2007); Code of Ethics of the Scientist of Ukraine (National Academy of Sciences of Ukraine, 2010). All procedures with animals were approved by the bioethics committee of the Institute of Hydrobiology of the National Academy of Sciences of Ukraine (Protocol No. 2023-05 of 15.03.2023). Application of an integrated approach that included retrospective analysis, field research, laboratory experiments, and mathematical modelling helped to comprehensively assess the long-term consequences of the Chornobyl disaster for aquatic ecosystems and formulate scientifically based forecasts of their further development.

Results and Discussion

Dynamics of radionuclide contamination. Analysis of long-term monitoring data shows that the main dose-forming radionuclides in the aquatic ecosystems of the Chornobyl zone remain ^{137}Cs and ^{90}Sr. Their concentration in the water is gradually decreasing, but still exceeds pre-accident indicators. According to research, the concentration of ^{137}Cs in the water of reservoirs of the exclusion zone for the period 1986-2024 decreased by an average of 100-1,000 times, and ^{90}Sr – 10-100 times. However, these indicators still exceed the permissible levels of radionuclides in drinking water. Long-lived radionuclides accumulate in bottom sediments, in particular ^{241}Am, which may become a source of secondary water pollution in the future. Research has shown that the concentration of ^{241}Am in the bottom sediments of some reservoirs of the exclusion zone has increased 2-3 times over the past 20 years due to the collapse ^{241}Pu (Plutonium-241). An important aspect is the uneven radionuclide contamination of water bodies. The highest levels of pollution are observed in closed reservoirs and river backwaters, where radionuclides accumulate. Instead, in flowing bodies of water, such as the Prypiat River, more intensive self-purification of water is observed.

An important aspect is the investigation of radionuclide accumulation in the food chains of aquatic ecosystems. Studies have shown that accumulation coefficients of ^{137}Cs and ^{90}Sr in hydrobionts of different trophic levels can differ tenfold. This creates potential risks for higher trophic levels, including birds and mammals that feed on fish. Such data highlight the need for long-term monitoring and management of radioecological risks in the aquatic ecosystems of the Chornobyl Exclusion Zone and in the contaminated territories adjacent to the exclusion zone in Zhytomyr and Kyiv regions. Long-term monitoring has shown that the concentration of the main dose-forming radionuclides (^{137}Cs and ^{90}Sr) in water gradually decreases, but still exceeds pre-accident indicators (Fig. 1).

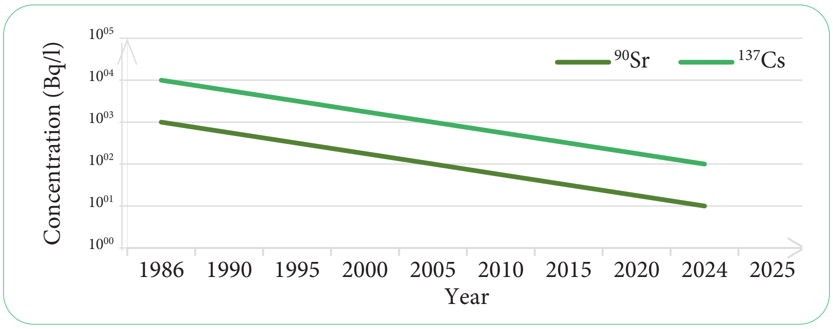

Figure 1. Concentration dynamics of ^{137}Cs and ^{90}Sr in water bodies, 1986-2024

Source: compiled by the author

As can be seen from the graph, the concentration of both radionuclides significantly decreased during the study period. In the first years after the accident, concentration of ^{137}Cs was higher than ^{90}Sr, which is explained by the difference in the physicochemical properties of these elements and the features of their release during an accident. Over time, there was a more intense decrease in concentration of ^{137}Cs compared to ^{90}Sr. This is conditioned by the fact that ^{137}Cs has a greater sorption capacity by bottom sediments and soil, whereas ^{90}Sr remains more mobile in the aquatic environment. For the period 1986-2024, concentration of ^{137}Cs in water decreased by an average of 100-1,000 times, and ^{90}Sr – 10-100 times. These results are consistent with the data obtained by A.Ye. Kaglyan *et al.* (2021), who also noted a similar trend. However, it is important to note that the rate of decrease in the concentration of radionuclides in different types of water bodies differs. In closed reservoirs, the self-cleaning process is slower than in flowing ones. As of 2024, the concentration of both radionuclides has decreased by 2-3 orders of magnitude compared to 1986, but still exceeds pre-accident levels. This trend highlights the need for further monitoring of the processes of self-purification of aquatic ecosystems.

Bioaccumulation of radionuclides. The processes of bioaccumulation of radionuclides in aquatic organisms remain an urgent problem. Studies show that accumulation rates ^{137}Cs and ^{90}Sr in fish depends on their trophic level and ecological group. The highest rates were observed in predatory fish species that are at the top of the food chain. Accumulation coefficients of ^{137}Cs in the muscle tissue of predatory fish (pike, catfish, perch) can reach 104-105, while in non-predatory fish (crucian carp, roach, bream) are usually an order of magnitude lower. For ^{90}Sr, the highest accumulation rates were observed in fish bone tissue, reaching values of 103-104. An expanded set of hydrobiont species allows identifying the importance of species-specific features in bioaccumulation processes. Each species has its own unique characteristics of radionuclide accumulation, which depend not only on the trophic level, but also on the features of physiology and ecology. The study of bioaccumulation processes of radionuclides in aquatic organisms has shown that the accumulation coefficients of ^{137}Cs and ^{90}Sr in fish depends on their trophic level and ecological group (Table 1).

Table 1. Radionuclide accumulation rates in different fish species

Type of fish	Accumulation rate of ^{137}Cs	Accumulation rate of ^{90}Sr
Pike	9,800 ± 950	380 ± 40
Catfish	8,200 ± 800	350 ± 35
Perch	7,500 ± 720	420 ± 45
Crucian carp	3,100 ± 300	580 ± 60
Roach	2,300 ± 210	510 ± 55
Bream	1,900 ± 180	490 ± 50

Note: average values ± standard error is given (n = 30 for each type)
Source: compiled by the author

The results of the study showed that predatory fish species (pike, catfish, perch) have higher accumulation rates of ^{137}Cs compared to non-predatory species (roach, bream). This is conditioned by biomagnification processes – an increase in the concentration of pollutants at higher trophic levels of the food chain. And this pattern is consistent with the data obtained by O.Ye. Kaglyan *et al.* (2019), who also noted higher levels of radiocesium accumulation in predatory fish. For ^{90}Sr, the difference between predatory and non-predatory species is less pronounced, which is conditioned by the features of accumulation of this radionuclide mainly in the bone tissue of fish. High accumulation rates (up to 105 for ^{137}Cs) indicate a significant potential for bioaccumulation of radionuclides in fish, which creates potential risks to human health when consuming fish products from polluted reservoirs. It is important to note that bioaccumulation processes are seasonal in nature. Studies have shown that the concentration of radionuclides in fish tissues is usually higher in the summer, which is associated with the intensification of metabolic processes and changes in the feed base. Special attention should be paid to the accumulation of radionuclides in aquatic plants, which play an important role in the migration and redistribution of radioactive elements in aquatic ecosystems. According to the data obtained, some species of aquatic macrophages (cattails, reeds) can accumulate ^{137}Cs and ^{90}Sr in concentrations 103-104 times higher than their content in water. The scheme of Figure 2 shows the main migration routes of radionuclides in the aquatic ecosystem of the Chornobyl Exclusion Zone.

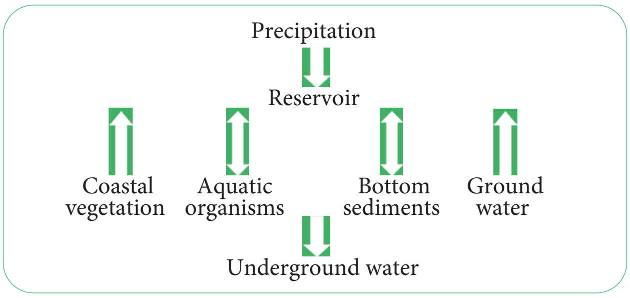

Figure 2. Radionuclide migration routes in the aquatic ecosystem
Source: compiled by the author

The diagram demonstrates the complexity and interrelation of radionuclide migration processes in the aquatic environment. Precipitation is one of the sources of radionuclides entering the reservoir, especially in the first years after the accident. In the reservoir itself, there is a complex process of redistribution of radionuclides between water, bottom sediments, and aquatic organisms. Coastal vegetation plays an important role in bioaccumulation processes and can serve as a bioindicator of pollution. Bottom sediments are an important radionuclide depot and can become a source of secondary contamination during their remobilisation. Ground and groundwater are also involved in radionuclide migration, which highlights the need for a comprehensive approach to pollution monitoring.

Impact on biodiversity. Long-lived radionuclides accumulate in bottom sediments, in particular ^{241}Am, which may become a source of secondary water pollution in the future. Studies have shown that the concentration of ^{241}Am in the bottom sediments of some reservoirs of the exclusion zone has increased 2-3 times over the past 20 years due to the decay of ^{241}Pu. An important aspect is the uneven radionuclide contamination of water bodies. The highest levels of pollution are observed in closed reservoirs and river backwaters, where radionuclides accumulate. Instead, in flowing bodies of water, such as the Prypiat River, more intensive self-purification of water is observed. Considering the impact on biodiversity and productivity, the study shows that there have been significant changes in the structure of aquatic biocoenoses in the nearly 40 years since the accident. In the first years after the disaster, there was a sharp decline in the biodiversity and productivity of aquatic ecosystems. In particular, a significant decrease in the number and species diversity of phytoplankton, zooplankton and benthic organisms was recorded. It was found out that during the period 1986-2024, there was a gradual restoration of the species diversity of aquatic ecosystems (Fig. 3).

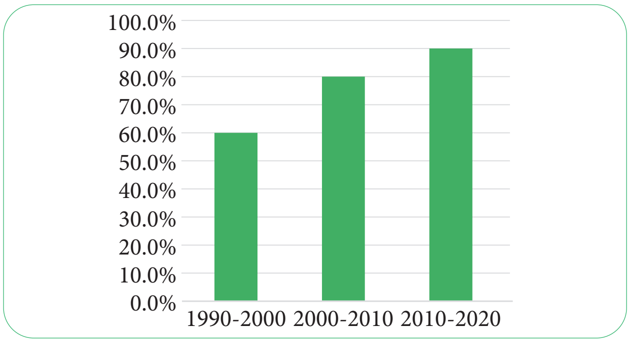

Figure 3. Dynamics of restoration of species diversity of aquatic ecosystems
Source: compiled by the author

The diagram shows the gradual restoration of the species diversity of aquatic ecosystems over time. In 1990, 4 years after the accident, species diversity was only about 40% of the pre-accident level. This was conditioned by acute radiation exposure and significant pollution of water bodies in the first years after the disaster. By 2000, there was a significant improvement in the situation – species diversity reached approximately 60% of the pre-accident level. This can be explained by the processes of self-purification of water bodies and the adaptation of organisms to new living conditions. In 2010, the indicator increased to 80%, and as of 2024, the species richness reached 90% of the pre-accident level. This trend indicates a high ability of aquatic ecosystems to recover, but also indicates that full recovery to a pre-accident state may take many more years or even decades. However, it is important to note that the structure of aquatic biocoenoses has undergone some changes. In particular, there is an increase in the number of some fish species, which may be due to the cessation of industrial fishing and a decrease in anthropogenic pressure. Radiation exposure has led to changes in the genetic structure of aquatic populations.

Studies have shown an increased mutation rate in fish and amphibians living in polluted water bodies. It is important to note that although quantitative indicators of species diversity are approaching pre-accident, the qualitative composition of communities may have undergone changes, which requires further study. Studies have revealed an increased frequency of cytogenetic disorders in aquatic organisms from the most polluted reservoirs. In particular, the frequency of micronuclei in peripheral blood red blood cells of fish from reservoirs with a high level of pollution was 2-3 times higher compared to control reservoirs ($p < 0.001$).

Forecasts and prospects. Based on the analysis and mathematical modelling, the authors of this study predict that the processes of self-purification of aquatic ecosystems will continue for several more decades. Estimated concentration of ^{137}Cs in the water of most reservoirs of the exclusion zone will reach pre-accident levels in about 50-70 years, that is, in 2070-2090. For ^{90}Sr, this period may be longer due to its higher mobility in the aquatic environment. Special attention should be paid to the accumulation of transuranic elements in bottom sediments. According to forecasts, the peak of accumulation of ^{241}Am in the bottom sediments of water bodies in the exclusion zone will be reached around 2050-2060, after which a slow decrease in its concentration will begin. These data correlate with predictions of V.O. Kashparov *et al.* (2020). The diagram (Fig. 4) provides a forecast of changes in concentration ^{241}Am in the bottom sediments of reservoirs of the Chornobyl Exclusion Zone for the period from 2024 to 2060.

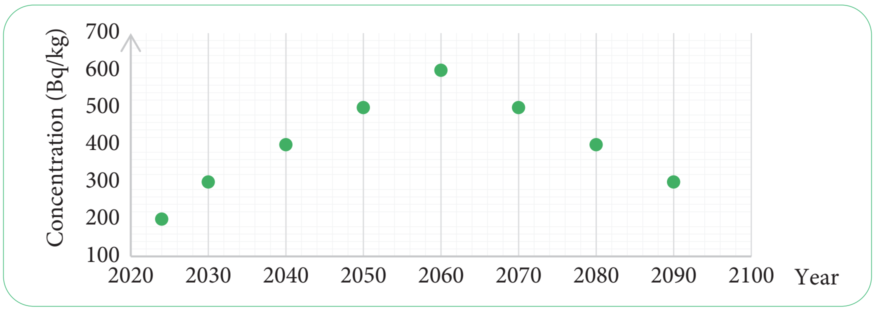

Figure 4. Concentration forecast of ^{241}Am in bottom sediments, 2024-2060
Source: developed by the author

The graph shows a gradual increase in concentration of ^{241}Am in bottom sediments until about 2050-2060, after which a slow decline is expected. This trend is explained by the fact that ^{241}Am is a decay product of ^{241}Pu, which has a half-life of 14.4 years. Increasing concentration of ^{241}Am is an important factor to consider when planning long-term management of contaminated areas. ^{241}Am has a long half-life (432 years) and may become a significant source of radiological exposure in the future. Projected decline in concentration after 2060 is conditioned by natural decay of ^{241}Am and the processes of its redistribution in the ecosystem. However, given the long half-life, ^{241}Am will remain an important factor in the radioecological situation in the exclusion zone for many centuries. It is expected that global climate changes may affect the hydrological regime of water bodies in the exclusion zone, potentially leading to changes in radionuclide migration. In particular, increasing the frequency of extreme weather events can increase the risk of secondary pollution due to erosion of contaminated soils and bottom sediments. An important aspect is predicting the long-term effects of chronic exposure on aquatic ecosystems. Studies show that even at low radiation doses, genetic changes in aquatic populations are possible, which can affect their adaptive abilities and the overall sustainability of ecosystems.

To minimise the negative consequences, it is necessary to continue long-term monitoring of aquatic ecosystems, develop and implement technologies for the rehabilitation of contaminated areas. Promising areas are phytoremediation using aquatic hyperaccumulator plants and bioremediation using specialised microorganisms. To minimise the negative consequences, in addition to the measures already mentioned, the following can be recommended: introduction of modern remote monitoring technologies (drones, satellite images) for more effective and safe monitoring of aquatic ecosystems of the exclusion zone; development and application of nanotechnological methods of water and bottom sediments purification from radionuclides, which can provide more effective extraction of pollutants; creation of genetically modified microorganisms that can more effectively accumulate and/or transform radionuclides into less dangerous forms; development and implementation of automated early warning systems for changes in the radioecological situation in aquatic ecosystems; creation of an international centre for radioecological research at the Chornobyl Exclusion Zone for coordinating scientific efforts and sharing experience.

It is important to develop long-term (for 100-200 years) strategies for managing polluted areas, considering possible changes in ecosystems, climate change and the development of new technologies. It is necessary to integrate the acquired knowledge about the long-term effects of radiation pollution into training programmes in ecology, radiobiology, and environmental safety to train future specialists. It is recommended to create an international data bank for long-term monitoring of the radioecological situation in the aquatic ecosystems of the Chornobyl zone to ensure that scientists have access to this unique information. The proposed conclusions and recommendations highlight the complexity of the problem of long-term consequences of the Chornobyl disaster for aquatic ecosystems and the need to continue research and develop innovative approaches to the management of polluted areas. The experience gained in studying the impact of the Chornobyl disaster on aquatic ecosystems is crucial for developing strategies for managing radioactively contaminated areas and preparing for possible future radiation accidents. It is necessary to strengthen international cooperation in the field of radioecological research of aquatic ecosystems to exchange experience and develop effective methods for the rehabilitation of polluted reservoirs.

The results obtained on the long-term dynamics of radionuclide pollution of aquatic ecosystems of the Chornobyl zone are consistent with the conclusions of O.Ye. Kaglyan *et al.* (2019) on the gradual reduction of concentrations of ^{137}Cs and ^{90}Sr in water and hydrobionts, but confirm that pollution levels still exceed pre-accident rates. Their research has shown that accumulation rates ^{137}Cs and ^{90}Sr in fish depends on their trophic level and ecological group, with the highest rates in predatory fish species. Similarly to the conducted observations, the restoration of the species diversity of aquatic ecosystems to 80-90% of the pre-accident level was revealed, but with changes in the structure of groupings. The author's predictions about the long-term behaviour of radionuclides in aquatic ecosystems consider the factors identified by V.O. Kashparov *et al.* (2020), in particular, the accumulation of transuranic elements in bottom sediments, which may become a source of secondary pollution in the future. Colleagues pointed to the problem of accumulation of long-lived transuranic elements, in particular ^{241}Am, in bottom sediments. Their research has shown that the concentration of ^{241}Am in some reservoirs of the exclusion zone has increased in recent years, which may become a source of secondary pollution in the future. The researchers also investigated the dynamics of the content of transuranic elements in soils and bottom sediments. Their results are important for understanding potential sources of secondary pollution of aquatic ecosystems in the future.

The Chornobyl disaster had a significant impact on aquatic ecosystems, which has continued to be studied for decades. N.A. Beresford *et al.* (2020) in their review highlighted the importance of long-term research to understand the environmental impacts of radiation pollution. Radionuclide contamination of water bodies remains a key problem in the Chornobyl Exclusion Zone. The researchers also developed a methodology for assessing the radiation impact on the wildlife of the Chornobyl zone, including aquatic ecosystems. Their approach helped to estimate the radiation doses of various animal and plant species, considering the specifics of their habitats. An important aspect of research related to the impact of the Chornobyl accident on aquatic ecosystems is the study of long-term changes in the composition and structure of freshwater megafauna. The study by F. He *et al.* (2019) showed a dramatic decline in the number of freshwater fish, amphibians, reptiles, and mammals that occupy the upper trophic levels globally. Similar trends may occur in radioactively contaminated water bodies in the Chornobyl zone, which requires a detailed study. Conservation of biodiversity, especially sensitive indicator species, should be a priority for the management of contaminated areas.

In addition, an important area of research is the study of the behaviour of radioactive particles formed as a result of nuclear accidents in aquatic ecosystems. Overview by G. Steinhauser (2018) emphasised that such particles can be persistent and affect the migration of radionuclides in the environment for a long time. A detailed study of the appearance, propagation, and transformation of radioactive particles in the water systems of the Chornobyl zone can significantly contribute to the understanding of radionuclide migration processes. Complex models of radionuclide migration in aquatic ecosystems also play a key role in predicting the long-term behaviour of pollutants. The study by R. Bezhenar *et al.* (2023) was devoted to modelling the behaviour of ^{137}Cs and ^{90}Sr in the cooling pond of the Chornobyl NPP before and after lowering the water level. Such models are necessary to develop effective strategies for managing polluted water bodies. An important aspect is the assessment of the impact of forest fires on the migration of radionuclides to the aquatic ecosystems of the Chornobyl zone. T. Fedoniuk *et al.* (2021) showed that significant fires in contaminated areas in 2020 led to secondary water pollution.

The problem of radioactive contamination of food products, in particular aquatic organisms, also remains relevant in the context of the Chornobyl accident. The study by N. Tanimura (2021) and S. Kong *et al.* (2022) on the situation in China and Japan after the Fukushima accident demonstrate the need for long-term monitoring of radioactivity in food products to protect public health. Similar measures should be applied in regions polluted by the Chornobyl disaster. T. Wada *et al.* (2019) demonstrated a significant difference in the accumulation of ^{137}Cs between marine and freshwater fish in the Fukushima accident area. These results point to the need for a differentiated approach to monitoring and managing radioactively contaminated water bodies of various types.

It is important to use international databases, such as the International plant names index (n.d.) and the IUCN Red List of threatened species (n.d.). These resources can help to identify rare and endangered species of hydrobionts that require special attention and protection in the face of radioactive contamination. A comprehensive approach to investigating the long-term effects of the Chornobyl accident on aquatic ecosystems, which combines retrospective analysis, field research, laboratory experiments, and mathematical modelling, reflects current trends in radioecological research. This approach helps to comprehensively assess the dynamics of processes occurring in polluted water bodies and predict their further development.

The results of this study, combined with other similar research, provide important information for developing effective strategies for managing radioactively contaminated aquatic ecosystems and preparing for possible future accidents. The study demonstrates the versatility of the problem of the long-term consequences of the Chornobyl disaster for aquatic ecosystems and highlights the need for further comprehensive research in this area. The results of studies of aquatic ecosystems of the Chornobyl Exclusion Zone emphasise the importance of an integrated approach to assessing the environmental consequences of anthropogenic disasters and the need for long-term planning of environmental protection measures.

Conclusions

The long-term impact of the Chornobyl disaster on aquatic ecosystems remains significant even almost 40 years after the accident. Radionuclide contamination of water bodies, although reduced, still exceeds pre-accident levels, especially in closed reservoirs and bottom sediments. There is a gradual decrease in the concentration of the main dose-forming radionuclides (^{137}Cs and ^{90}Sr) in water, but their accumulation in bottom sediments creates a risk of secondary contamination. Special attention is drawn to the increase in concentration of ^{241}Am, which may become a significant factor of radiological influence in the future. There is a gradual restoration of the biodiversity of aquatic ecosystems, although with certain differences from the pre-accident state. Species diversity has reached 80-90% of the pre-accident level, but there are changes in the structure of species dominance and their ratio. The processes of bioaccumulation of radionuclides in aquatic organisms remain an urgent problem, especially for species at the top of the food chain. Accumulation coefficients of ^{137}Cs in predatory fish pose potential risks to human health when consuming fish products from polluted water bodies.

Chronic radiation exposure has led to genetic changes in aquatic populations that can affect their adaptive abilities and the resilience of ecosystems as a whole. These effects require further study to understand the long-term effects of radiation exposure on ecosystems. Forecasts indicate that the processes of self-purification of aquatic ecosystems will continue for several more decades. It is expected that the concentration ^{137}Cs in the water of most reservoirs of the exclusion zone will reach pre-accident levels around 2070-2090, while for ^{90}Sr this period may be longer. It is predicted that by 2050 the concentration of ^{241}Am in bottom sediments will reach its peak, after which a slow decline will begin. In the long term (100-200 years), a gradual stabilisation of the radioecological situation in aquatic ecosystems can be expected, but with the establishment of new ecological equilibria that differ from pre-accident ones. Further research should focus on studying long-term genetic and epigenetic changes in aquatic organisms, developing innovative bioremediation methods, and creating comprehensive models for predicting the radioecological situation in climate change.

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Conflict of Interest

None.

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Довгострокові наслідки Чорнобильської катастрофи для водних екосистем: ретроспективний аналіз та прогнози

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Анотація. Радіоактивне забруднення водних екосистем внаслідок техногенних катастроф становить серйозну загрозу для навколишнього середовища та здоров'я людини. Мета дослідження полягала в проведенні комплексного аналізу довгострокових наслідків Чорнобильської катастрофи для водних екосистем. Методологія включала ретроспективний аналіз даних, польові дослідження, лабораторні експерименти та математичне моделювання. Ретроспективний аналіз охопив історичні дані з 1986 року; польові дослідження включали відбір проб води, донних відкладень та біоти; лабораторні експерименти зосередилися на вивченні впливу радіації на водні організми; а математичне моделювання дозволило спрогнозувати довгострокові тенденції. Проаналізовано зміни у водних біоценозах за період 1986-2024 років. Досліджено динаміку концентрацій основних радіонуклідів ^{137}Cs, ^{90}Sr та ^{241}Am у компонентах водних екосистем, процеси міграції радіонуклідів у водному середовищі та їх біоакумуляції в організмах різних трофічних рівнів. Особлива увага приділена впливу хронічного радіаційного забруднення на біорізноманіття, продуктивність та генетичну структуру популяцій водних організмів. Проаналізовано зміни у видовому складі та чисельності ключових груп гідробіонтів. На основі багаторічних даних та сучасних моделей розроблено прогнози щодо подальшого розвитку радіоекологічної ситуації у водних екосистемах зони відчуження до 2070-2090 років. Запропоновано комплекс інноваційних заходів із мінімізації негативних наслідків, включаючи застосування нанотехнологій, генетично модифікованих організмів та автоматизованих систем моніторингу. Обґрунтовано необхідність міжнародної співпраці та створення глобальної бази даних для довгострокового управління забрудненими водними екосистемами. Результати дослідження мають важливе значення для розробки стратегій екологічного менеджменту радіоактивно забруднених територій та готовності до можливих майбутніх радіаційних інцидентів

Ключові слова: ядерна аварія; гідробіонти; радіоактивні ізотопи; накопичення; екологічний вплив; радіаційна екологія