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Pollution of the atmosphere, soil and water resources as a result of the Russian-Ukrainian war

Mykola Matkivskyi*

PhD in Technical Sciences, Associate Professor
Vasyl Stefanyk Precarpathian National University
76018, 57 Shevchenko Str., Ivano-Frankivsk, Ukraine
https://orcid.org/0000-0001-5039-0260

Tetyana Taras

PhD in Chemical Sciences, Associate Professor
Vasyl Stefanyk Precarpathian National University
76018, 57 Shevchenko Str., Ivano-Frankivsk, Ukraine
https://orcid.org/0000-0002-5801-1285

Abstract. Pollution of the atmosphere, soil, and water resources in Ukraine resulting from the Russian-Ukrainian war is a problem that requires immediate resolution, as the ecocide's consequences on the environment will be long-lasting and have a global impact. The aim of the study was to analyse the impact of active military actions on the atmospheric air, water resources of Kharkiv and Kharkiv Region, and the soils of the Ivory Coast of Sviatoslav National Nature Park in Mykolaiv Region by assessing their eco-geochemical state. The study of the impact of fires on the soil properties of the Ivory Coast of Sviatoslav National Nature Park using potentiometric, luminescence-bituminological, and spectrofluorometric methods revealed that the content of polycyclic aromatic hydrocarbons (PAHs) is the highest in pyrogenic areas, where low molecular weight PAHs are predominant; high molecular weight PAHs are also present, indicating recent burning of the territory. It was found that the PAH content is lower at microelevations. The aspiration method was used to investigate the atmosphere. It was shown that the level of air pollution in Kharkiv is low at all observation points, with a level of less than 5 on the scale of the air pollution index. It was found that the largest number of exceedances in the water bodies of the Kharkiv Region was recorded for such pollutants as sulphates (recorded at 17 points), ammonium nitrogen (at 16 points), biochemical oxygen demand (at 14 points), and dissolved oxygen (at 11 points). In all the most polluted water bodies, the maximum permissible concentration exceedances were recorded for 4, 3, and 2 hydrochemical indicators. The study results can be used in practice by ecologists to develop and implement measures to improve the ecological condition of the eastern and southern regions of Ukraine

Keywords: ecology; environmental consequences; economic losses; damages; national nature park; rivers

Introduction

Regular ecological pollution research plays a crucial role in maintaining a favourable ecological state in the territories of the southeastern regions and Ukraine as a whole, as one of the main ecological and economic problems of Ukraine is the environmental pollution problems of the eastern and southern regions due to the military actions of the Russian occupation forces. The concentration of various sources of pollutants in the occupied settlements is high; the impact of the Russian-Ukrainian war contributes to an increase in emissions of harmful substances, which leads to a serious impact on the natural environment. The research problem is confirmed by the fact that the war unleashed by Russia has

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*Corresponding author

caused total damage to Ukraine's environment of more than 2 trillion UAH (€55.6 billion) (The total damage…, 2023). Half of this amount is the damage from air pollution from forest fires, missile attacks, and the burning of oil products. As of October 12, 2022, emissions of pollutants into the atmosphere have been recorded, including, as noted by O. Angurets *et al.* (2023), 499,473 tonnes of combustion products released as a result of the burning of oil products.

According to the Department of Ecology and Natural Resources of Mykolaiv State Region Administration, as of August 22, 2023, 6,130 thousand hectares of land have burned in the Ivory Coast of Sviatoslav National Nature Park (Slobodianiuk, 2023). The impact of the war on the biome ecosystems of the flatland part of Ukraine includes several different aspects. Among them, the most widespread is the spread of landscape fires caused by ammunition explosions in relatively dry weather. The results of the research by T. Sak *et al.* (2022) showed that, as a result of hostilities, as of May 2, 2022, the physical volume of lost or damaged land assets amounted to 4.2 thousand hectares, and the total amount of losses were $873 million. The analytical report by Mine Action Review described the key environmental consequences of contamination with explosive ordnance and land release operations, as well as the potential impact of climate change on land release (Mitigating the environmental impacts…, 2021). The authors propose that states should have a national standard for mine action environmental management. However, the provided report only broadly addresses the issue. The pollution of water sources as a result of hostilities is more deeply analysed in the research of Ukrainian scientists O. Semenenko *et al.* (2022), where the authors consider the impact of ammunition corrosion and the decomposition of toxic substances on the pollution of groundwater in Donetsk Region.

The damage caused to Ukraine's environment by the military invasion was investigated by E. Bezsonov (2022). The author's calculations of the environmental damage caused by Russian tanks as of April 20, 2022, showed that the damage from air pollution by exhaust gases was $2.436 billion ($43.5 thousand per day), the damage to agroecosystems was $45.111 billion, and the damage to ecosystems and ecosystem services was $93.45 billion. In the study by I. Krasovska & K. Podorozhko (2022), using the spatial analysis tools of ArcGis 10.5, the authors modelled the trajectory of the movement of the cloud with nitric acid vapours. The authors compiled cartographic models of the atmospheric state, containing information about the strength and direction of the wind from April 5 to April 10, 2022. Although the topic of the impact of hostilities on the ecological state of Ukraine is now actively being researched, insufficient attention has been paid to the study of the consequences of mechanical impact during military-technogenic loads on the soil cover of environmentally protected sites, as well as the consequences of fires. The aim of the research was to establish the exceedances of the maximum permissible concentration of pollutants in water bodies of the Kharkiv Region, to establish the level of air pollution in Kharkiv, to identify the features of background areas and soils damaged by fire, and to determine the nature of the accumulation of polycyclic aromatic hydrocarbons (PAHs) in the soil cover of the Ivory Coast of Sviatoslav National Nature Park as a result of military operations.

Materials and Methods

During the soil pollution study, methodologies were regulated by the State Committee of Ukraine for Water Management (2001), the State Standard of Ukraine (hereinafter DSTU) DSTU 4287:2004 (2004), DSTU ISO 10381-2:2004 (2004), DSTU ISO 5667-6:2009 (2009), and Order of the State Emergency Service of Ukraine No. 30 "On the Approval of the Instructions for the Selection and Preparation of Water and Soil Samples for Chemical and Hydrobiological Analysis by Hydrometeorological Stations and Posts" (2016). Field investigations were conducted on sites located on the Ivory Coast of Sviatoslav National Nature Park, which is located within the Ochakiv and Berezan districts of the Mykolaiv Region. Six plots were investigated to determine the accumulation of PAHs and other characteristics of soil profiles: burned-out plots of 2023, fire-damaged areas of 2022, and background plots. These points were selected through reconnaissance routes, depending on the age of the fire. The plots were selected on different types of microrelief (microdepressions and microelevations). Sections were dug at each of the sites (30 sites in total). Soil samples were taken from each section according to soil horizons for further analytical work. The research data included field and analytical methods of research on the selected samples and the processing of the data results. Using the analytical method, the samples were analysed. Soil sampling was carried out in the first half of August 2023.

The soil samples were dried at room temperature in the shade. The soils were sieved through a sieve with holes of 0.25 mm and 1 mm, depending on the chemical analyses. During the research, the pH of the water suspension was determined using the potentiometric method on an ionometer "Expert-001" (Ekonix-Expert, RF). Total dissolved solids (TDS) were determined by the titrimetric method in a ratio of 1:5 (soil:water). Volatile organic carbon was determined by the titrimetric method using the Tyurin method with phenylanthranilic acid. The quantitative and qualitative characteristics of PAHs were studied using the luminescent-bituminological and spectrofluorometric methods. Eleven individual PAHs were determined in hexane bitumoid: diphenyl, naphthalene homologues, fluorene, phenanthrene, anthracene, chrysene, pyrene, tetraphene, perylene, benzo[*a*]pyrene, and benzo[*ghi*]perylene. Measurements were carried out by the method of spectrofluorimetric analysis at low temperature (Shpolsky spectroscopy) on the spectrofluorometric complex "Fluorat-Panorama" (Lumeks, Russia). Calculations were performed for the volatile organic carbon content by horizons and its subsequent averaging; the content of TDS by horizons and its subsequent averaging by microrelief; the content of PAHs accumulation; and the creation of graphs in the Statistica.

The methodology used for the atmospheric pollution study was regulated by DSTU 8812:2018 (2018) to determine the state and quality of atmospheric air. Sampling was carried out at measuring points in accordance with DSTU 8725:2017 (2017). Observations were carried out at stationary observation posts for air pollution (SOPAP) equipped with complete POST-1 and POST-2 laboratories. Using the aspiration method, air samples were taken in September 2023. The sampling was carried out by the Kharkiv Regional Centre for Hydrometeorology at 10 posts. Observations were carried out daily, except for Sundays. These data have been analysed in this study. Air sampling was carried out at a height of 1.5-3.5 m above the ground. Air samples were taken by pumping outside air through a special cartridge with an absorbent filter. Each substance had its specific absorbent filter. The pumping duration for determining single concentrations was 20-30 minutes. For daily average measurements, the duration was also 20-30 minutes and 24 hours for continuous sampling. Meteorological observations lasted for 10 minutes. The following devices were used for air sampling by the aspiration method: an electric aspirator (a device designed to draw air through absorbent materials) and a liquid rheometer (used to determine the volume of air sampled for analysis). Water sampling was conducted using the surface sampling method in September 2023. The analysis of the state of surface waters in the region was carried out according to the data of the Regional Office of Water Resources in the Kharkiv Region at 20 monitoring points, and the data obtained were analysed in this article. Monitoring was carried out for the content of dissolved oxygen, biochemical oxygen demand (BOD_5), ammonium nitrogen, nitrite nitrogen, chlorides, and sulphates in surface waters. The equipment, reagents, and materials used for water sampling included washed, degreased, and rinsed containers of the required volume; a Meyer's bottle; a thermometer; H_2SO_4; HNO_3; chloroform; and a pipette.

Results

Soil samples for the study were taken on the Ivory Coast of Sviatoslav National Nature Park. Soil profiles are represented by two types of soils, depending on their location in the relief. Plot 1 and Plot 2 represent the 2023 fire. Like all plots, the fire plots are represented by microdepressions and microelevations. In the plot, six sections are laid in microdepressions, and four sections are on microelevations. The plot is a flattened surface with burnt and successional vegetation. The vegetation after the fire is represented by such an herbaceous plant as feathergrass (*Stipa capillata*). Meadow grass (*Poa*) and camelthorn (*Alhagi*) are also present. Soils are represented by light humus soils post-pyrogenic and aeolian-stratified post-pyrogenic psammozem. Plot 3 and Plot 4 represent the 2022 fire. In the plot, six sections are laid on microelevations and four sections on microdepressions. Soils are represented by aeolian-stratified psammozem and light humus soils. The vegetation of the plot is represented by bromes (*Bromus*), *Stipa capillata*, *Poa*, and *Alhagi*. There is no burned vegetation on the surface of these plots. Plots 5 and 6 are background plots. In the plot, 6 sections are laid on the microelevation and 4 sections on the microdepression. Soils are represented by light humus soils. The vegetation of the plot is represented by: mugwort (*Artemísia vulgáris*), *Stipa capillata*, *Poa*, and *Bromus*. The soils of the background plots are represented by light humus soil. The profile has the following horizons: AJ-Csa (microdepression); AJ-AC-Cca (microelevation) (Fig. 1).

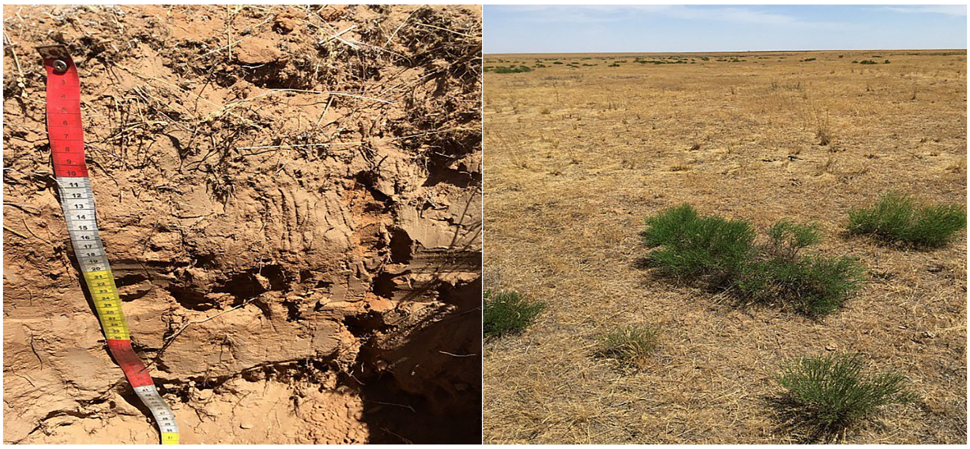

Figure 1. The soil profile of the background plots and the corresponding landscape
Source: made by the authors

The light humus soil of microdepressions is represented by AJ (depth 0-12 cm) light humus horizon: grey fawn, dry, structureless, fine sandy loam, slightly compacted, penetrated by roots (1-3 mm, medium amount), does not boil, the transition is clear in colour and structure, and the border is flat. Cca (depth 12-38 cm) soil-forming rock:

dark fawn, fresh, structureless, fine sandy loam, dense, roots (few, 1-3 mm), carbonate formations (few, loose), boils violently. The light-humus soil of microelevations is represented by AJ (depth 0-13 cm) light humus horizon: grey fawn, dry, structureless, dusty sand, poorly compacted, permeated with roots (average amount, 1-5 mm), does not boil, the transition is clear in colour and structure, and the border is slightly wavy. AC (depth 13-43 cm) transitional horizon: fawn, dry, structureless, fine sandy loam, dense, roots (1-3 mm, few), does not boil, the transition is clear in colour and structure, and slightly wavy. Cca (depth 43-60 cm) soil-forming rock: fawn, fresh, structureless, fine sandy loam, dense, single roots (1-3 mm), carbonate formations (many, loose), boiling violently. In the microdepressions of the burned site in 2023, the soil is represented by a light humus post-pyrogenic soil and has the following profile: AJpir-Acd-Cca (2004 classification) (Fig. 2). AJpir (depth 0-8 cm) light humus post-pyrogenic horizon: grey spots on fawn grey background (0.1-0.3 cm, few), dry, structureless, fine sandy loam, poorly compacted, ash (few), roots (0.1-0.2 cm, many), does not boil, the transition is clear in colour and structure, and the border is slightly wavy. ACd (depth 8-44 cm) transitional horizon on a fawn background fawn-grey spots (1-2 cm, average amount), streaks (0.5-1 cm, average amount), dry, structureless, fine sandy loam, dense, plant roots (1 mm, average amount), boiling violently, transition clear in colour, and smooth boundary. Ssa (depth 44-65 cm) soil forming rock residual carbonate: light fawn with greyish fawn spots (1 cm, average amount), fresh structureless, dense, fine sandy loam, boiling violently. The plant associations in the microdepressions of the burned site in 2023 are represented by meadow bentgrass. In the microelevations of the background site, the soil is represented by aeolian-stratified post-pyrogenic psamozem with a profile: RJae, pir-aj-D (Fig. 3).

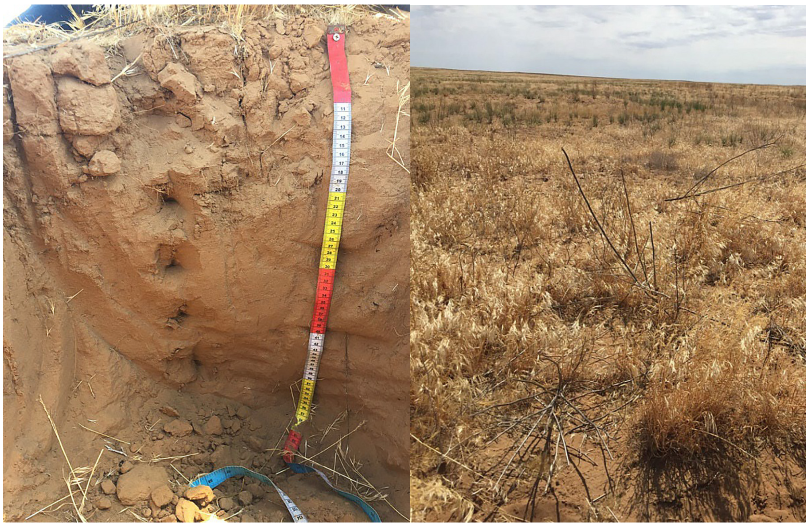

Figure 2. The soil profile of a microdepression and the corresponding landscape
Source: made by the authors

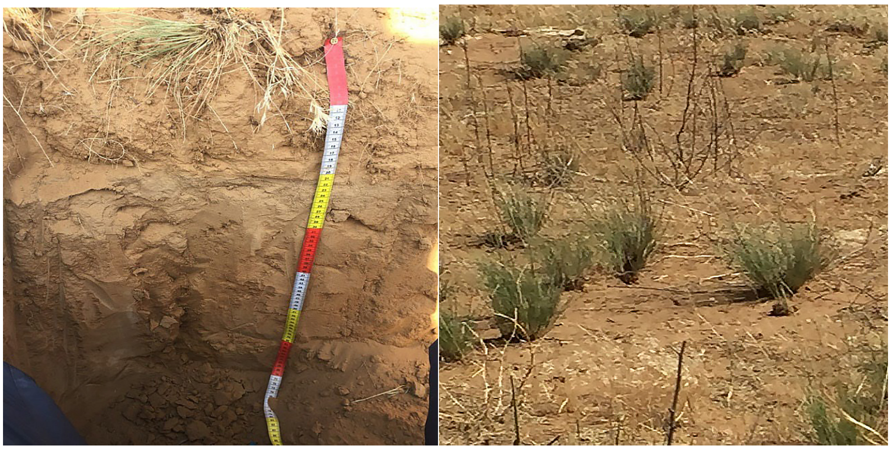

Figure 3. The soil profile of microelevations and the corresponding landscape
Source: made by the authors

RJae, pir (depth 0-21 cm) light humus stratified post-pyrogenic horizon: light fawn, dry, structureless, fine sandy loam, compacted, ash (few), roots (1-3 mm, medium), not boiling, transition clear in colour, and flat boundary. [AJ] (depth 21-28 cm) light humus horizon: light grey dry, structureless, fine sandy loam, dense, roots (2 mm, medium abundance), the transition is clear in structure, and the border is slightly wavy. [D] (depth 28-60 cm) bedrock: on an ochre-fawn background, light grey spots (3-4 cm, medium amount), dry, structureless, fine sandy loam, very dense, and single roots (1 mm, few). Plant associations in the microelevations of the background area are represented by meadow fescue grass (*Lolium pratense*). A total of 87 samples were collected from the genetic horizons of soil profiles at the key sites. Soils of the Ivory Coast of Sviatoslav National Nature Park are characterised by a neutral or slightly alkaline reaction. The measured pH values across the burn sites and background sites, mainly considering microrelief, showed the following results: in all soils, pH values range from neutral to slightly alkaline from the upper to the lower horizons. On the background sites, an increase in pH is observed in both microelevations and microdepressions towards the lower horizons. The lowest pH value was found in the upper horizons of soils in microelevations and microdepressions (7.8 and 7.9, respectively). The highest pH value on the background sites was observed in the lower soil horizons, with 8.1 in microdepressions and 8.4 in microelevations.

On the 2022 fire site, there was also an increase in the reaction of the medium to the lower horizons of the soil and a higher pH value on microelevations. The highest value is observed in the lower horizons: on microelevations, 7.55, and on microdepressions, 7.35. The minimum values are reached in the upper horizons of microelevations and microdepressions (7.38 and 7.35, respectively). On the 2023 fire sites, the pH value differed by microrelief. The minimum pH value was observed in the upper horizons (RJae and AJ). Predominantly on microdepressions, the pH is slightly higher in the upper part of the profile (7.35) than on microelevations (7.3). The maximum pH value was reached in the lower horizon of the soils (Cca or Cs) and was 7.35 on microelevations and 7.55 on microdepressions. The tendency for a decrease in pH values in post-fire soils compared to background sites is likely explained by the fact that ash water-soluble compounds penetrate the soil and saturate the absorption complex with alkaline earth elements. Electrical conductivity characterises the soil's ability to conduct electrical current by utilising the property of salts to conduct it. Thus, electrical conductivity measures the concentration of soluble salts present in the soil solution. The higher the value, the easier it is for electrical current to pass through the soil due to the higher concentration of salts.

A gradual increase in electrical conductivity was observed with the depth of the soil profile. The maximum values are reached at a depth of 45 cm and more on all considered sites. A similar pattern was observed in the background areas. The lowest electrical conductivity values in the upper soil layers are 60 mS/cm (microelevation) and 45 mS/cm (microdepression). The highest electrical conductivity values were reached on the 2022 fire site on microdepressions (500 mS/cm), and the lowest values were observed in the upper soil horizons are 50 mS/cm (microelevation) and 65 mS/cm (microdepression). On the 2023 fire sites, the minimum electrical conductivity value was observed in the near-surface part of the profile and is 50 mS/cm on microelevations and 60 mS/cm on microdepressions. The largest values are reached on microelevations 100 mS/cm and on microdepressions 300 mS/cm. On all sites, there was a gradual, small increase in electrical conductivity on microdepressions and a more pronounced, sharp increase on microdepressions.

The increase in electrical conductivity towards the lower soil horizons is directly caused by highly mineralised groundwater. The fact is that the Ivory Coast of Sviatoslav National Nature Park is located in an arid zone, and the groundwater is highly mineralised and lies at a depth of 3 meters. The analytical determination of TDS in the soil profile is directly related to the presence of salt crystals in the soil horizons. The sum of the salts was determined by the titrimetric method. On the background areas, there was no accumulation of TDS at a depth of 20 cm. The least salinisation of soils was observed in the upper horizons of microelevations and microdepressions (0.05% and 0.07%). The presence of salts in the soil profiles was noted across all studied sites. On the fire sites of 2023 and 2022, there was a presence of salts from the surface, but not in large quantities (0.05%). An increase in the sum of salts was observed along the soil profile on microdepressions at a depth of 20 cm. On the fire sites of 2023, the sum of salts at a depth of 20 cm of microdepressions is 0.25%; on the fire sites of 2022, it is 0.18%. The soils of microdepressions are slightly saline.

The presence of TDS is often observed in the soils of arid regions. Light humus soils and psammozem are directly located in the arid region of the country. The accumulation of TDS in the soil profile of arid territories is one of the main indicators of soil salinisation. The accumulation of salts in the middle of the soil profile is directly related to the insufficient amount of precipitation. Thus, the accumulation of TDS on the fire sites at a depth of 20 cm is associated with a moisture deficit. Since evaporation in this area is higher than the amount of precipitation, a moisture deficit was observed in the soil. In the process of mineralisation of organic residues, TDS were formed, which were not washed out of the soil profile, but accumulated at a depth of 20 cm.

The most important negative ecological effect of fires is the loss of organic matter by the ecosystem as a whole, including the loss of organic matter in the soil. Research has shown that there is a tendency for humus content to decrease in the 0-10 cm layer in soils that have been exposed to thermal effects. Fires have the greatest impact directly on the upper humus horizon of the soil. The organic carbon content of the background sites was decreasing before the fires. In background areas, the organic carbon values are higher than in burned areas of different ages. The maximum organic carbon value in background soils was 0.4% on microelevations and 0.7% on microdepressions. The 2022 burnt area showed a slight increase in organic carbon in the upper humus horizon of the soils, approximately 0.42% on microelevations and 0.46% on microdepressions, compared to the less recent fire. The minimum values of organic carbon are reached in the lower parts of the soil profile, approximately 0.35%. On the 2023 burnt areas, the organic carbon content is only 0.33% and 0.38% (microdepression and microelevation, respectively), decreasing down the profile to 0.1% and 0.12% (microdepression and microelevation, respectively). Thus, the decrease in organic carbon content is directly related to the impact and consequences of fires. It is most likely a consequence of the thermal impact of fires on the upper soil layer, which led to the transformation and destruction of the humus horizon of the soil.

The following results were obtained during the study of soils in the reserve that suffered from the fires of 2022 and 2023. In general, the absolute total content of PAHs in soils is low. The sum of PAHs in background areas is 6.7-37.2 ng/g; in the 2022 fire sites, 9.8-25.1 ng/g; and in the 2023 fire sites, 7.1-66.9 ng/g. The sum of PAHs changes from background areas to burned sites. The qualitative composition of PAHs changes from background areas to increasing fire age. In the background, phenanthrene (48%), naphthalene homologues (46%), diphenyl (4%), and fluorene (2%) were predominant. The presence of high molecular weight PAHs in background areas was not found. On the 2022 fire sites, the predominant groups were low molecular weight PAHs: naphthalene homologues (44%), phenanthrene (40%), diphenyl (14%), and fluorene (2%). Very small concentrations of high molecular weight PAHs such as anthracene, chrysene, and benzo[*ghi*]perylene (1%) were found. On the 2023 fire sites, the predominant groups were low molecular weight PAHs – naphthalene homologues (44%), phenanthrene (40%), diphenyl (14%), and fluorene (2%). high molecular weight PAHs (perylene, benzo[*ghi*]perylene, tetraphene, benzo[*a*]pyrene) (3%) were released in sufficiently large quantities compared to the 2022 fires. Thus, during pyrogenic damage to landscapes, PAHs in soils accumulate weakly. The differences in pollutant content between background and fire-affected soils do not exceed 1.5-2 times. This is due to the fact that free access to oxygen and high temperatures prevent the formation of PAHs during a fire. Conditions are also created for the intensive dispersion of combustion products: a convective column is formed above the fire zone – a stream of heated pyrolysis products of organic matter.

To understand the distribution and concentration of the total amount and composition of PAHs in the territory of the reserve, microelevations and microdepressions of this territory were considered separately. The total amount of PAHs on microdepressions also varied at different intervals on different sites. In the 2023 burnt areas, the total amount of PAHs ranged from 7.1 to 37.6 ng/g; on the 2022 fires, 9.8-32.5 ng/g; and in the background areas, 21.5-54.6 ng/g. The qualitative characteristics of PAHs on the sites are also different. In background areas, phenanthrene (51%), naphthalene homologues (42%), diphenyl (4%), and fluorene (3%) are predominant. On the 2022 fires: naphthalene homologues (63%), phenanthrene (24%), diphenyl (12%), and fluorene (1%). On the 2023 burned areas: naphthalene homologues (56%), diphenyl (27%), phenanthrene (14%), and fluorene (3%). An increase in naphthalene homologues, a decrease in phenanthrene, an increase in diphenyl, and the same amount of fluorene were observed from background areas to burnt areas. Also, the presence of high molecular weight PAHs was observed in the fires. During steppe fires, less material burns than during forest fires, while oxygen access remains free. These factors contributed to the lower formation of PAHs compared to forest fires, so even in soils with a high organic matter content, no intensive accumulation of polyarenes was observed. The total amount of PAHs on microelevations was characterised by different values. The largest total amount of PAHs was reached on the 2023 fires in the range of 7.1-25.7 ng/g, on the background areas 6.7-66.9 ng/g, and on the 2022 fires this value is 7.8-21.2 ng/g.

The qualitative characteristics of PAHs also differ from the values of microdepressions. In background areas, the predominant polyarenes were naphthalene homologues (52%), phenanthrene (43%), diphenyl (4%), and fluorene (1%). On the 2022 fires: naphthalene homologues (73%), phenanthrene (25%), and diphenyl (2%). On the 2023 fires: phenanthrene (48%), naphthalene homologues (39%), diphenyl (12%), fluorene (1%), and the presence of high molecular weight PAHs (1%) was also found. There was a decrease in the values of naphthalene homologues on the 2023 burnt areas and an increase in naphthalene homologues on the 2022 fires compared to background areas; an increase in diphenyl; a decrease in fluorene; a decrease in phenanthrene on the 2022 fires; and an increase in it on the 2023 fires compared to the background values. Thus, the indicators and qualitative composition of PAHs in the microrelief differ. This may be due to the uneven passage of the fire through the territory, where the soil in small areas is less disturbed and possibly less prone to fires. The formation of high molecular weight PAHs in the microrelief is directly related to the activity of fires. In total, 4549 air samples were collected and analysed in September 2023. The results of the study of the state of atmospheric air in Kharkiv are presented in Table 1.

Table 1. Indicators of the air pollution index in Kharkiv in September 2023

No.	Address	Pollution index	
		August 2023	September 2023
9	34 23 Serpnia Str. District	3.54	2.99
11	6 Teatralna Aly., Centre District	2.72	2.24
12	44 Hvardiets-Shyroninets Str., 607 Micro-District	2.43	1.83

Table 1, Continued

No.	Address	Pollution index	
		August 2023	September 2023
13	4 Pashchenkivska Str., Ivanivka District	4.12	3.39
16	4 Kholodnohirska Str., Kholodna Hora District	3.21	2.87
17	Crossroads of Derevianka Str. and Kharkivskyi Rd., Sokolnyky District	2.76	2.52
18	3 Bairon Ave. District	3.21	3.04
19	120 Saltivska Rd. District	2.14	1.97
21	53 Vrubel Str., Novobavarsk District	1.43	1.47
24	15 Municipal Hospital No. 15 at 46 Akademik Pavlov Str. District	2.2	1.85

Source: made by the authors based on Information on the ecological state of the Kharkiv and the Kharkiv Region for September 2023 (2023)

According to the observations in September 2023, the level of air pollution in the city at all stationary observation points was characterised as low (according to the Atmospheric Pollution Index (API) scale, a level of less than 5.0 is considered low). Observation data from the Kharkiv Regional Centre for Hydrometeorology indicated that the most polluted area was 4 Pashchenkivska Str., Ivanivka District (SOPAP No. 13) with an index of 3.39; the lowest level of pollution was found in 53 Vrubel Str., Novobavarsk District (SOPAP No. 21) with an index of 1.47. The reason for the increased pollution in the area of 4 Pashchenkivska Str., Ivanivka District, was the air pollution caused by the remnants of explosives (TNT, hexogen, etc.), shells containing radioactive substances, dust, and combustion products, which are related to the poor quality of roads in the area, as well as missile attacks. During September 2023, samples were taken from rivers and a reservoir in the Kharkiv Region. In total, 20 points (location of the sampling site) were investigated, and 40 surface water samples were collected (2 samples from each point of the water body). The results of the study of surface water bodies in the Kharkiv Region are presented in Table 2.

Table 2. Surface water quality indicators in the Kharkiv Region for September 2023

No.	Name of the water body	Sampling date	Measurement results, mg/dm^3					
			Dissolved oxygen	BOC_5	Ammonium nitrogen	Nitrite nitrogen	Chlorides	Sulphates
	quality standards for fishery water (mg/dm3)		6	2	0.39	40	300	100
1	Khotomlia River, Novooleksandrivka Village	September 11, 2023	6.99	2.37	0.706	0.036	34.5	116
2	Tetleha River, river mouth, Kochetok Village	September 11, 2023	8.15	0.95	0.543	0.008	37.4	122
3	Udy River, above Kharkiv	September 6, 2023	6.11	1.23	0.685	0.014	37.4	101
4	Lopan River, river mouth, Kharkiv	September 6, 2023	5.82	6.5	0.658	0.154	84.1	175
5	Kharkiv River, river mouth, Kharkiv	September 6, 2023	4.66	4.38	0.276	0.089	58.6	141
6	Murom River, river mouth	September 11, 2023	8.73	0.66	0.396	0.006	23.0	152
7	Rohan River, river mouth	September 12, 2023	8.44	1.82	0.613	0.061	45.7	299
8	Nemyshlia River, river mouth, Kharkiv	September 6, 2023	6.99	2.65	0.503	0.038	79.8	215
9	Mozh River, above Merefa	September 5, 2023	3.5	2.95	0.530	0.008	48.2	49.5
10	Mozh River, river mouth, Zmiiv	September 6, 2023	4.08	3.06	2.743	0.009	48.5	43.7
11	Kniazhna River, Brazhnyky Village	September 5, 2023	8.73	5.54	0.543	0.008	57.5	43.7
12	Lebiazha River, river mouth, Lebiazhe Village	September 11, 2023	8.73	2.68	0.348	0.021	25.9	582

Table 2, Continued

No.	Name of the water body	Sampling date	Measurement results, mg/dm³					
			Dissolved oxygen	BOC_5	Ammonium nitrogen	Nitrite nitrogen	Chlorides	Sulphates
13	Udy River, river mouth, Eskhar Village	September 12, 2023	7.27	9.40	0.947	0.123	103	236
14	Siverskyi Donets River, Pechenihy Reservoir, Pechenihy Village	September 11, 2023	7.85	2.37	0.543	0.043	34.1	103
15	Siverskyi Donets River, below the river mouth of Udy River, Eskhar Village	September 12, 2023	5.82	3	0.03	0.06	54.3	146
16	Siverskyi Donets River, Zadonetske	September 6, 2023	4.94	1.86	0.383	0.059	56.8	145
17	Orilka River, Chervona Dolyna Village	September 5, 2023	4.95	1.79	0.458	0.003	150	961
18	Orilske Reservoir, channel Dnipro-Donbas, 170 km, Orilka Village, Orilske Reservoir, sluice water outlet	September 5, 2023	5.53	2.66	0.511	0.018	163	999
19	Berestova River, Krasnohrad	September 5, 2023	11.9	8.06	1.123	0.014	44.9	202
20	Voshyva River, Kobzivka Village	September 5, 2023	3.2	2.95	1.328	0.008	152	671

Source: compiled by the author based on Information on the ecological state of the Kharkiv and the Kharkiv Region for September 2023 (2023)

The results of the study of surface waters in the Kharkiv Region showed that the largest number of exceedances were recorded for such pollutants as sulphates (at 17 points), ammonium nitrogen (at 16 points), BOD_5 (at 14 points), and dissolved oxygen (at 11 points). Exceedances of nitrate nitrogen and chloride were not detected at any of the monitoring sites. According to the results carried out in September 2023, the most polluted water bodies in the Kharkiv Region were: for 4 hydrochemical indicators Khotomlia River (Novooleksandrivka Village), Nemyshlia River (river mouth, Kharkiv), Udy River (river mouth, Eskhar Village), Siverskyi Donets River (Pechenihy Reservoir, Pechenihy Village), Berestova River (Krasnohrad); for 3 hydrochemical parameters Tetleha River (river mouth, Kochetok Village), Udy River (above Kharkiv), Lopan River (river mouth, Kharkiv), Kharkiv River (river mouth, Kharkiv), Murom River (river mouth), Rohan River (river mouth), Kniazhna River (Brazhnyky Village), Lebiazha River (river mouth, Lebiazhe Village), Orilske Reservoir (channel Dnipro-Donbas, 170 km, Orilka Village, Orilske Reservoir, sluice water outlet), Voshyva River (Kobzivka Village); for 2 hydrochemical parameters Mozh River (above Merefa), Mozh River (river mouth, Zmiiv), Siverskyi Donets River (below the river mouth of Udy River, Eskhar Village), Orilka River (Chervona Dolyna Village). The least polluted water body in the Kharkiv Region was: for 1 hydrochemical indicator, Siverskyi Donets River (Zadonetske). In the most contaminated rivers and reservoir in the Kharkiv Region, the source of the most dangerous contamination is Unsymmetrical dimethylhydrazine (UDMH) $(CH_3)_2N_2H_2$ (heptyl), a component of highly toxic rocket fuel that oxidises easily to form more dangerous compounds, including nitrosodimethylamine, a yellow liquid partially soluble in water, and many organic solvents. Thus, the highest number of exceedances of the maximum permissible concentration in water bodies of the Kharkiv Region was found for such pollutants as sulphates, ammonium nitrogen, biochemical oxygen consumption, and dissolved oxygen. The study of the atmosphere in Kharkiv showed that the level of air pollution at all observation points is low and does not pose a threat. The study of the impact of fires on soil properties showed that the content of surfactants is highest in pyrogenic areas, where low molecular weight PAHs are predominant.

Discussion

Analysing the obtained research results, it can be concluded that the pollution of the atmosphere, soil, and water resources as a result of military actions has negatively impacted natural ecosystems. All natural resources have suffered as a result of hostilities: lands from pollution of various types of waste and fires, atmospheric air from constant emissions from missile explosions and fires, water bodies, forest resources, fauna, the natural reserve fund from enemy equipment, pollution, and deliberate destruction. As a result of the ecocide, the upper fertile layer of the soil, which has been formed for centuries, was destroyed. It is known that over the past 100 years, Ukrainian soils have lost about 30% of humus (The war in…, 2022). Due to the influence of the war, this process has accelerated. Soils are losing their fertility due to changes in their physical, chemical, and physicochemical properties.

The research by R. Shaheb *et al.* (2021) focused on studying the effect of soil compaction due to the movement of heavy machinery and vehicles, which causes damage to the soil structure and degradation of the soil environment, sharing similarities with the present study. The authors' results revealed that soil compaction increases soil bulk density and strength, its porosity and hydraulic properties decrease, the growth of plant roots in crops is delayed, and the yield decreases by 50% or more, depending on the magnitude and degree of soil compaction. To improve the situation, the authors make suggestions for mitigating the effect of soil compaction, such as adhering to advanced soil management methods that help crops effectively assimilate applied nutrients, growing crops with a deep root system in crop rotation, and practising conservative soil tillage. In Ukraine, according to the authors of the study, conservation agriculture could be implemented to mitigate soil erosion; in particular, a project of a soil-protective contour-meliorative farming system could help prevent erosion in the system of soil protection tillage.

The research by R. Lasaponara *et al.* (2023) focused on studying the value of using Sentinel-1 (S1) and Sentinel-2 (S2) data together to assess fire severity in heterogeneous, fragmented ecosystems. In the study, the effectiveness of S1 and S2 fire indices was initially statistically analysed using the ISODATA clustering algorithm combined with field investigations conducted during the fire that occurred on July 13, 2019, in Sardinia. To automatically map burn areas and classify fire severity, the fire indices of S1 and S2 were integrated through multi-level classification performed at pixel and object levels. The results of the authors' research showed that the accuracy is above 94% compared to independent datasets and field investigations. The authors recommended using additional information about forest structures to improve SAR-based fire assessment. In Ukraine, the Google Earth Engine cloud service to obtain and process satellite data on forest fires and their consequences and methods for processing, analysis, and visualisation of geospatial data can be implemented, which would improve the operational efficiency of detecting hazardous areas. G. Alarcon-Aguirre *et al.* (2022) presented algorithms for mapping fire severity based on Sentinel-1 backscatter data in the southeastern Peruvian Amazon. The results of the study showed that Sentinel-1 cross-polarisation data is sufficiently accurate for detecting and quantifying fires. According to the authors, studies should also be conducted on the integration of global optical images, such as Sentinel-2 and Landsat, with synthetic aperture radar (SAR) images to assess detection and accuracy compared with independent analysis of optical images or SAR images. In Ukraine, methods for using the normalised burn ratio and supervised classification for pre- and post-fire satellite imagery could be implemented. The proposed GIS (geographic information system) technologies can be used to identify areas and calculate the areas of vegetation damaged by fires.

In the study by S. Pinakana *et al.* (2023), air pollution in South Texas was examined, establishing a correlation between human health and air pollution. The assessment was conducted for pollutants such as particulate matter, volatile organic compounds, pesticides, CO, CO_2, O_3, benzene, NO_2, SO_2, and PAHs. The results of the research showed that industry, vehicle emissions, agricultural burning, construction, and dirt roads are the major sources of pollution, causing detrimental health effects such as respiratory and cardiovascular diseases. The authors recommend increasing the number of CAMS automatic stations throughout South Texas to accurately determine the burden of air pollution on the population. In Ukraine, it is necessary to create and implement networks of automatic stations for monitoring air pollution from emissions of industrial enterprises, energy facilities, and vehicles, as well as stations for recording meteorological parameters and environmental radioactivity. For indoor and outdoor air quality monitoring, the AQMesh portable air monitoring station with small AQMesh sensors can be implemented to provide localised real-time data.

Researchers B. Ghosh *et al.* (2023) determined the distribution of heavy metals in the air and the potential health risks in three different regions of West Bengal, India. The results of the research showed that the sum of non-cancerous risks (HI) for all heavy metals exceeded the risk threshold of the U.S. Environmental Protection Agency ($HI < 1$) in both Kolkata and Durgapur, except for Bolpur. Kolkata had the highest estimated lifetime cancer cases compared to Bolpur and Durgapur. The authors emphasised the need for the implementation of cleaner industrial technologies, emission control norms, and sustainable urban planning. In Ukraine, it is worth implementing methods for assessing the health risk of the population from the impact of soil pollution by heavy metals by evaluating using a probit regression model. The difference between the studies is that the works analysed above consider only those pollutants and circumstances that are inherent in peacetime, while in Ukraine, the problem of pollution due to hostile actions is added to these problems.

S. Panico *et al.* (2023) examined the concentrations of potentially hazardous elements and studied the impact of metal contamination on soil quality and human health risks in three different land areas (forest, fire-prone forest, and urban area) in the Mediterranean region. The research results showed high concentrations of V, Mg, and Mn in forest and fire-prone forest soils, as well as high concentrations of Al, Fe, Ni, Pb, and Zn in urban soils. The authors propose the development of further forest management practices aimed at monitoring soil contamination. In Ukraine, it is necessary to apply biological methods of soil purification from heavy metals, such as phytoremediation, which is based on the use of plants to extract heavy metals from the soil. In the study by J. Da Gama (2023), soils under the threat of anthropogenic and climatic pressure were investigated. The author considers it advisable to implement innovative solutions such as closed-loop economy approaches and sustainable biomass use, which are necessary to reduce greenhouse gas emissions. In Ukraine, it is worth implementing bioenergy technologies and using all types of biofuels – solid, liquid, gaseous, and it is also necessary to develop a Biomass Action Plan document. N. Iliopoulos *et al*. (2023) studied smoke dispersion from a forest fire in Penteli-Attica (Greece) on July 19, 2022, which burned an area of 2,781.7 ha. According to the results of the Penteli wildfire study and the measurement of gases and particles at measuring stations near the fire, it was found that the concentrations of PM 10 and PM 2.5 (air pollutants that are particularly harmful to human life and the environment) were almost four times higher on the day after the fire, July 20. The authors propose to apply such a protective measure as the evacuation of the population from the areas affected by the wildfire. The use of monitoring equipment, including an air quality monitoring network consisting of five permanent monitoring stations installed in residential areas, could be proposed in Ukraine.

Researchers S. Stefanidis *et al*. (2023) investigated changes in soil loss rates due to rain erosion in Southern Europe during the period 1980-2018. The research results showed that the average annual soil erosion rates in Southern Europe were 6.82, 4.90, 4.89, and 5.26 t/ha/year for the decades 1981-1990, 1991-2000, 2001-2010, and 2011-2018, respectively. The authors believe that it is necessary to apply an approach that combines freely available geospatial datasets and an empirical erosion prediction model. Z. Cheng *et al*. (2023) examined the impact of different fire intensities and key environmental factors on soil microbial diversity and biomass in taiga forests in northeastern China that were damaged by light, moderate, or severe fires. The results showed that all three fire intensities significantly increased the concentrations of soil microbial carbon, moisture content, and total nitrogen content, but they significantly decreased soil available potassium content compared to unburned taiga forest. The authors suggest applying a set of measures to optimise anthropogenic landscapes by creating ecologically sustainable plant cover on them – land phytoremediation. In Ukraine, technologies for soil remediation based on plants – phytoremediation technologies – should be utilised. In the study by F. Niccoli *et al*. (2023), the consequences of a wildfire that affected a black pine forest in Central Italy in 2017 were investigated. The results demonstrated the importance of using remote sensing for accurately delineating fire-affected areas and for precise ground action planning. The authors propose to combine remote sensing analysis with ground-based forest surveys. In Ukraine, a combined approach of satellite and ground-based research could be applied to accurately determine fire-affected areas. For instance, Ukrainian researchers O. Soshenskyi et al. (2022) assessed forest damage in Luhansk Region due to severe fires using the composite burn index and the geometrically structured composite burn index methods with satellite data. Although these studies analysed various impacts of fires on soils, they did not account for heavy machinery loads on land and explosions of ammunition, which also adversely affect soils and can create or intensify fires, leading to the burning of larger territories.

In a study by H. Haller *et al*. (2023), the ability of *Amaranthus hypochondriacus* plants to extract Cd from a nutrient-poor acidic substrate to which Cd was added in different concentrations (2 and 20 mg/kg dry weight) for 180 days was investigated. The authors believe that the application of phytoremediation technologies and the use of *Amaranthus hypochondriacus* plants are important for improving ecology and human health. According to the authors of this article, plants such as switchgrass and silver grass, which are hyperaccumulators and can actively absorb heavy metals and partially accumulate them in their underground and aboveground parts, can also be used in conditions of heavy metal pollution, which can help improve the condition of soils in the post-war period. Thus, in this section, a review was conducted, and studies on soil compaction due to the movement of heavy equipment and vehicles, the severity of fires in heterogeneous, fragmented ecosystems, and so on were considered. As a result of comparing these studies with the realities of Ukraine, the modified solutions described above can be considered. Although the studies considered describe the experiences of other countries in the world, some of their results and ideas coincide with the opinions of the authors of this article.

Conclusions

The pollution of the ecosphere and soils affected by the war unleashed by Russia in Ukraine was investigated. The results of studies on the impact of fires on soil properties showed that, as a result of fires, there was a mixing of the upper horizon of microelevations with living and burnt plant roots with the soil mass, reaching a depth of 15 cm. The tendency to decrease the pH values in post-fire soils is explained by the fact that ash water-soluble compounds, penetrating the soil, saturate the absorbing complex with alkaline earth elements. The accumulation of salts at a depth of 20 cm is likely associated with the formation of TDS during the mineralisation of organic residues, which are not washed out of the soil but accumulate in it. In soils damaged by fire, there was a decrease in organic carbon, which is associated with the direct destruction of the upper horizon due to thermal exposure. The highest content of PAHs was observed in pyrogenic areas, where low molecular weight PAHs predominated, and high molecular weight PAHs were also present, which characterised the recent burning of the territory of the Ivory Coast of Sviatoslav National

Nature Park. Different total content and composition of PAHs in soils on microelevations and in microdepressions were established. The content of PAHs is lower on microelevations, probably they are less exposed to the pyrogenic factor than microdepressions. In soils from burned areas of different ages, high molecular weight PAHs are present in larger quantities than in background areas. Low molecular weight PAHs predominate on all investigated sites.

An analysis of the results of studies of water bodies in the Kharkiv Region highlighted that the largest number of exceedances of pollutants in September 2023 were sulphates and ammonium nitrogen (recorded at 17 and 16 points, respectively). Exceeding the maximum permissible concentration was also noted in the water for 4, 3, and 2 hydrochemical indicators. Exceeding the nitrate and chloride content was not detected at any observation point. An analysis of the results of studies of air pollution in Kharkiv revealed that in September 2023, the level of pollution was characterised as low, as the API scale revealed a level of less than 5.0. In Kharkiv, the most contaminated was 4 Pashchenkivska Str., Ivanivka District (SOPAP No. 13), where the pollution index was 3.39; the least polluted was 53 Vrubel Str., Novobavarsk District (SOPAP No. 21), where the pollution index was 1.47. Directions for further research may include the implementation of clear interaction between the main participants in monitoring programmes at the regional level, standardisation of regulatory norms and measurement methods, and a well-founded correction of the programme and observation sites in accordance with local conditions.

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Conflict of Interest

None.

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Забруднення атмосфери, ґрунту та водних ресурсів унаслідок російсько-української війни

Микола Матківський

Кандидат технічних наук, доцент
Прикарпатський національний університет імені Василя Стефаника
76018, вул. Шевченка, 57, м. Івано-Франківськ, Україна
https://orcid.org/0000-0001-5039-0260

Тетяна Тарас

Кандидат хімічних наук, доцент
Прикарпатський національний університет імені Василя Стефаника
76018, вул. Шевченка, 57, м. Івано-Франківськ, Україна
https://orcid.org/0000-0002-5801-1285

Анотація. Забруднення атмосфери, ґрунту та водних ресурсів в Україні внаслідок російсько-української війни є проблемою, що вимагає негайного вирішення, оскільки наслідки екоциду для екології будуть довготривалими та матимуть глобальний характер. Метою дослідження був аналіз впливу активних військових дій на атмосферне повітря, водні ресурси міста Харкова й Харківської області та на ґрунти Національного природного парку «Білобережжя Святослава» в Миколаївській області шляхом оцінки їхнього еколого-геохімічного стану. Дослідження впливу пожеж на властивості ґрунтів Національного природного парку «Білобережжя Святослава» за допомогою потенціометричного, люмінесцентно-бітумінологічного та спектрофлуометричного методів виявили, що вміст поліциклічних ароматичних вуглеводнів (ПАВ) найбільший на пірогенних ділянках, де переважаючими групами є легкі ПАВ; також наявні важкі ПАВ, які характеризують недавнє вигорання території. Встановлено, що вміст ПАВ менший на мікропідвищеннях. Для дослідження атмосфери використано аспіраційний метод. Показано, що рівень забруднення повітря у Харкові на всіх пунктах спостереження низький, за шкалою індексу забруднення атмосфери виявлено рівень менше 5. Встановлено, що найбільша кількість перевищень у водних об'єктах Харківської області зафіксована по таких забруднюючих речовинах як: сульфати (зафіксовано на 17 точках), азот амонійний (на 16 точках), біохімічне споживання кисню (на 14 точках), розчинений кисень (на 11 точках). У всіх найбільш забруднених водних об'єктах зафіксовано перевищення гранично допустимої концентрації по 4, 3 та 2 гідрохімічним показникам. Результати дослідження можуть бути використані на практиці екологами з метою розробки та впровадження заходів для поліпшення екологічного стану східних та південних регіонів України

Ключові слова: екологія; екологічні наслідки; економічні втрати; збитки; національний природний парк; річки