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ANALYSIS OF PREVIOUS RESEARCH RESULTS ON GROUNDWATER MERCURY CONTAMINATION AT THE TERRITORY OF THE FORMER "RADYKAL" PLANT

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This article examines groundwater contamination levels in the area of the former "Radykal" plant. Particular attention is paid to the presence of mercury, which acts as a persistent pollutant within the hydrological system. The research highlights the anthropogenic impact of the enterprise on local aquifers. The study analyzes the hydrogeological conditions that facilitate the migration of contaminants from the industrial site to the surrounding environment, assessing the vulnerability of the saturation zone. Human-induced pressure on groundwater often results in its degradation. In dense urban agglomerations, such degradation threatens the safety of potential drinking water sources and disrupts the region's natural ecological balance. The "Radykal" plant, located in Kyiv, serves as a vivid example of an industrial facility whose operations led to significant environmental pollution, including the contamination of groundwater. The production of chemical substances, including chlorine and pesticides, left behind a toxic legacy that requires long-term and comprehensive remediation efforts.

Following the shutdown of the plant in 1996, which had produced agricultural chemicals, caustic soda, polydichloro compounds, potassium chlorate, and other substances, large quantities of chemicals remained on-site, creating conditions that facilitated the release of pollutants into groundwater. Quantitative analysis indicates that concentration levels significantly exceed permissible limits, posing a direct threat to the environment. It can be concluded that the former "Radykal" plant caused a negative anthropogenic impact on groundwater in the area due to mismanagement and improper operational practices. Despite a number of studies, the issue of groundwater contamination at the former "Radykal" site remains insufficiently investigated and requires further action to mitigate the environmental impact on the surrounding area. Future research should focus on modeling contaminant plume migration to develop effective cleanup technologies tailored to the site's specific geological characteristics. *Key words:* contamination, groundwater, remediation, aquifer, mercury, bottom sediments, vadose zone, groundwater.

Аналіз результатів попередніх досліджень забруднення підземних вод ртуттю на території колишнього заводу «Радикал». Жикевич Є. І., Верховцев В. Г.

В цій статті розглядається дослідження рівня забруднення підземних вод на території колишнього заводу «Радикал». Особлива увага приділяється наявності ртуті, яка діє як постійний забруднювач у гідрологічній системі. Це дослідження показує антропогенний вплив підприємства на підземні водоносні горизонти. Дослідження аналізує гідрогеологічні умови, які сприяють міграції забруднюючих речовин з промислового майданчика до навколишнього середовища, оцінюючи вразливість зони насичення. Антропогенний вплив на підземні води часто призводить до їхнього забруднення. Завод «Радикал», що розташований у Києві, є яскравим прикладом промислового підприємства, діяльність якого призвела до значного забруднення навколишнього середовища, зокрема підземних вод. Виробництво хімічних речовин, включаючи хлор та пестициди, залишило після себе токсичний спадок, який потребує комплексної та тривалої ремедіації. Внаслідок призупинення діяльності підприємства у 1996 році, яке здійснювало виробництво хімічних засобів захисту рослин, каустику, бертолетової солі та інших, хімічні речовини залишилися на території заводу, що створило передумови потрапляння забруднюючих речовин у підземні води. Кількісний аналіз показує, що рівні концентрацій значно перевищують допустимі граничні норми, становлячи пряму загрозу довкіллю. Може бути підсумовано, що колишній завод «Радикал» спричинив негативний антропогенний вплив на підземні води в місті його розташування, внаслідок безгосподарної діяльності. Незважаючи на проведення низки досліджень, питання забруднення підземних вод на території колишнього заводу «Радикал» залишається недостатньо вивченим, а також потребує подальших дій для зменшення антропогенного впливу на навколишнє середовище даного об'єкту. Майбутні дослідження повинні бути зосереджені на моделюванні міграції шлейфу забруднюючих речовин для розробки ефективних технологій очищення, адаптованих до конкретних геологічних характеристик ділянки. *Ключові слова:* забруднення, підземні води, ремедіація, водоносний горизонт, ртуть, донні відклади, зона аерації, ґрунтові води.

Problem Statement. The former "Radykal" plant, located in Kyiv, was for decades one of the largest chemical enterprises in Ukraine. JSC "Radykal" (previously Enterprise P/S 172, Kyiv Chemical Plant, and later the Radykal Production Association) began its industrial activity in 1951 with the commissioning of DDT production. In 1954, chlorine and caustic soda production facilities were launched. Over the following years, the plant expanded to include the production of chlorine-containing products – potassium chlorate, chloromethanes, monochloramine, chlorinated paraffins, chemical plant-protection agents – as well as

polyurethane foams, sealants, adhesives, and consumer goods [1].

Its operations resulted in significant environmental pollution, particularly the contamination of groundwater. The main concern lies in the negative anthropogenic impact on groundwater in the area where the former "Radykal" plant is located, manifested in substantial mercury pollution and the presence of other hazardous substances. The consequences of this contamination are multifaceted, affecting not only the ecological state of the environment but also public health and the sustainable development of the surrounding territory.

Relevance of the Study. Groundwater contamination at the site of the former "Radykal" plant remains a pressing issue for several reasons. Polluted groundwater may contain toxic substances such as organic pollutants, mercury, and other heavy metals that can enter the human body through drinking water, food products, or direct contact with soil. This exposure can lead to various health problems, including cancer, neurological disorders, and reproductive system impairments.

In addition, groundwater pollution negatively affects ecosystems by contaminating soils and surface waters. Such impacts may result in reduced biodiversity, soil degradation, and disruptions of ecological balance. It is also important to note that contamination of aquifers limits the use of land resources, decreases property value, and complicates the economic development of the region. Furthermore, the remediation of contaminated areas requires substantial financial investments.

Relation of the Author's Contribution to Important Scientific and Practical Tasks. This research is directly connected to addressing key scientific and practical challenges in the field of environmental safety and nature protection. Its primary objective is to examine the impact of the former "Radykal" plant on groundwater in order to develop effective remediation strategies aimed at reducing contamination levels and restoring the ecological stability of water resources.

The findings of this study will help clarify crucial aspects of environmental safety and the sustainable use of natural water resources in industrial regions. Moreover, they can serve as a basis for designing effective environmental management strategies and improving decision-making processes in the context of contaminated sites.

Analysis of Recent Studies and Publications. The issue of groundwater contamination at the site of the former Radykal chemical plant in Kyiv has drawn the attention of researchers and the public for many years. Recent studies and publications provide valuable insights into the scale of pollution, the types of contaminants present, their migration pathways, and the potential risks they pose to human health and the environment.

Comprehensive investigations of soils, groundwater, and bottom sediments at the former plant site and adjacent areas were conducted between 1992 and 2012 by the Northern State Regional Geological Enterprise "Pivnichgeologia", the State Enterprise "Ecoinform", the Ukrainian-Polish Joint Venture "EuroChem" (2012), and the Joint-Stock Company "Kyiv Research Institute of Synthesis and Ecology 'Synteko' with an experimental plant". The results revealed significant contamination with mercury and other hazardous pollutants.

Identification of Previously Unresolved Aspects of the Overall Problem. Despite multiple research efforts, groundwater contamination at the former "Radykal" plant site remains insufficiently investigated and requires further action to reduce the anthropogenic impact on the environment. A detailed assessment of the ecological consequences is still lacking, particularly the evaluation of how contamination affects biodiversity, ecosystem functioning, and soil quality. There is also no comparative analysis of the effectiveness of different remediation methods, which is essential for determining the most efficient and economically feasible approaches to groundwater cleanup. Additionally, the mechanisms and pathways of vertical and horizontal mercury migration in groundwater remain poorly understood. Further research is required to predict its dispersion, assess environmental risks, and support the development of appropriate groundwater remediation strategies.

Novelty. The scientific novelty of this study lies in the systematization and comprehensive analysis of many years of research on mercury contamination of groundwater at the former "Radykal" plant site, which makes it possible to obtain a more holistic understanding of the ecological situation.

Methodological and General Scientific Significance. This research holds substantial methodological value for developing approaches to the assessment and monitoring of groundwater contamination in industrial regions. The findings can serve as a foundation for designing environmental remediation strategies for industrial sites, creating groundwater quality monitoring systems, forecasting environmental risks, and shaping policies related to natural resource management and water protection. The integrated approach applied in this study – combining both quantitative and qualitative analytical methods – provides an in-depth examination of the environmental impacts associated with the former "Radykal" plant. This approach can be effectively used for investigating similar contaminated sites both in Ukraine and internationally.

Materials and Methods. A systemic approach was used in this study to analyze groundwater contamination, allowing these processes to be understood as complex and interrelated phenomena. The methodological framework was based on a combination of classical and modern environmental analysis methods.

The research was conducted on the territory of the former "Radykal" plant, which between 1951 and 1996 produced chemical plant-protection agents, caustic soda, polydichloro compounds, potassium chlorate, and hermobutyl. It is well documented that mercury was used in the production processes, which resulted in soil and groundwater contamination [2].

Sampling of soil and groundwater was carried out periodically from 1992 to 2012 [4, 2, 1, 3]. A monitoring network of 126 sampling points was used, evenly distributed across the plant territory and surrounding areas. At each point, soil samples were collected from depths of 0–5 meters, and groundwater samples from depths of 0–25 meters.

Samples were analyzed for mercury content using a combination of methods, including geochemical analysis of groundwater, mathematical modeling of contamination processes, and laboratory and field experiments. Soil samples were dried, crushed, and extracted; mercury levels in the extracts were determined using atomic absorption spectrometry. This approach integrates experimental, laboratory, theoretical, and field methods to obtain a comprehensive understanding of the problem and to develop effective remediation strategies. Statistical analysis included the collection, processing, and interpretation of data related to soil and groundwater contamination [3].

An integrated methodology combining quantitative and qualitative analytical techniques was applied, ensuring a thorough investigation of the environmental impacts of the former "Radykal" plant on groundwater.

Results and Discussion. Study area description: the study area is located in the left-bank part of Kyiv, in its eastern outskirts, and belongs to the Desnianskyi and Dniprovskyi districts of the city.

The study area covers 3 km^2, bounded on the north by Brovary Highway, on the northwest by Leonid Kadeniuk Avenue, on the southwest by Hnat Khotkevych Street, and on the south and east by the channel of Pliakhovyi Stream. This territory hosts chemical industry enterprises (former "Radykal", "Darna", and "Khimvolokno" plants) and a thermal power plant (TPP-4), the construction of which began in the 1950s [3].

In geomorphological terms, the study territory belongs to the first above-floodplain terrace of the Dnipro River, which forms part of the left-bank section of the Prydniprovska Lowland. Absolute elevations in the study area range from 100 to 103 meters [5].

The territory is practically horizontal, covered with alluvial sands and fill soils. It is dissected by the valley of Pliakhovyi Stream, which bounds the study area on the east and southeast. The stream originates near the village of Kniazhydi in Brovary district and flows into Nyzhniy Telbin Lake, and then into the Dnipro River. Within the industrial zone and before flowing into the lake, the stream channel has been engineered and is used as a drainage canal into which industrial wastewater is discharged.

The Dnipro River flows from north to south, 5 km west of the study area. The general surface slope of the area is directed westward toward the Dnipro River channel [7].

To assess the distribution of mercury contamination in the vertical cross-section within the study area, 22 exploratory monitoring wells were drilled in 2002, in which interval sampling was conducted to determine mercury content in the sediments of the vadose zone and the first aquifer from the surface [3]. In addition to the exploratory monitoring well, data from monitoring wells drilled in 1992 during previous investigations at the territory of the former «Radykal» plant were used to characterize the vadose zone.

The vadose zone in the study area consists of alluvial and fill sands and sandy loams with clays, locally containing construction waste that accumulated during the industrial zone development period. The thickness of the vadose zone materials ranges from 1.6 to 5.4 meters. Rock sampling intervals were: up to 1 m depth – every 0.25 meters, after 1 m to the water table – every 0.5 meters, from water-bearing layers to the bottom of the monitoring well – every 1 meter [3].

According to instrumental-laboratory measurements, significant exceedances of maximum permissible concentrations of mercury were detected. The results of the highest concentrations depending on depth and monitoring well are presented in Table 1.

Based on analytical data from mercury content analyses in vadose zone materials [3], a graph was constructed that shows the average differentiated mercury concentration values depending on the depth of rock occurrence in the vadose zone and the first aquifer from the surface at the territory of the "Radykal" plant.

The Quaternary alluvial aquifer in the area of the former "Radykal" plant is the first from the surface and contains unconfined groundwater.

Samples were collected from depths of 5–20 meters after pumping the monitoring wells for 1.5–2 hours. Based on the analysis results, it was established that mercury contamination plumes in groundwater practically coincide with the contaminated areas on the surface and in the vadose zone, but cover a larger area, facilitated by the spreading of mercury-contaminated waters from pollution sources in the direction of groundwater flow. The research results are presented in Table 2.

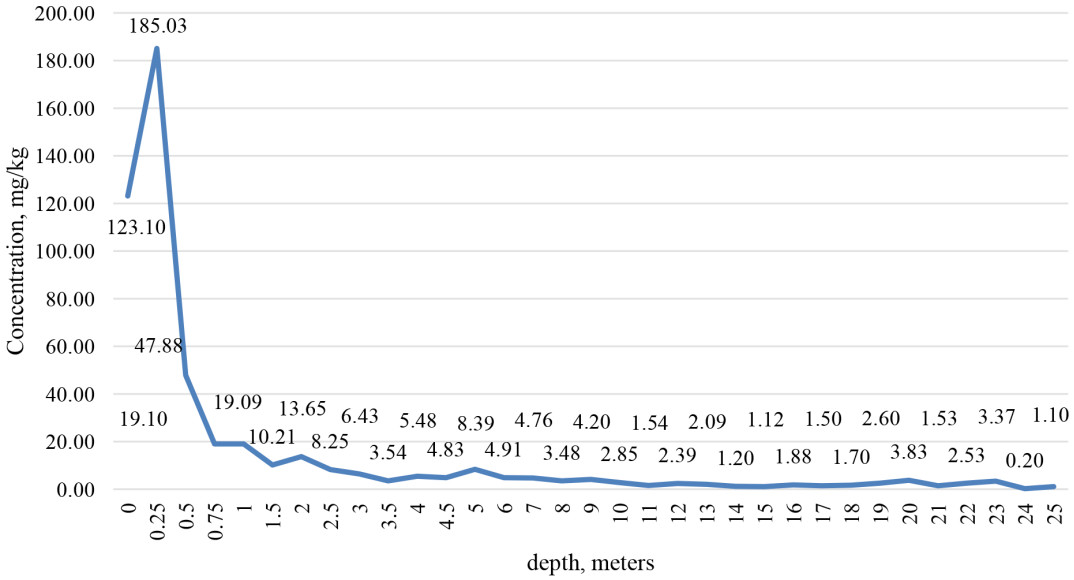
The analysis shows that the highest mercury contamination of soils in the vertical cross-section occurs to a depth of 1.0 meter and spatially coincides with the most heavily contaminated areas on the surface. It is concentrated mainly in the western part of the former "Radykal" plant and, partially, in the eastern part, where the main sources of mercury contamination are located – electrolyzers, brine dissolver, thermal sludge regeneration unit, sludge storage facility, and settling tanks.

Sources of groundwater mercury contamination were identified in the area of buildings of the former "Radykal" plant Nos. 1, 2, 3, 88, 102, 105, and 140, where mercury and water were used in production and from which groundwater contamination occurred through losses of mercury-containing compounds via leaking equipment and underground utilities. These buildings are located mainly in the western part of the former "Radykal" plant territory and border the territory of JSC "Khimvolokno" [3].

Table 1

Results of mercury content in vadose zone materials

Monitoring well No.	Depth, m	Concentration, mg/kg	Monitoring well No.	Depth, m	Concentration, mg/kg	Monitoring well No.	Depth, m	Concentration, mg/kg
94	0	877	68	0.75	232.8	68	3	18.6
67	0	506	69	0.75	23	69	3	64
68	0	162.4	94	0.75	45.4	82	3	21.5
69	0	712	110	0.75	83.4	94	3	9.2
82	0	39.2	111	0.75	31.3	66	3	44.8
97	0	69	69	1	27.3	105	3	10.3
81	0	249.5	82	1	52.8	69	3.5	38
66	0	76.5	87	1	58.8	82	3.5	18.9
91	0	29.1	101	1	191.4	94	3.5	10.4
67	0.25	340.5	110	1	127.8	93	3.5	6
68	0.25	264.5	111	1	29.2	105	3.5	9.56
69	0.25	752	68	1.5	23	67	4	16
82	0.25	192	84	1.5	61.2	69	4	39.5
97	0.25	86.4	87	1.5	28.5	94	4	19.4
81	0.25	97.5	101	1.5	79	80	4	10.8
93	0.25	85.2	110	1.5	30.6	105	4	12.74
105	0.25	191.2	111	1.5	27.6	85	4	10.8
98	0.25	82.6	68	2	132	67	4.5	9.4
101	0.25	90.5	69	2	27.4	69	4.5	44.7
110	0.25	196	82	2	17.2	94	4.5	12.3
94	0.25	3000	66	2	146.4	80	4.5	9.5
68	0.5	436	98	2	17.2	105	4.5	14.8
69	0.5	330	87	2	44.1	85	4.5	9.5
97	0.5	64.5	112	2	20.2	68	5	150.4
102	0.5	59.8	68	2.5	72.5	82	5	10.7
87	0.5	81.6	69	2.5	106	94	5	19.7
101	0.5	126.8	82	2.5	10.8	105	5	16.3
110	0.5	199.8	108	2.5	11.418	99	5	10.1
111	0.5	59.6	105	2.5	9.36	94	6	14
67	0.75	47	110	2.5	8.7	105	6	14.5

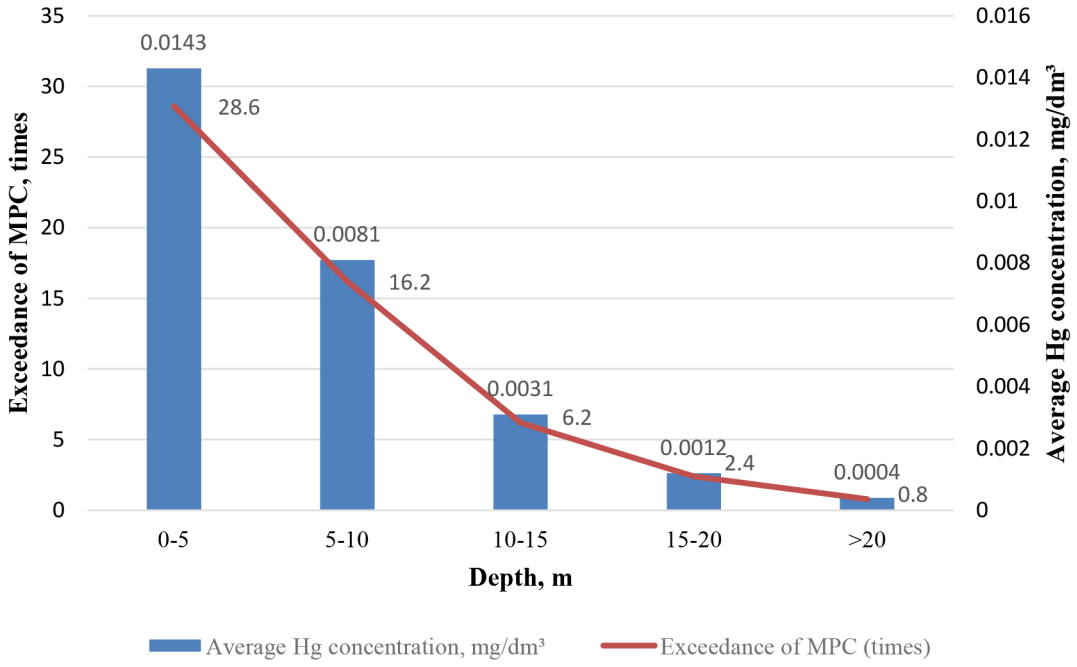


Graph 1. Average differentiated mercury concentration values in vadose zone materials depending on depth of occurrence

Table 2

Results of mercury determination in water from monitoring wells

Monitoring well No.	Number of samples	Min depth, m	Max depth, m	Hg min, mg/dm³	Hg max, mg/dm³	Hg average, mg/dm³
1	2	5.0	14.5	0.00016	0.00052	0.00034
2	2	4.9	14.5	0.00015	0.00025	0.00020
3	1	14.5	14.5	<0.0001	<0.0001	<0.0001
4	2	4.2	13.5	<0.0001	0.0001	0.0001
5	2	6.5	13.5	<0.0001	0.00068	0.00034
6	3	6.0	19.2	<0.0001	0.00064	0.00031
7	1	13.5	13.5	<0.0001	<0.0001	<0.0001
8	3	5.25	19.2	0.176	0.997	0.453
9	2	5.0	14.5	<0.0001	0.00056	0.00028
10	3	6.9	19.2	<0.0001	0.0013	0.00062
11	1	14.5	14.5	0.00065	0.00065	0.00065
12	3	6.2	18.7	0.0080	0.0589	0.0252
13	2	4.5	14.5	<0.0001	0.00062	0.00031
14	3	10.2	18.2	0.00066	0.00716	0.00441
15	2	4.75	13.5	0.00032	0.00058	0.00045
16	1	4.7	4.7	0.15	0.15	0.15
6-н	1	6.0	6.0	<0.0001	<0.0001	<0.0001
25-н	1	6.0	6.0	<0.0001	<0.0001	<0.0001
27-н	1	6.0	6.0	<0.0001	<0.0001	<0.0001
28-н	1	6.0	6.0	<0.0001	<0.0001	<0.0001
38-н	1	6.0	6.0	<0.0001	<0.0001	<0.0001
40-н	1	6.0	6.0	<0.0001	<0.0001	<0.0001



Graph 2. Distribution of groundwater contamination by depth

With increasing distance from the contamination sources along the direction of groundwater flow in territories adjacent to the former “Radykal” plant (the “Khimvolokno” enterprise), in monitoring wells Nos. 6, 10, 12, 14, and in the coastal part of Pliakhovyi Stream in monitoring well No. 16, the mercury content in all monitoring wells decreases tenfold with depth. However, the undeniable fact remains that in monitoring wells Nos. 8, 12, and 14 at terminal depth (21.0–21.5 meters), its content remains 1 to 372 times higher than the maximum permissible concentration, which indicates the spread of contamination to depths greater than the depths of the drilled monitoring wells.

Mercury contamination of groundwater has spread in western, southwestern, and southern directions to a distance of 700–900 meters from the contamination source. The greatest groundwater mercury contamination occurred near buildings where water, mercury, and its compounds were used in production and where there were losses of solutions and effluents through leaking tanks and collectors.

A map of the results from previous groundwater contamination studies is shown in Fig. 1 [3].

The main aquifers used for water supply to the population in the left-bank part of Kyiv, where the former “Radykal” plant is located, are the Cenomanian-Kelowian aquifer complex and the Middle Jurassic (Bajocian) aquifer. The Cenomanian-Callovian aquifer system in the left-bank territory of Kyiv is conditionally protected from surface contamination. It is overlain by a marl-chalk sequence up to 10 m thick and higher by Kaniv clays 5–7.0 m thick and the Eocene (Buchak) aquifer up to 40 m thick. When penetrating through the overlying aquifers and aquitards, mercury contamination

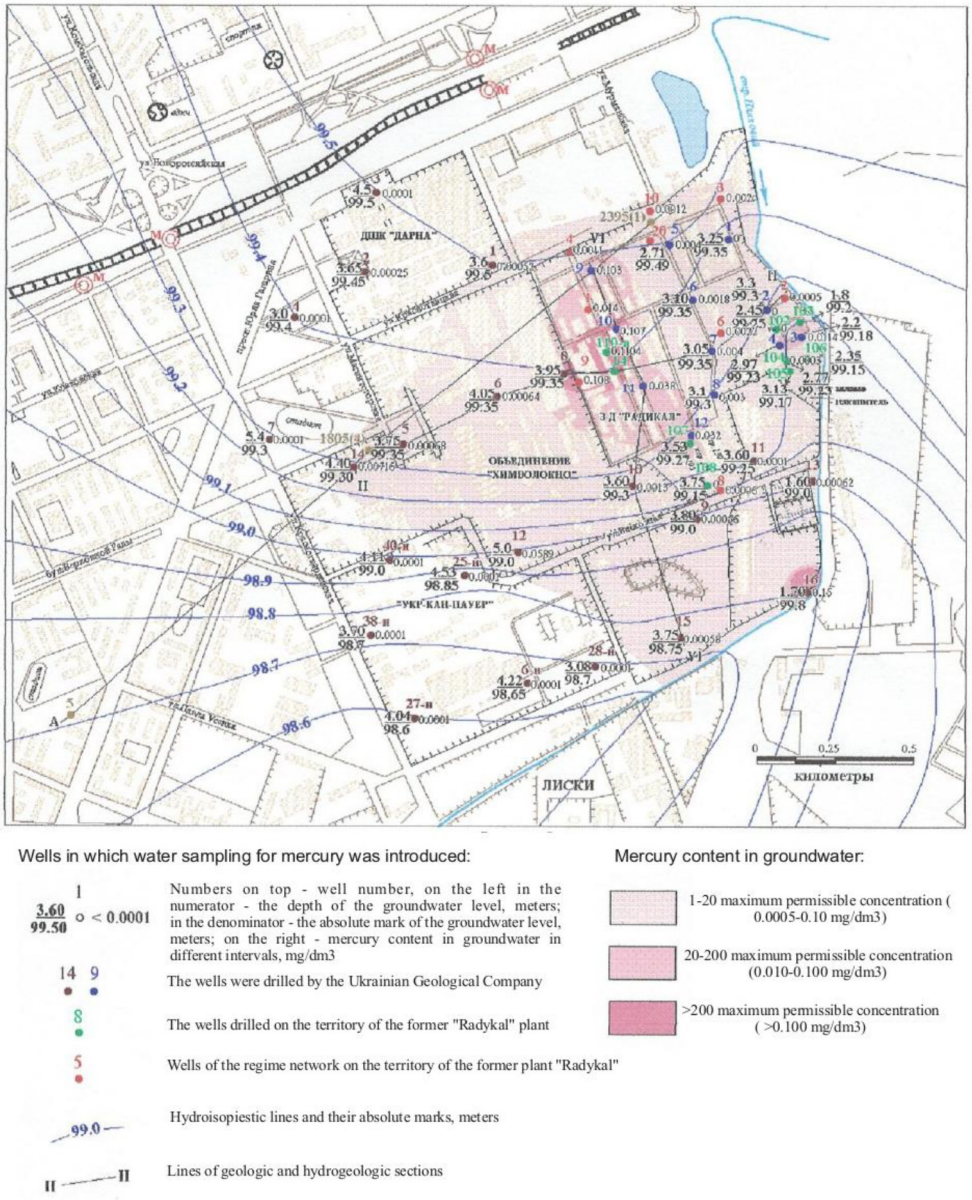


Fig. 1. Map of groundwater contamination previous research results

will be retained and diluted to a level below the maximum permissible concentration.

The mercury content in water from well No. 11 does not exceed the maximum permissible concentration (0.0005 mg/dm^3) but is 4 times higher than in other monitoring wells of this aquifer and equals 0.0004 mg/dm^3. This fact indicates vertical migration of contamination.

According to geological and hydrodynamic criteria, the aquifer of Bajocian deposits of the Middle Jurassic is classified as naturally protected.

Within the framework of previously conducted work, water samples were collected for mercury content determination from 9 monitoring wells exploiting this aquifer. Laboratory studies showed that the mercury content in water from these monitoring wells is less than 0.0001 mg/dm^3, i.e., below the detection limit of the method.

The study showed that the level of groundwater mercury contamination at the territory of the former "Radykal" plant significantly exceeds permissible standards. The assessment of aquifers by degree of protection from contamination is presented in the following table.

The plant's activities over many years, followed by its improper decommissioning, caused damage to the environment and posed a threat to the health of people living in this area.

Although groundwater may be contaminated with mercury due to the activities of the former «Radykal» plant, it is important to identify additional pollutants and specific sources causing this contamination. This may include a thorough analysis of the plant's operational history, including types of production, waste, and treatment systems. Further research should focus on:

– identifying sources of groundwater contamination with mercury as well as other chemical substances;

– developing methods for groundwater remediation;

– investigating the effects of mercury on human health.

It is necessary to conduct research aimed at studying the mechanisms and pathways of mercury migration in soil and groundwater. This may include analysis of hydrogeological conditions, soil cover characteristics, and hydrological processes. Additional studies aimed at examining the specific consequences of groundwater contamination with mercury and other pollutants will help understand the impact on the ecosystem.

Assessment of effectiveness and development of remediation and treatment strategies for contaminated groundwater may include testing various water treatment technologies for mercury compounds and determining the most effective methods for this specific case.

The obtained data indicate the need for urgent groundwater remediation measures at the territory of the former "Radykal" plant. Establishment of a monitoring and control system for groundwater mercury contamination levels can serve as a tool for continuous tracking of dynamics and effectiveness of contamination management measures. The mentioned additional research will help not only to better understand the scale of the groundwater mercury contamination problem but also guide the process of developing and implementing strategies for its resolution.

It is important to note that the problem of groundwater contamination is not unique to Ukraine. This is a global problem that requires comprehensive solutions at the international level.

Conclusions. Groundwater contamination at the territory of the "Radykal" plant has significant magnitude. Contaminated areas extend several kilometers from the plant and cover the industrial zone. Previous groundwater quality studies were predominantly conducted only for mercury content; however, other contaminants have not been fully investigated.

Pollutants migrate in groundwater through aquifers, negatively affecting soils and surface waters. This creates a risk of contaminants entering the human body through drinking water, food products, and contact with soil, as well as destruction of natural ecosystems.

Groundwater contamination poses serious risks to public health. Prolonged exposure to pollutants can lead to the development of various diseases.

Despite the conducted research, there is a lack of data regarding:

– the impact of contamination on public health, which indicates the need for appropriate studies as well as identification of potential links between contamination and disease;

– the impact of contamination on ecosystems, which indicates the need to conduct more detailed research

Table 3

Assessment of aquifers by degree of protection from contamination at the territory of the former "Radykal" plant

Aquifer	Depth of occurrence, m	Thickness, m	Degree of protection	Presence of mercury contamination
Quaternary alluvial	2–5	up to 30	Unprotected	Detected (up to 1994 MPC)
Eocene (Buchak)	15–35	up to 40	Weakly protected	Local (up to 8 MPC)
Cenomanian-Callovian	100–115	10–30	Conditionally protected	Not detected (<1 MPC)
Bajocian	210–65	40–50	Naturally protected	Not detected

to assess the impact of contamination on biodiversity, ecosystem functioning, and soil quality;

– the effectiveness of remediation methods. It is necessary to conduct a comparative analysis of different remediation methods to determine the most effective and economically feasible approaches to groundwater treatment.

The following directions for further research can be identified:

– studying pathways of contaminant migration in groundwater to predict their spread and assess environmental risks;

– research and implementation of innovative technologies for groundwater treatment;

– development of models for predicting contamination spread and risk assessment for various development scenarios.

Conducting the aforementioned research will provide the opportunity to more thoroughly investigate the impact on groundwater in the area of the former «Radykal» plant.

Prospects for using research results. The research results identify important aspects of environmental safety and sustainable use of natural water resources in industrial regions. The obtained data indicate the need for urgent measures for groundwater remediation at the territory of the former «Radykal» plant. Establishment of a monitoring and control system for groundwater mercury contamination levels can serve as a tool for continuous tracking of dynamics and effectiveness of contamination management measures.

The following directions for further research can be identified: studying pathways of contaminant migration in groundwater to predict their spread and assess environmental risks using mathematical modeling and GIS technologies; research and implementation of innovative technologies for groundwater treatment, such as nanotechnologies, bioremediation, and phytoremediation; development of models for predicting contamination spread and risk assessment for various development scenarios.

Implementation of the aforementioned actions will improve the environmental situation in the area of the former «Radykal» plant and ensure protection of public health and the environment. These additional studies will help not only to better understand the scale of the groundwater mercury contamination problem but also guide the process of developing and implementing strategies for its resolution.

It is important to note that the problem of groundwater contamination is not unique to Ukraine. This is a global problem that requires comprehensive solutions at the international level. The experience of remediation at the territory of the former «Radykal» plant can be useful for addressing similar problems in other regions of Ukraine and the world.

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