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TRANSFORMATION OF GROUNDWATER HYDRODYNAMIC AND HYDROGEOCHEMICAL REGIMES UNDER THE INFLUENCE OF LONG-TERM COAL MINE OPERATION IN THE WESTERN DONBAS

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The article presents the results of a comprehensive study of the transformation of the hydrodynamic and hydrogeochemical regimes of groundwater within the zone of influence of coal mining enterprises in the Western Donbas. The research is based on long-term monitoring of groundwater levels in different aquifers during 2010–2025, together with data on mine water mineralization and groundwater inflow rates. Spatial-statistical, cartographic, trend, and correlation analyses integrated with GIS technologies were applied to assess the long-term evolution of the groundwater system. The study identified the principal patterns of spatio-temporal transformation of the hydrodynamic regime caused by prolonged mine dewatering. Localized cones of depression were found to develop within the Paleogene aquifers, where groundwater levels declined by up to 8 m, while the Quaternary aquifer experienced a regional groundwater-level decrease of up to 2.5 m. A mechanism explaining the inversion of piezometric level changes in the Buchak and Obukhiv formation aquifers is proposed and substantiated. This inversion is associated with the transformation of the natural groundwater recharge and drainage system under the influence of continuous mine drainage. Analysis of long-term monitoring data demonstrated that groundwater inflow to the Dniprovska Mine increased more than tenfold, whereas the average mineralization of mine water increased almost fourfold. Third-order polynomial trend models ($R^2 = 0.6855$ and $R^2 = 0.7375$) reveal the staged transformation of the hydrodynamic and hydrogeochemical regimes during prolonged coal mining.

The scientific novelty of the study lies in identifying the regularities of the spatio-temporal transformation of groundwater within different aquifers of the WD based on a fifteen-year monitoring dataset and in substantiating the mechanism responsible for the inversion of piezometric levels induced by long-term mine drainage. The practical significance of the research consists in the applicability of the obtained results for predicting the development of groundwater depression cones, assessing environmental risks, improving groundwater monitoring systems, and supporting sustainable groundwater resource management in mining regions. *Key words:* groundwater; hydrodynamic regime; hydrogeochemical regime; mine drainage; cone of depression; mineralization; groundwater inflow; Western Donbas; aquifer groundwater; monitoring.

Трансформація гідродинамічного та гідрохімічного режимів підземних вод під впливом тривалої експлуатації вугільних шахт західного Донбасу. Д'яченко Н.О.

Означені результати комплексного дослідження трансформації гідродинамічного та гідрогеохімічного режиму підземних вод у зоні впливу вугледобувних підприємств Західного Донбасу. Наукова праця виконана на основі багаторічних режимних спостережень за рівнями підземних вод різних водоносних горизонтів упродовж 2010–2025 рр., даних щодо мінералізації шахтних вод та інтенсивності водоприпливів. Під час науково-екологічних досліджень використовувалися методи просторово-статистичного, картографічного, трендового та кореляційного аналізу із застосуванням ГІС-технологій. Встановлено закономірності просторово-часової перебудови гідродинамічної системи під впливом тривалого шахтного водовідливу. Виявлено формування локальних депресійних лійок у палеогенових водоносних горизонтах із максимальним зниженням рівнів до 8 м та регіональне зниження рівнів четвертинного водоносного горизонту до 2,5 м. Обґрунтовано механізм інверсії змін п'єзометричних рівнів у бучацькому та обухівському водоносних горизонтах, пов'язаний із трансформацією природної системи живлення та дренування підземних вод. Аналіз багаторічних моніторингових даних показав, що інтенсивність водоприпливів до шахти «Дніпровська» збільшилася більш ніж у десять разів, тоді як середня мінералізація шахтних вод зросла майже у чотири рази. Поліноміальні тренди третього порядку ($R^2 = 0{,}6855$ та $R^2 = 0{,}7375$) відображають стадійний характер перебудови гідродинамічного та гідрогеохімічного режимів у процесі тривалої експлуатації родовища.

Наукова новизна дослідження – визначення закономірностей просторово-часової трансформації підземних вод різних водоносних горизонтів Західного Донбасу за результатами п'ятнадцятирічного моніторингу та обґрунтуванні механізму інверсії п'єзометричних рівнів під впливом шахтного водовідливу. Практичне значення наукової праці – використання отриманих результатів під час прогнозування розвитку депресійних лійок, оцінювання екологічних ризиків, удосконалення систем моніторингу та управління водними ресурсами. *Ключові слова:* підземні води; гідродинамічний режим; гідрогеохімічний режим; шахтний водовідлив; депресійна лійка; мінералізація; водоприплив; Західний Донбас; водоносний горизонт; моніторинг, екологія довкілля.

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Problem statement. The Western Donbas (WD) is currently one of the largest underground coal mining regions in Ukraine, where industrial mine operation has continued for more than sixty years. Long-term mine drainage, the development of new mining horizons, the formation of mining-induced rock mass fracturing, and the intensification of hydraulic connections between aquifers have resulted in significant transformation of the natural hydrogeological environment. These processes lead to the formation of groundwater depression cones, changes in groundwater flow directions, redistribution of groundwater recharge and discharge areas, and deterioration of groundwater hydrochemical characteristics [1]. Mine water is one of the major sources of contamination of surface water bodies and the hydraulically connected groundwater [2].

Of particular environmental concern is the transformation of hydraulic interaction between aquifers of different geological ages, accompanied by the involvement of more highly mineralized confined groundwater in the mine drainage system, changes in groundwater recharge conditions, and the potential deterioration of groundwater quality used for domestic and drinking water supply. Under the current conditions of transformation of Ukraine's coal mining industry, forecasting long-term changes in the hydrodynamic and hydrogeochemical regimes of groundwater has become particularly important. Groundwater contamination caused by mining activities further aggravates the adverse environmental impacts of mineral extraction and may result in long-term and irreversible consequences for the environment. The current environmental legislation of Ukraine [3] requires environmental impact assessment of industrial activities, including their impact on groundwater.

Research relevance. The current stage of development of the coal mining industry is characterized not only by the operation of active mines but also by the closure of individual mining enterprises and changes in mine drainage regimes. Under these conditions, assessing long-term changes in the hydrodynamic and hydrogeochemical regimes of groundwater becomes particularly important, as these changes determine environmental safety, the condition of groundwater resources, and the extent of potential secondary contamination of the geological environment [4]. Despite the considerable number of previous studies, most of them have focused on individual aspects of mine drainage or local groundwater-level changes. Comprehensive investigations of the spatio-temporal transformation of the multi-aquifer groundwater system of the WD based on long-term monitoring observations are virtually absent. Therefore, an integrated analysis of long-term monitoring data using modern spatial analysis methods is of considerable scientific and practical importance.

Relationship of the study to important scientific and practical tasks. The study was carried out within the research activities of the State Institution «Scientific Centre for Mining Geology, Geoecology and Infrastructure Development of the National Academy of Sciences of Ukraine», aimed at assessing the technogenic transformation of the geological environment, ensuring the environmental safety of mining regions, and providing a scientific basis for the rational use and protection of groundwater resources. The objective of the study was to identify the patterns of spatio-temporal transformation of the hydrodynamic and hydrogeochemical regimes of groundwater within the zone of influence of coal mining enterprises in the WD based on long-term monitoring observations, statistical analysis, and GIS modelling, as well as to assess the degree of technogenic impact of mine drainage on aquifer conditions. The study is consistent with the current national priorities in the fields of environmental protection, water resources management, adaptation of mining regions to environmental challenges, and implementation of the provisions of the State Environmental Policy Strategy of Ukraine. The practical significance of the study lies in the possibility of applying the obtained results for predicting the development of groundwater depression cones, assessing changes in the hydrogeochemical regime, improving groundwater monitoring systems, and substantiating mine drainage management strategies.

Research methods. The study was based on long-term monitoring observations of groundwater levels and hydrochemical parameters obtained from 85 observation wells located within the Pavlograd–Petropavlivka Coal Mining District. To achieve the research objective, comparative hydrogeological regime analysis, spatial-statistical analysis, cartographic modelling, trend analysis, and correlation analysis were applied. Spatial interpretation of the results was carried out using GIS technologies through the construction of groundwater-level change maps and analysis of the patterns of groundwater depression cone development.

Analysis of recent research and publications. Research into the impact of mining activities on groundwater regimes is one of the key areas of modern hydrogeology and geoecology. In Ukraine, significant contributions to the study of the mechanisms governing mine drainage, the development of groundwater depression cones, and the transformation of hydrogeochemical regimes have been made by V. Suyarko [5], I. Sadovenko [6], D. Rudakov [7], O. Ulytskyi [8], and other researchers. Their studies identified the characteristics of technogenic hydrodynamic regime formation in coal mining regions, evaluated the impact of mine drainage on the quality of groundwater and surface water, and substantiated the principal mechanisms responsible for the development of mining-induced groundwater depression. In studies [9, 10], the authors addressed the formation of regional groundwater depression cones caused by mine dewatering and groundwater abstraction, as well as the correlation between groundwater chemical composition and hydrogeological conditions.

At the same time, recent international studies demonstrate that geoinformation technologies, spatial analysis,

mathematical modelling, and long-term monitoring methods are increasingly applied to assess long-term changes in hydrogeological systems. Particular attention is paid to predicting the transformation of aquifer systems following prolonged mine operation, evaluating the relationships between hydrodynamic and hydrochemical processes, and quantitatively assessing environmental risks [11].

Unresolved aspects of the general problem addressed by this study. Despite the considerable body of previous research, the patterns of spatio-temporal transformation of the multi-aquifer system of the WD under the combined influence of mine drainage, groundwater abstraction, and mining-induced modification of the filtration environment remain insufficiently understood. Comprehensive assessments of groundwater-level changes in different aquifers based on long-term monitoring observations using modern GIS technologies, statistical analysis, and integrated interpretation of hydrodynamic and hydrogeochemical processes are virtually absent.

Further investigation is required into the inversion of piezometric levels in the confined Paleogene aquifers, the characteristics of groundwater flow reorganization, and the relationships between the development of cones of depression, the intensity of mine drainage, and changes in mine water mineralization. The present study is aimed at addressing these issues.

Scientific novelty. The scientific novelty of this study lies in identifying the patterns of spatio-temporal transformation of the hydrodynamic and hydrogeochemical regimes of groundwater in the Western Donbas based on the results of fifteen years of monitoring observations. For the first time in the study area, an inversion pattern of piezometric-level changes has been identified in the Upper Paleogene aquifers. The mechanism responsible for its formation under the influence of long-term mine drainage has been substantiated, and the staged transformation of the hydrogeochemical regime has been established on the basis of long-term observations of mine water mineralization and groundwater inflow.

Main text. Coal mining in the Western Donbas has been carried out for more than six decades and has become one of the principal factors controlling the transformation of the region's hydrogeological conditions. Industrial development of the coal basin began in 1959 with the commissioning of the Ternivska Mine. Between 1963 and 1975, ten additional mines were brought into operation: Pershotravneva, Zakhidno-Donbaska, Pavlogradska, Blagodatna, Heroes of Space, Yuvileina, Stashkova, Samarska, Dniprovska, and Stepova (Fig. 1).

The Stashkova Mine completed extraction of its principal coal reserves in 2019, after which mining continued only within adjacent reserve blocks. Since 2021, the mine has been undergoing closure, accompanied by the gradual natural flooding of underground workings. At present, coal production is carried out by nine operating mines, with the greatest production concentrated within the central mining group, which accounts for the majority of current coal output in the WD [12, 13].

In addition to the coal mines, the study area includes a system of centralized groundwater wellfields (Verbskyi, Pavlogradskyi, Samarskyi, Ternivskyi, Svitlogorskyi, Pervomaiskyi, etc.), which mainly exploit groundwater from aquifers occurring within the Buchak and Kyiv Formations. Their long-term operation has resulted in the development of regional cones of depression superimposed on the technogenic drawdown cones produced by continuous mine dewatering. Groundwater regime and hydrochemical monitoring has been conducted since 1989 through a network of 85 observation wells (Figure 1) covering the principal aquifers of the Meso-Cenozoic hydrogeological sequence. Monitoring has been performed by Ukrgeologia LLC in accordance with approved hydrogeological monitoring programs [14, 15]. These long-term observations constitute the primary database for assessing temporal changes in groundwater hydrodynamic and hydrochemical regimes.

Geological and hydrogeological characteristics of the study area. From a geostructural perspective, the Pavlograd–Petropavlivka coal mining district is confined to the southwestern part of the Novomoskovsk–Petropavlivka monocline zone of the Dnieper–Donets Basin, which borders the northeastern slope of the Ukrainian Shield. The study area is located within the Samara horst uplift and is characterized by a complex block-faulted structure [16, 17], which controls the heterogeneity of groundwater flow conditions and the hydraulic interconnection between individual aquifers.

The relief is represented by a gently undulating denudation–accumulation plain dissected by the valleys of the Samara, Vovcha, Ternivka, and Byk rivers, as well as by a dense network of gullies and ravines. Absolute ground elevations range from +60 to +210 m, determining the characteristics of present-day surface runoff and groundwater flow.

The geological structure of the study area comprises Precambrian crystalline basement rocks overlain by a thick succession of Carboniferous, Triassic, Jurassic, Paleogene, Neogene, and Quaternary sedimentary deposits. Quaternary deposits are represented by loess-like loams, clays, and alluvial sands that form the upper unconfined aquifer. The thickness of the Quaternary sediments ranges from 5 to 35 m, while groundwater occurs at depths between 6 and 14 m below ground surface. Groundwater mineralization generally varies from 0.5 to 5.0 g/L.

Neogene deposits occur only locally and do not play a significant role in supplying groundwater inflows to the mines. The principal aquifer systems of the study area are associated with the Paleogene deposits, represented by the Buchak, Kyiv, Mezhigirska, and Berek Formations. The most productive groundwater reservoir is formed by the quartz sands of the Buchak Formation, which are extensively exploited for centralized municipal drinking water supply. These deposits are charac-

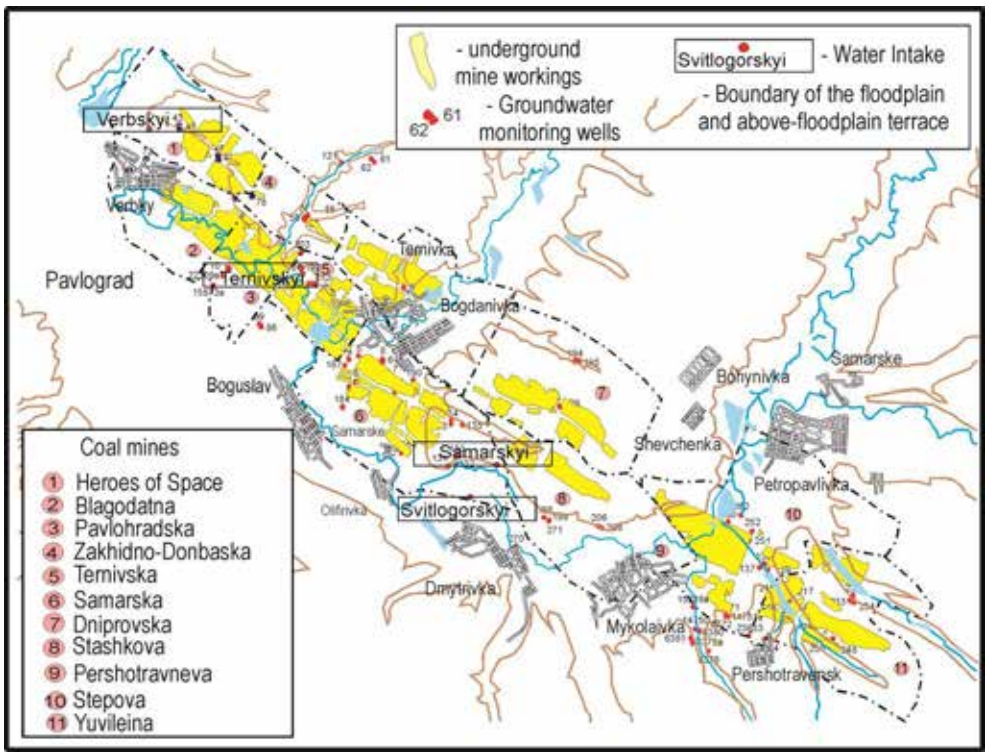


Fig. 1. Detailed layout of the study area and monitoring network

terized by high hydraulic conductivity and are hydraulically connected with the underlying aquifers.

The Carboniferous aquifer complexes, which constitute the principal source of groundwater inflows into underground mine workings, occur immediately beneath the Paleogene deposits. Owing to the discontinuous distribution and limited continuity of aquitards separating the individual stratigraphic units, active vertical groundwater exchange occurs throughout the study area. This hydraulic interaction has been substantially intensified by long-term mine dewatering.

Results of the monitoring data analysis. The transformation of the groundwater hydrodynamic regime was assessed by comparing the absolute groundwater level elevations obtained from monitoring observations conducted in June 2010 and June 2025. The analysis included measurements from 18 observation wells completed in the Quaternary aquifer, 19 wells in the Buchak–Obukhiv aquifer formation, and 36 wells in the Mezhigirska–Berek aquifer formation. In total, the study included 73 representative observation wells, providing uniform spatial coverage across the territories of eleven mining lease areas. The comparative analysis (Figure 2) indicates pronounced spatial heterogeneity in groundwater-level changes.

The largest amplitudes of groundwater-level change were recorded within the Buchak–Obukhiv aquifer system, where absolute piezometric-level variations range from +6 to –8 m. In contrast to the Paleogene aquifers, the Quaternary aquifer exhibits a predominantly regional decline in groundwater levels of approximately 2–2.5 m, spatially associated with river valleys and the gully–ravine network. This pattern indicates the predominance of natural drainage through the surface hydrographic network, which is further enhanced by the technogenic lowering of the regional groundwater table.

Cartographic modelling of the monitoring data (Figures 3–4) made it possible to characterize in greater detail the spatial configuration of the groundwater depression zones.

The largest drawdowns (up to 8 m) were identified in the Mezhyhirska and Berek aquifers within the areas of intensive mining operations [16, 17], namely at the Zakhidno-Donbaska, Blagodatna, Dniprovska, and Samarska mines, where new mining blocks and coal seams have been developed in recent years (Fig. 4).

The spatial coincidence of the maximum groundwater-level declines with the currently active mining areas indicates the dominant role of mine dewatering in shaping the present-day hydrodynamic field. The expansion of the depression zones beyond the initial boundaries of the mining areas confirms the involvement of adjacent aquifers in the drainage process. Particularly noteworthy is that the present-day depression troughs are formed not only above active longwall mining panels but also extend over large areas between adjacent mine fields. This indicates the development of an integrated regional system of anthropogenic drainage.

At the same time, the Buchak–Obukhiv Formations exhibits an inverse pattern of groundwater-level changes. Areas that were characterized by elevated piezometric levels under natural conditions have become the zones

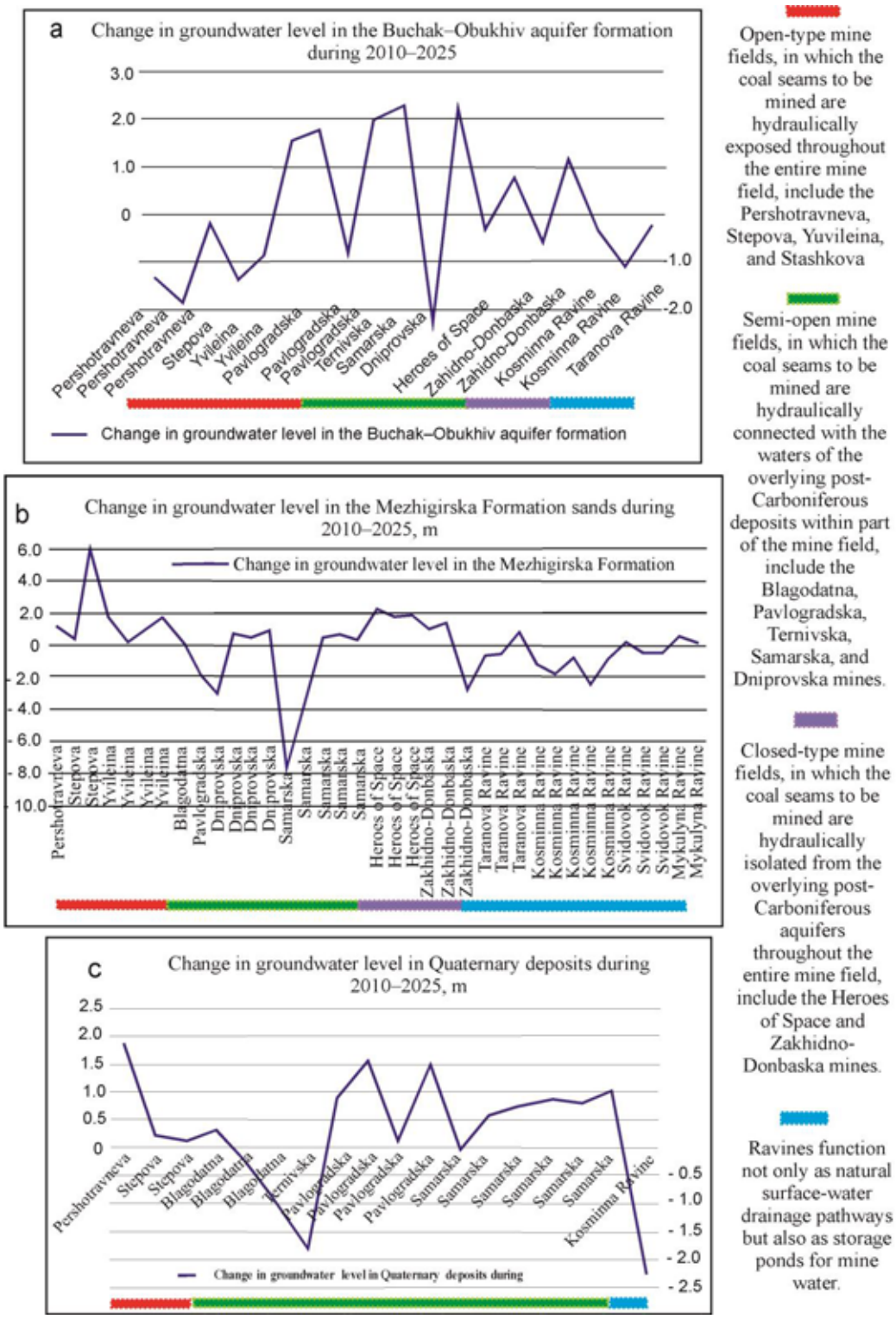


Fig. 2. Results of the comparative analysis of groundwater-level changes in different aquifer systems over a 15-year period

of the greatest groundwater-level decline under present-day conditions.

This distribution pattern indicates an inversion of the hydrodynamic regime caused by the transformation of the natural groundwater recharge system under the influence of mine drainage. Confined aquifers that formerly functioned as groundwater accumulation zones have gradually become areas of intensive discharge, while the direction of groundwater flow has changed from predominantly lateral to vertically downward.

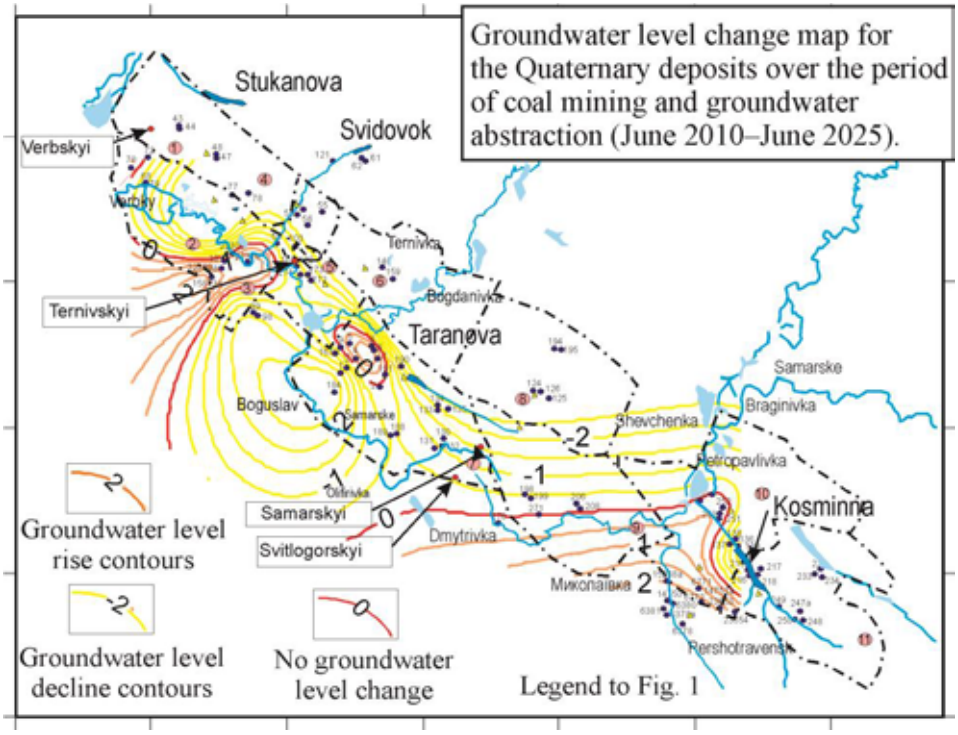


Fig. 3. Maps of groundwater level changes (2010–2025) in the Quaternary deposits within the study area

The nearly ubiquitous decline in groundwater levels within the Quaternary aquifer, reaching up to 2.5 m (Fig. 3), indicates the formation of a regional cone of depression spatially controlled by the present-day hydrographic network. This confirms the decisive role of the surface drainage system in the redistribution of groundwater resources under the influence of prolonged mine dewatering.

Thus, the results of the cartographic analysis demonstrate that long-term coal mining has led not only to the formation of local cones of depression but also to a regional restructuring of the entire hydrodynamic system of the Western Donbas.

Analysis of Long-Term Monitoring Data on Mine Water Inflow and Mine Water Mineralization (Case Study of the Dniprovska Mine). To evaluate the long-term transformation of the hydrogeochemical regime of groundwater, long-term monitoring data on mine water inflow and mine water mineralization at the Dniprovska Mine for the period 1975–2019 were analyzed. This mine was selected because of its long operational history, the completeness of the monitoring records, and its relatively simple hydrogeological conditions, which make it possible to identify the patterns of hydrological regime transformation during the progressive development of mining operations. The Dniprovska Mine is characterized by relatively low natural groundwater inflow. During the initial stage of mine operation, groundwater inflow originated predominantly from the Carboniferous aquifer system. Only coal seam C_{10}^{v} is in direct hydraulic contact with the water-bearing deposits of the Buchak Formation, whereas the remaining productive coal seams are overlain by a thick sequence of low-permeability rocks. In addition, the Bohdanivskyi and Pozdovzhnii faults act as regional hydrogeological barriers, substantially restricting groundwater inflow from adjacent areas.

As mining operations progressed and the mined-out area expanded, the cone of depression gradually enlarged, resulting in the involvement of groundwater from adjacent aquifers in the drainage process. This was reflected in both an increase in mine water inflow and changes in the chemical composition of mine water (Fig. 5).

The monitoring data indicate that during the study period the mineralization of mine water increased from 5.8–7.0 g/L at the initial stage of mine operation to 20–22 g/L under present-day conditions (Fig. 5). During the same period, the average mine water inflow increased more than tenfold, from 41 m³/h to 454 m³/h.

The obtained relationships indicate that changes in mine water mineralization are not monotonic. The curve clearly demonstrates several distinct stages corresponding to different phases in the development of the depression system. The initial stage is characterized by a relatively stable chemical composition of mine water, which can be explained by the predominance of drainage from the upper, weakly mineralized aquifers. The subsequent increase in mineralization indicates the gradual involvement of deeper confined groundwater from the Paleogene and Carboniferous aquifer systems in the mine dewatering process.

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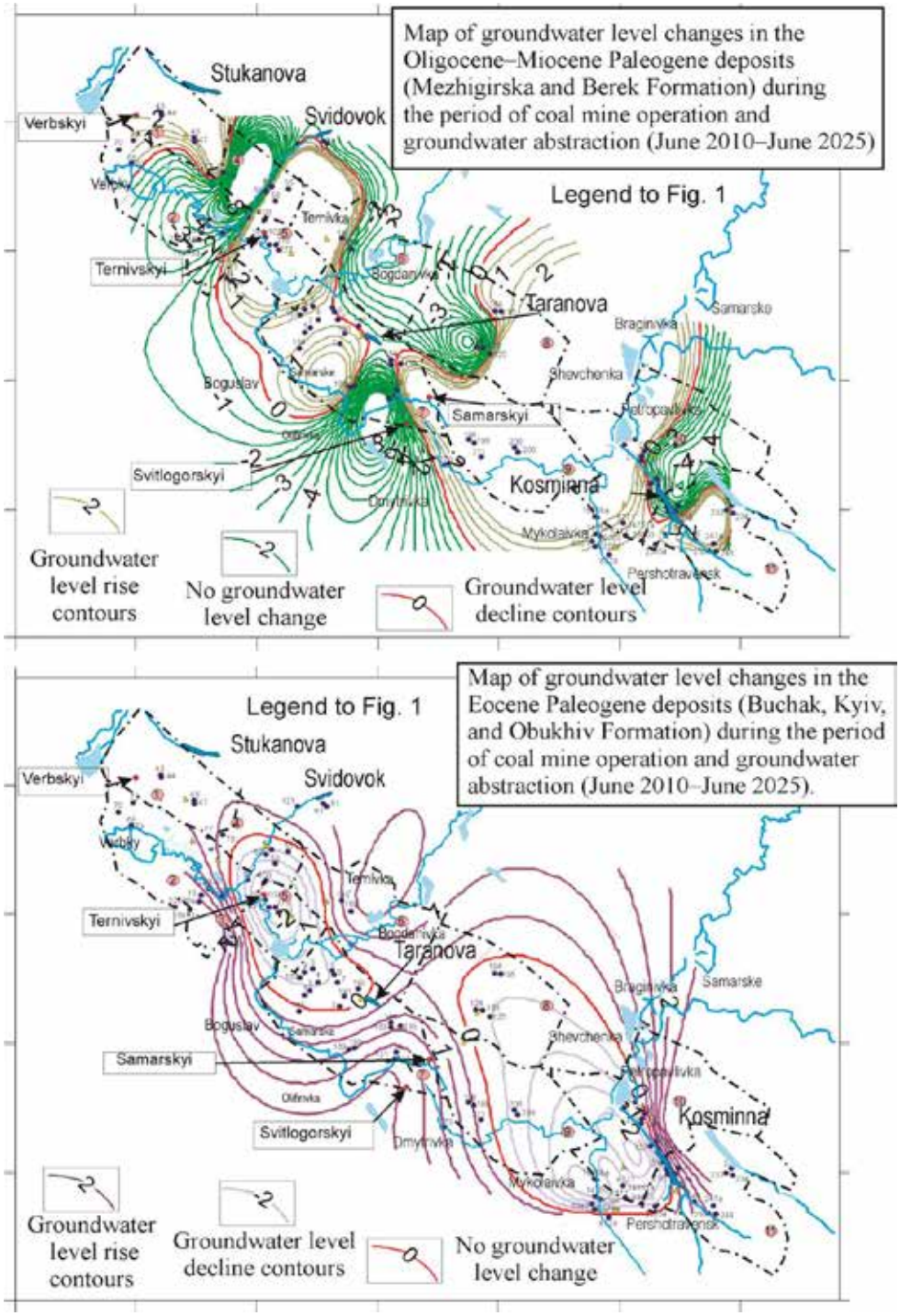


Fig. 4. Maps of groundwater level changes (2010–2025) in the Oligocene–Miocene (a) and Eocene (b) Paleogene deposits within the study area

To quantitatively evaluate the relationship between the hydrodynamic and hydrogeochemical parameters, the dependence between mine water inflow and mine water mineralization was analyzed (Fig. 6).

The correlation analysis yielded a correlation coefficient of r = 0.29, indicating a positive, although moderate, relationship between these parameters. This suggests that the increase in mine water inflow is not accompanied by dilution of mine water, as would typically be expected where recharge is dominated by atmospheric precipitation or groundwater from the Quaternary aquifer. Instead, the progressive development of mine dewatering results in the gradual involvement of more highly mineralized confined groundwater, leading to a simultaneous increase in both mine water inflow and overall mineralization.

A distinctive feature of the observed relationships is their pronounced nonlinear character. Linear trend lines

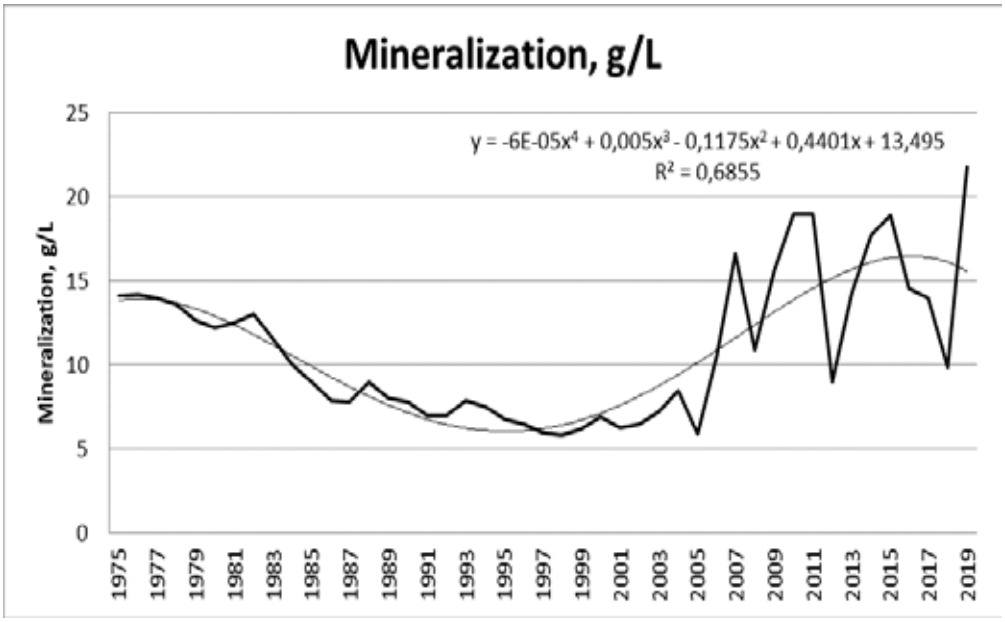


Fig. 5. Temporal changes in mine water mineralization over a 45-year period at the Dniprovska Mine

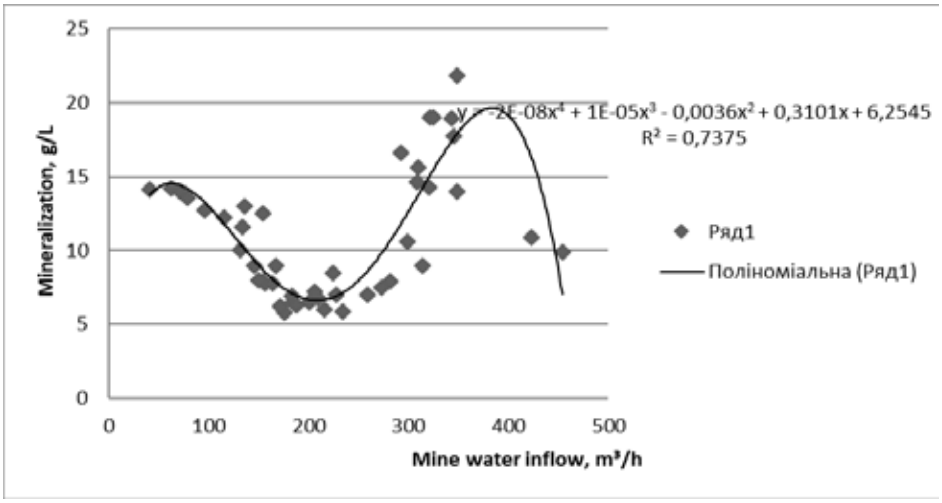


Fig. 6. Relationship between mine water inflow and mine water mineralization at the Dniprovska Mine

describe only the overall tendency of increasing mine water inflow (on average 6.7 m³/h per year) and mine water mineralization (approximately 0.09 g/L per year), but they do not adequately represent the evolution of the process. The best fit to the observed data is provided by third-order polynomial trend lines, with coefficients of determination of $R^2 = 0.7375$ for mine water inflow and $R^2 = 0.6855$ for mine water mineralization.

The shape of these trend curves indicates that the transformation of the hydrogeological system did not occur continuously but proceeded in distinct stages corresponding to the progressive development of mining operations and the sequential involvement of additional aquifers within the zone affected by mine dewatering.

Three principal stages of this process can be distinguished. The first stage (1975–mid-1980s) was characterized by relatively low mine water inflow (less than 100 m³/h) and comparatively low mine water mineralization (5.8–7.0 g/L). During this period, groundwater inflow originated predominantly from the Carboniferous aquifer system and the upper weakly mineralized aquifers.

The second stage (late 1980s–early 2000s) corresponded to the active expansion of the cone of depression. During this period, mine water inflow increased to 150–300 m³/h, while mineralization rose to 8–14 g/L, indicating the progressive involvement of groundwater from the Bucha and Obukhiv aquifers.

The third stage (after 2005) is characterized by the development of an integrated regional drainage system. Mine water inflow exceeded 300 m³/h, whereas mine water mineralization reached 20–22 g/L. These changes

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indicate the intensive inflow of deep confined groundwater, enhanced hydraulic interaction between aquifers, and the increasing role of tectonically disturbed zones as preferential groundwater flow pathways.

The obtained results clearly demonstrate that prolonged mine operation leads not only to an increase in mine water inflow but also to a fundamental restructuring of the regional hydrodynamic system. The development of a regional cone of depression is accompanied by changes in groundwater flow directions, enhanced hydraulic connectivity between previously isolated aquifers, and the progressive involvement of deep, highly mineralized groundwater in the mine drainage system. These processes govern the present-day transformation of the hydrogeochemical regime of groundwater in the WD.

Conclusions. The present study provides a comprehensive assessment of the long-term transformation of the hydrodynamic and hydrogeochemical regimes of groundwater within the Pavlohrad–Petropavlivka coal mining district under conditions of prolonged coal mining. Analysis of monitoring data collected during 2010–2025, together with statistical processing of long-term observations, made it possible to identify the principal patterns of aquifer transformation induced by mine dewatering.

The results demonstrate that during the last fifteen years a system of local cones of depression has developed within the Paleogene aquifers in the central group of mines of the Western Donbas, with groundwater-level declines reaching 8 m, whereas the maximum decline within the Quaternary aquifer is approximately 2.5 m. The spatial distribution of these depression zones closely corresponds to the areas of the most intensive current mining activity.

For the first time within the study area, a comparative analysis of hydroisohypse maps for 2010 and 2025 has revealed fundamentally different responses of individual aquifer systems to anthropogenic loading. The Quaternary aquifer exhibits a regular groundwater-level decline spatially consistent with the hydrographic network, whereas the Buchak and Obukhiv aquifers Formations display an inversion of piezometric levels caused by the redistribution of groundwater flow and the transformation of natural recharge areas into zones of intensive anthropogenic drainage.

The study demonstrates that mine dewatering results not only in local groundwater-level decline but also in a comprehensive restructuring of the regional hydrodynamic system. The principal manifestation of this transformation is the change in groundwater flow patterns from predominantly lateral natural flow to vertically downward flow, which promotes the active involvement of confined groundwater from the Paleogene and Carboniferous deposits in the mine drainage system.

Analysis of long-term monitoring data from the Dniprovska Mine revealed a persistent simultaneous increase in mine water inflow and mine water mineralization. During the study period, the average mine water inflow increased by approximately 6.7 m^3/h per year, while the average mineralization increased by 0.09 g/L per year. The obtained correlation coefficient ($r = 0.29$) indicates a positive, although moderate, relationship between these variables, confirming the progressive involvement of more highly mineralized confined groundwater in the mine drainage system.

Temporal variations in both mine water inflow and mineralization are best described by third-order polynomial trends ($R^2 = 0.7375$ and $R^2 = 0.6855$, respectively), reflecting the stagewise evolution of the hydrogeological system. Three principal stages of this evolution were identified: the initial drainage of shallow aquifers, the progressive involvement of the Paleogene aquifer systems, and the present stage characterized by the intensive inflow of confined and more highly mineralized groundwater.

The obtained results indicate that prolonged coal mining in the Western Donbas is accompanied not only by the depletion of individual aquifers but also by enhanced hydraulic connectivity between aquifers, changes in groundwater flow directions, mixing of groundwater of different origins, and the development of new hydrogeochemical conditions within the anthropogenically transformed geological massif.

Prospects for the Application of the Research Results. The results obtained may be applied to predict the development of cones of depression and changes in the hydrogeochemical regime of groundwater at operating mines and prospective mining areas of the WD. The developed spatial models of groundwater-level changes and the identified patterns of hydrodynamic regime transformation can be used in the development of regional groundwater flow models, the assessment of groundwater resources, the prediction of mine water inflows, and the optimization of mine dewatering systems.

The practical significance of the study lies in the possibility of applying the identified patterns during environmental impact assessments, the planning of new mining blocks, the optimization of hydrogeological monitoring networks, and the development of environmental protection measures aimed at preserving groundwater resources in areas of intensive coal mining. A promising direction for future research is the integration of long-term monitoring data with GIS technologies and numerical modeling to develop a digital decision-support system for groundwater management in mining regions.

Література

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