https://www.sworldjournal.com/index.php/swj/article/view/swj33-02-010
DOI: 10.30888/2663-5712.2025-33-02-010

UDC 502.7.57 (075.8)+528.5

INFLUENCE OF THE MINING INDUSTRY ON GULLY-RAVINE SYSTEM TRANSFORMATION: USING THE EXAMPLE OF KRYVYI RIH IRON-ORE BASIN, UKRAINE.

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Abstract. *The presented article observes the influence of the mining industry in the Kryvyi Rih Iron-Ore Basin on the transformation of gully-ravine systems. The author demonstrates how long-term exploitation of mineral deposits has led to significant landscape changes, converting natural ecosystems into technogenic ones. The main focus is on the hydrological network, specifically the gullies in the Inhulets and Saksahan river basins, which have been substantially altered or completely destroyed by the placement of industrial waste, such as tailings storage facilities, spoil heaps, and sludge collectors. A study of the water's chemical composition in these gully ponds reveals a significant increase in mineralization and hardness, along with elevated concentrations of sulfates, chlorides, and heavy metals. The long-term data collected show a steady trend of rising water mineralization, indicating a worsening condition of the entire regional hydro-ecosystem. The results of this research highlight the need for measures to reduce the technogenic load and restore the natural ecosystems.*

Key words: *Gully-ravine system transformation, mining industry, Kryvyi Rih iron-ore basin, PJSC Northern GOK, PJSC Central GOK.*

Introduction.

Long-term, extensive exploitation of ore deposits fundamentally alters the environment, initiating a profound shift from natural to technogenically dominated ecosystems. This transformation is not confined to a single environmental component; instead, it concurrently or progressively affects the entire system, encompassing the biota, hydrosphere, atmosphere, and lithosphere. Consequently, a distinct technogenic ecosystem emerges, characterized by novel organizational structures that diverge significantly from the pre-existing natural spatial-biotic continuum.

According to current estimates, the areas broken by mining in the whole world make up about 0,075% of the land area (about 101,583 km²) [1]. According to the State GeoCadastre data, the total amount of disturbed land area in Ukraine is estimated at 142,7 thousand hectares, among which Dnipropetrovsk region is the leader – 37,7 thousand hectares [2]. The land allotment for mining since the beginning of the 3-rd millennium in Ukraine has reached 16 km^2/year. It has been determined that the contribution of the Kryvyi Rih iron-ore basin to waste generation is 92,08% of the total volume of waste accumulations in Dnipropetrovsk region and 65,5% in Ukraine as a whole, amounting to 10,7 billion tons. It is determined that 65,25% of the total disturbed land area is industrial waste, 34,76% – quarry cavities and mine failure zones, occupying 49% of the Kryvyi Rih city area [3,4].

The Kryvyi Rih iron-ore basin stands out as a critical area, holding nearly half (48,6%) of Ukraine's primary iron ore reserves. This region is characterized by a high concentration of mining and processing facilities, including numerous quarries, mining-processing plants, mines, and metallurgical plant. Mining generates substantial volumes of waste, such as overburden and mine rock dumps, tailings dams, and metallurgical slag dumps, which collectively occupy and disturb a significant portion of the land surface. The scale of land disturbance varies significantly with the mining method. For open-pit iron ore mining, extracting just one million tons of raw material can lead to a land loss ranging from 14 to 640 hectares. In contrast, underground mining methods, while less impactful on the immediate surface, still result in a loss of approximately 4 hectares of land per million tons due to the need for dumps and surface deformations [4,5].

Specific for Ukraine and in particular for Kryvyi Rih iron-ore basin is the significant waste dominance generated during the development of mineral deposits (75% of the total volume) and ore enrichment (13-14%) [4,5]. The modern technology of iron ore enrichment involves the production waste ("tails") storage in special tailings storage facilities, into which they come in the form of water pulp. Today, about 2,7 – 3,0 billion cubic meters of ore enrichment wastes are accumulated in the tailings storage facilities of the Dnipropetrovsk region, of which more than 2 billion cubic meters are in Kryvyi Rih. Where process solutions are not undergone to industrial treating, they are actively ended up into hydroecosystem.

The principal **aim of the research** is to identify and characterize the patterns of transformation within the gully-ravine system of the Kryvyi Rih region, specifically focusing on the morphogenetic impact of mining and quarrying operations.

Materials and methods.

The study is based on the results of water samples analyses from the gullies taken in expeditions during 2008-2023, analysis of retrospective data and literature data.

Results.

The Inhulets River with tributary the Saksahan, along with an extensive system of large ravines and watercourses, primarily define the Kryvyi Rih hydrological network. These features reflect both the region's historical development and ongoing physical and geographical processes. However, within the Inhulets River basin, particularly in areas hosting mining and processing plants, the landscape undergoes fundamental transformations. This leads to the emergence of specific geochemical processes that significantly alter the chemical composition of water in both natural and technogenic water bodies.

In steppe regions of Ukraine, the gullies – the result of soil erosion by running water, are a common form of relief and the basis for the formation of the hydrological network. The geomorphology of the Kryvyi Rih area is characterized by pervasive gully incision. A considerable proportion of these incised features have been anthropogenically modified to accommodate various industrial by-products and effluents, specifically functioning as sludge and tailings storage facilities, settling ponds, waste rock dumps, and technogenic water impoundments.

The primary process shaping the relief in the region is sheet erosion, with gully erosion playing a lesser role. The watersheds of the Kryvyi Rih rivers are associated with granitoid domes and anticlinal ridges of the folded basement. Upstream from the confluence of the Inhulets and Saksahan Rivers, the watersheds are narrow and well-drained. The Inhulets-Saksahan watershed itself is narrow and relatively poorly drained. In the central part of Kryvyi Rih, the ravines are flat, with their bottoms being marshy and dominated by accumulation processes. There are also trapezoidal ravines that are gently convex, featuring grassed slopes with gradients of 6-12°. Their lower sections contain incised terraces, and their heads are conical. Small watercourses emerge in the middle sections of these ravines. The largest ravines extend for 10-15 km.

Within the Kryvyi Rih territory, there are 36 gullies and their branches draining into the Inhulets basin, and 33 gullies (with some sources indicating 40 [6]) in the Saksahan basin. These formations can exhibit significant incision, with edge depths sometimes reaching 20-30 meters.

The Saksahan basin's gully system is predominantly right-bank (67,5%), with a smaller proportion (32,5%) on the left bank. A notable aspect is the severe transformation, often leading to complete destruction, of most gullies. This impact is particularly pronounced on the right-bank gullies, which have been subjected to over a century of mining operations and extensive construction.

Streams frequently flow along the bottom of the gullies, primarily formed by the outflow of groundwater along the ravine slopes, as well as by the drainage and discharge (sometimes emergency) of process waters. Where gully elevations are low, these streams expand into small ponds. These ponds are typically modest in size, covering 1 to 50 hectares, with depths between 2 and 4 meters. Significantly, no stable fresh water bodies were identified among the studied ponds. The hydrochemical analysis reveals a prevalence of sulphates and chlorides among anions, and magnesium and sodium among cations. The water is extremely hard.

A brief description of several gullies in the Saksahan River basin is presented below. These gullies are located in the northern part of Kryvyi Rih and are influenced by the Private Joint Stock Company Northern Iron Ore Enrichment Works (PJSC Northern GOK) (Fig. 1). The paper also describes a number of gullies in the central part of the city, which are confined to the Inhulets River basin.

One of the largest right-bank gullies of the Saksahan River, the *Pivnichna Chervona gully*, extends for 24 km and has a catchment area of 78 km^2, it is currently partially filled with waste rock dumps resulting from the development of the Northern Iron Ore Enrichment Works quarry. The surface topography of the gully is gentle; as the elevation decreases, the contours become more defined, a valley floor emerges, and the thalweg widens, gradually narrowing toward the central section of the gully. A short stream flows along the valley floor, which is marshy. The total water mineralization in the gully fluctuates within 1,5 g/dm^3, with a water hardness of 17 mmol/dm³. Weakly altered steppe plant communities have been preserved on the slopes, which led to the establishment of a nature reserve with the corresponding designation.

Figure 1 – The gullies of the Saksahan River basin, which are subject to man-made impacts from the Northern Iron Ore Enrichment Works.

(Google Earth Pro open platforms)

The *Hriadkuvata gully*, which extends for 6,5 km and has a drainage basin of 14 km², merges with the Saksahan River in the vicinity of the Pervomaiske Ore Management of the Private Joint Stock Company Northern Iron Ore Enrichment Works (PJSC Northern GOK). The initial 3 km of the gully feature an intermittent water flow and minor channel erosion on gentle slopes, which are covered by vegetation and stand at a height of 2 to 3 meters. In the lower sections of the gully, a continuous stream is present, flowing through a marshy valley floor rich with characteristic wetland plants. The water chemistry is of the sulfate-hydrocarbonate-chloride type, dominated by magnesium, calcium, and sodium ions, and exhibits a moderate total dissolved solids concentration of 1,7 g/dm³ and a water hardness of 20 mmol/dm³. The gully's terminal section widens into a small, fan-shaped alluvial deposit, where several homes are located before the channel disappears entirely. The gully has undergone significant degradation, initiated by pre-revolutionary mining on its right slope. This process was exacerbated from the 1960s onward by the expansion of spoil heaps from the Pervomaiske quarry of the Northern Iron Ore Enrichment Works, alongside residential development and the proliferation of waste disposal sites.

A microdistrict of Kryvyi Rih and the Kryvyi Rih Botanical Garden are situated along the left slope of the *Pryvorotna gully`s* middle section. The gully has a total length of 6,9 km, including its 5,2 km main thalweg and three left-side spurs, and its catchment area covers 15,6 km². The stream's water flow is weak. The water's chemical composition is sulfate-chloride, with dominant calcium, magnesium, and sodium ions, and a mineralization of 2,0 g/dm³ and a hardness up to 25 mmol/dm³. In its lower part, the gully widens dramatically to 50-55 m, and the slopes become steeper, reaching up to 12 m in height with an incline of 20-25°. The gully remains in a relatively good state of preservation, hosting forest plantations. Three of its left branches are now part of the Kryvyi Rih Botanical Garden, providing a protected habitat for steppe vegetation.

The *Petrikova gully* is a large gully with dendritic landform, similar in size and structure to the Pivnichna Chervona gully. Its main body is now occupied by the tailings storage facility of the Northern Iron Ore Enrichment Works, leaving only a 2,5 km lower spur intact. The gully's water, characterized by its high salinity, results from the discharge of process water from this facility. This water exhibits a mineralization of 6,9 g/dm³ and a hardness of 48 mmol/dm³, classifying it as a sodium-magnesium-calcium group chloride-sulfate type. The gully serves as a conduit for these highly mineralized process waters, which are ultimately discharged into the Saksahan River.

The *Motina gully*, located upstream of the Saksahan River, serves as a key site for examining patterns of change in water mineralization over time. As shown in Figure 2, data from a pond within this gully, which is less affected by the Northern Iron Ore Enrichment Works (PJSC Northern GOK) tailings than other local water bodies, demonstrates the impact of mining activities. A long-term hydrochemical observation series, spanning from 1978 to 2023, provides a robust basis for assessing these changes. The initial mineralization value of 1,1 g/dm³ in 1978 rose to 1,7 g/dm³ by 1986, followed by a sharp decline to 1,1-1,2 g/dm³ in 1987-1988 [7]. Although constant fluctuations were recorded throughout the entire period, their amplitude has diminished, while the overall mineralization has shown a continuous upward trend. This is evidenced by the increase from 2,2 g/dm³ in 2010 to 3,8 g/dm³ in 2023.

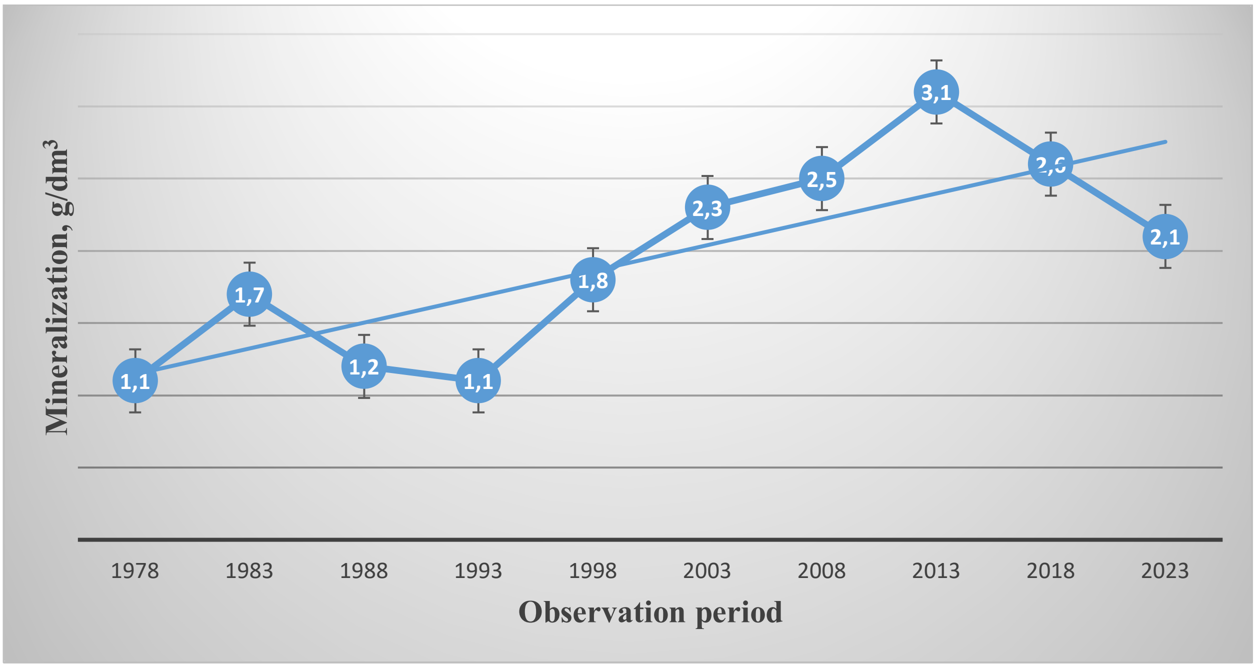

Figure 2 – Dynamics of the water mineralization level in the Motina gully (area of the Northern Iron Ore Enrichment Works influence), during 1978-2023 (Authoring [7], Alokhina T.)

The gullies within the central district of Kryvyi Rih belong to the Inhulets River basin and, like those in the Saksahan basin, have been significantly altered by mining activities. The tailings storage facility of the Private Joint Stock Company Central Iron Ore Enrichment Works (PJSC Central GOK) was established in the upper and middle sections of the Velyka and Mala Lozuvatka gullies, which flow into the Karachunivske Reservoir (Fig.3). The *Velyka Lozuvatka gully* was originally 10,7 km long with a catchment area of 19 km². It featured a temporary watercourse and several small ponds in its upper reaches. *The Mala Lozuvatka gully* was 4,6 km long, with a catchment area of 5 km². Several ponds were established in the Velyka Lozuvatka gully, including an upper pond (100 x 70 m) located directly below the Central Iron Ore Enrichment Works spoil heap. A drainage pump station on the pond's shore receives both filtered water from a horizontal drain along the spoil heap and water from dewatering wells. This system intercepts and returns an average of 125,000 m³ of water per year (14 m³/hour) to the tailings storage facility. The chemical composition of the pond water differs significantly from natural water. The water in the Velyka Lozuvatka gully pond is of the calcium-sodium-magnesium sulfate type, with a mineralization of up to 6,5 g/dm³ and a total hardness of 66,5 mmol/dm³ (Table 1). The water also shows elevated concentrations of fluorine, boron, bromine, and iron. The average iron content is 8,8 mg/dm³ (29 MPC).

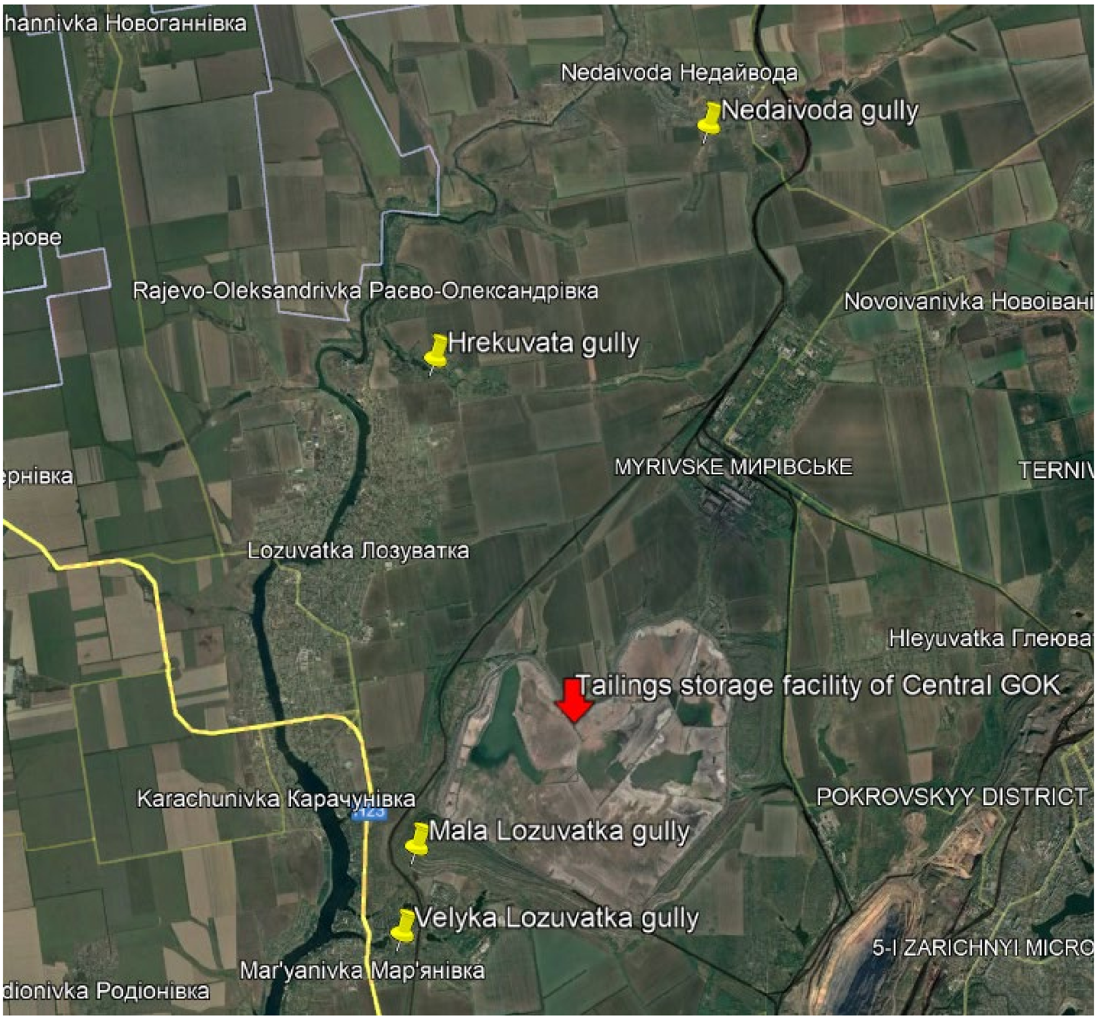

Figure 3 – The gullies of the Inhulets River basin, which are subject to man-made impacts from the Central Iron Ore Enrichment Works ***(Google Earth Pro open platforms)***

The water in the *Hrekuvata gully* pond is classified as chloride-sulfate, magnesium-calcium-sodium type, with a mineralization of up to 4,3 g/dm³ (Table 1). Among the hazardous components, the water shows an elevated concentration of bromine at 2,27 mg/dm³ (11,35 MPC). At the confluence of the Hrekuvata gully and the Inhulets River, a pond is situated. The water in this pond is of the calcium-magnesium-sodium sulfate type, with a mineralization of up to 4,0 g/dm³ and a hardness of up to 38 mmol/dm³.

Table 1 – Indicators of the gullies` water chemical composition located in the area of influence of the Central Iron Ore Enrichment Works

Object	Indicators, M±m			
	Mineralization, g/dm³	Water hardness, mmol/dm³	Cl^-, mg/dm³	SO_4^{2-}, mg/dm³
Velyka Lozuvatka gully	6,5±1,18	66,5±5,46	644,0±59,5	3311±287,5
Mala Lozuvatka gully	1,0±0,12	9,0±1,23	125,5±21,8	387±35,4
Hrekuvata gully	1,5±0,11	13,0±3,12	485,5±58,4	3732±410,0
Nedaivoda gully	2,5±0,22	24,0±4,11	319,0±28,9	1020±98,5

(Authoring [7], Alokhina T.)

Another gully located in the influence zone of the Central Iron Ore Enrichment Works' (PJSC Central GOK) tailings storage facility is the *Nedaivoda gully*. It had a length of 10,5 km with a catchment area of 33 km². The gully features a temporary watercourse with several small ponds in its upper reaches. The water in the Nedaivoda gully ponds is of the chloride-sulfate, calcium-magnesium-sodium type, with a mineralization ranging from 1,6 to 3,7 g/dm³ and a total hardness from 15 to 33 mmol/dm³. Among the elements of Hazard Classes II-III, elevated concentrations of manganese, bromine, and iron are observed.

Conclusions.

Thus, it can be concluded that the long-term and large-scale iron ore mining operations in Kryvbas have led to a significant transformation and, in some cases, the complete destruction of the region's gullies, which are integral parts of the hydrological network. Our research into the water chemistry of these gullies reveals substantial alterations, with long-term monitoring showing a persistent rise in water mineralization. The steady trend of rising water mineralization in the overall hydroecosystem of the Inhulets River results in a decrease in the system's buffering capacity, which in turn leads to a reduction in biodiversity.

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Article sent: 20.08.2025