Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XV, 2026
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

PHYSICOCHEMICAL DYNAMICS OF WATER QUALITY IN SAND AND GRAVEL POST-EXPLOITATION LAKES

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Abstract

The present study aims to evaluate the water quality of five lakes formed as a result of mineral aggregate extraction (sand and gravel) located in the administrative area of Ineu de Criș, Bihor County, Romania. To achieve this objective, two were carried out in May and October 2025, focusing on relevant physicochemical parameters commonly used to characterize the water quality of post-extraction lakes, including pH, dissolved oxygen (DO,), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and potassium (K^+). The obtained results indicated relatively small differences in water quality among the five analysed lakes. Based on the measured concentrations of total nitrogen (TN) and total phosphorus (TP), all lakes were classified in Quality Class I according to Romanian Order No. 161/2006. Regarding dissolved oxygen (OD), lake L3 exhibited the highest values, corresponding to Quality Class I, whereas the remaining lakes showed moderate spatial variability with the lowest values recorded in lake L2. Slight differences were also observed for the BOD_5, with most lakes falling within Quality class I, while lake Camelot was classified in quality class II. Overall, the investigated lakes exhibited good to very good physicochemical water quality, with no evidence of significant degradation during the monitoring period These findings suggest that the studied post-extraction lakes have developed relatively stable hydro chemical conditions and may represent valuable aquatic ecosystems within the local landscape, although a comprehensive ecological status assessment would require the inclusion of biological and hydro morphological quality elements in accordance with the European Water Framework Directive (European Parliament and Council, 2000).

Key words*: gravel pit lakes, physicochemical parameters, post-exploitation lakes, water quality, water quality assessment, Water Quality Index (WQI).*

INTRODUCTION

Water represents a fundamental resource at the planetary level, being the essence that sustains life and a critical element in the functioning of geosystems (Popa et al., 2019). Covering approximately two thirds of the Earth's surface, water is not merely a physical compound but an indispensable biological factor, participating in cellular structure, metabolic processes, and the maintenance of the thermal balance of all living organisms. At the macro scale, it acts as a driving force of natural cycles, shaping landforms, influencing climate, and representing the essential link connecting the atmosphere, soil, and biosphere. Water is a fundamental requirement for all forms of life, playing a significant role in sustainable development and the circular economy (Sandu & Vîrsta, 2021).

From a socio-economic perspective, the availability and quality of water are directly linked to food security, public health, and sustainable economic development. However, the relationship between humans and this vital resource has become increasingly complex and strained. The intensification and diversification of anthropogenic activities ranging from industrialization and urbanization to the intensive exploitation of natural resources have generated significant pressures on the hydrological cycle and aquatic ecosystems. At the European scale, recent assessments continue to identify substantial pressures on water quantity and quality and emphasize the need to strengthen water resilience and integrated management (European Environment Agency, 2024; Costa et al., 2025). At the local scale, land-use changes, may also support ecological restoration; for example, the conversion of former pasturelands into community forest in Ineu illustrates a local rehabilitation pathway relevant to landscape stabilization (Timofte & Racz, 2025).

In this context, lakes formed as a result of mineral aggregate extraction (stone and sand) can be considered emerging aquatic systems resulting from anthropogenic transformations of the

hydrographic landscape. At the global level, the exploitation of freshwater sand resources is increasingly associated with issues related to natural resource governance and pressures on aquatic ecosystems, being recently identified as a major challenge for sustainable resource management (United Nations Environment Programme, 2022; Yasmin et al., 2024). In this context, post-extraction lakes represent relevant examples of ecosystems resulting from anthropogenic interventions, which can gradually evolve into functional aquatic systems. Although artificially created, these water bodies may progressively develop into new lacustrine ecosystems in which water reflects both residual anthropogenic impacts and ecological regeneration processes, including the development of new trophic chains. These environments provide an excellent natural laboratory for studying secondary ecological succession and natural self-purification processes.

The main objective of the present study is to evaluate the water quality of lakes formed as a result of mineral aggregate extraction, based on the determination of physic-chemical and biochemical water quality indicators, in order to classify these water bodies according to the quality classes established by the national regulation regarding the classification of surface water quality (Order No. 161/2006, 2006).

The commune of Ineu is located in the central part of Bihor County (Figure 1) and represents the easternmost locality within the Oradea Metropolitan Area.

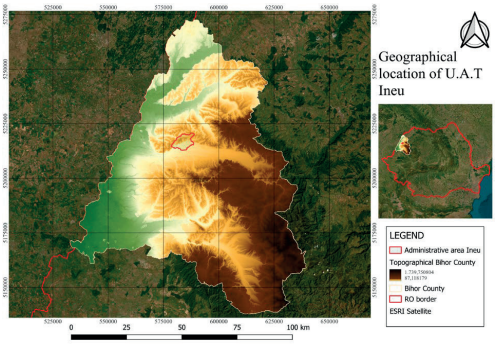


Figure 1. Map of the geographical location of the commune of Ineu using QGIS

The total surface area of Ineu commune is 49.51 km², and the locality is situated at a distance of approximately 20 km from the municipality of Oradea. The geographical coordinates are (47°06′05″ N, 22°06′10″ E). The evolution of the hydrographic landscape in the Ineu area provides an illustrative example of the long-term dynamics of the human-water relationship. The analysis of a historical map from 1782 (Figure 2), georeferenced using QGIS (Bellezza et al., 2014), demonstrates that the original course of the Crișul Repede River crossed the area where part of the present-day locality is currently situated. Naturally, the river branched into two main channels in the area of the locality of Tileagd, forming a complex and unstable hydrographic system. In response to the risks associated with flooding and to support urban development, hydraulic engineering works were implemented to regulate the river course, including the construction of diversion channels aimed at reducing flood risk and protecting the local population. Following the economic transformations that occurred after the 1990s, the upstream agricultural lands were increasingly used for extractive activities, particularly for gravel and sand exploitation, as well as for the expansion of urban areas. These interventions in the river system illustrate the progressive anthropogenic transformation of the landscape and have contributed to the formation of post-extraction lakes, which represent the main focus of the present study.

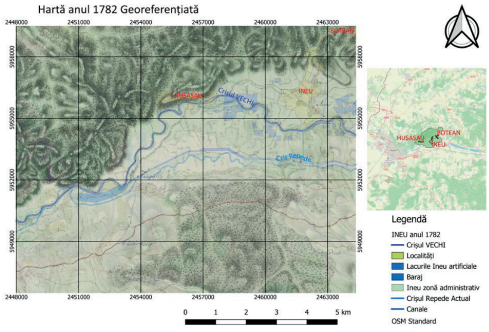


Figure 2. Georeferenced historical map location of the commune of Ineu 1782 using QGIS

The present research aims to:

a) assess the water quality status of lakes formed as a result of mineral aggregate extraction, based on the analysis of physicochemical parameters and their classification into the quality classes established by the applicable legislation;

b) analyze the influence of anthropogenic activities on these ecosystems and highlight their potential for ecological restoration and sustainable use.

MATERIALS AND METHODS

Specific quality standards are available to indicate the quality of different water sources, such as groundwater, springs, rivers, lakes, and streams, and there are specific water quality criteria for agricultural, industrial, domestic, or other water uses. For example, drinking water must be fresh and free from pollution, while irrigation water should not be excessively saline or toxic, and standards for industrial water use vary depending on the nature of the industrial processes involved. Various human practices and activities, industrial processes, and natural processes significantly and alarmingly affect the quality of water resources, particularly with respect to human well-being.

Study area

The research was conducted on five surface lakes formed as a result of mineral aggregate extraction (sand and gravel) (Bendixen et al., 2019), located in north-western Romania, in Bihor County, within the administrative area of Ineu. Gravel- pit lakes commonly maintain close hydraulic continuity with surrounding alluvial aquifers, so groundwater-lake exchanges may become a major control on their water balance and hydrochemistry (Jost et al., 2023). The analyzed lakes are arranged approximately along an east-west direction and are identified as follows: L1 - Utopia, L2 - Valer, L3 - Kings Land, L4 - Fildan, and L5 - Camelot Resort.

These water bodies represent anthropogenic lakes formed as a result of mineral aggregate extraction activities (Bendixen et al., 2019; Hackney et al., 2021). Some of them have subsequently been developed and integrated into areas with recreational and tourism functions, while others have remained in a post-extraction state, where natural regeneration processes and ecological succession are gradually shaping new aquatic ecosystems. The hydrological and ecological characteristics of these lakes are influenced both by natural processes and by anthropogenic activities carried out in the surrounding area.

Water samples were collected during two sampling campaigns conducted in May and October 2025. The first sampling campaign took place in May 2025, while the second was carried out in October 2025. During both campaigns, the following physicochemical parameters were determined: pH, water temperature, dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total nitrogen (TN), total phosphorus (TP), and potassium (K). This sampling strategy allowed the evaluation of seasonal variations in water quality between the spring and autumn monitoring periods.

Water samples were collected from the surface layer of the lakes at a depth of approximately 0-0.5 m, corresponding to the warm season when biological activity and biochemical processes in aquatic ecosystems are more intense.

Water sampling

Water sampling was carried out in accordance with the standardized procedures of the SR EN ISO 5667 series (Figure 3).

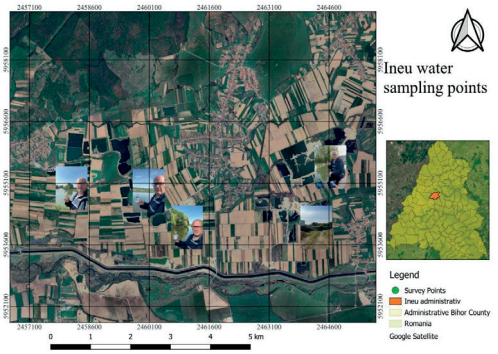


Figure 3. Water Sampling Map of Ineu, created using QGIS

The samples were collected in pre-cleaned glass and polyethylene containers suitable for physicochemical analysis and transported under controlled conditions to the laboratory, where they were analysed on the same day. The procedures for sampling, transport, and preservation were performed in accordance with the following standards:

- SR EN ISO 5667-3:2018 - Preservation and handling of water samples;
- SR EN ISO 5667-4:2016 - Sampling of lakes and reservoirs.

Compliance with these procedures ensures the representativeness of the samples and the integrity of the analyzed parameters until the laboratory analyses are performed.

Water quality analysis

For the evaluation of water quality, the following physicochemical parameters were determined:

• pH - determined in the laboratory according to SR EN ISO 10523:2012 PSLU-01;

• Dissolved oxygen (DO, mg O_2 L^{-1}) - determined by electrochemical method using a membrane electrode (ISO 5814:2012);

• Chemical oxygen demand (COD, mg O_2L^{-1}) - determined by the dichromate oxidation method (SR ISO 15705:2022 PSLU-3N);

• Biochemical oxygen demand (BOD_5, mg O_2L^{-1}) - determined using the 5-day incubation method (SR EN ISO 5815-1:2020 PSLU-04);

• Total phosphorus (TP, mg L^{-1}) - determined by molecular absorption spectrometry (SR EN ISO 6878:2005 PS-III-05);

• Total nitrogen (TN_t mg L^{-1}) - determined by the chemiluminescence method (SR EN ISO 20236:2024 PS-III-06);

• Potassium (K^+, mg L^{-1}) - determined by flame photometry (ISO 9964-3:1993 PS-V-04);

• Water temperature (°C) - measured in situ.

The expanded relative uncertainty of the analytical methods was calculated using a coverage factor k = 2, corresponding to a 95% confidence level.

Laboratory analyses were carried out by accredited laboratories of Oradea Water Company S.A. and the Crișuri Water Basin Administration, in accordance with the applicable national and European standards for the determination of water quality parameters.

Water samples were collected by the beneficiary in strict accordance with the sampling protocols and instructions provided by the laboratories to ensure the representativeness and validity of the analyses. Each stage was documented to ensure traceability and quality control.

Water quality classification

The interpretation of the physicochemical analysis results was carried out in accordance with Order No. 161/2006, approving the Normative regarding the classification of surface water quality for the determination of the ecological status of water bodies, in its updated form. The classification was performed by comparing the obtained values with the threshold limits corresponding to the quality classes established by the applicable legislation.

Water Quality Index (WQI*)

To obtain an integrated assessment of the overall water quality of the investigated lakes, a synthetic Water Quality Index (WQI*) was developed based on the ecological quality classes established by Order No. 161/2006 regarding the classification of surface water quality in Romania. Unlike internationally standardized Water Quality Index models, the proposed WQI* represents a comparative tool specifically adapted to the objectives of this study by integrating the ecological quality classes assigned to selected physicochemical parameters into a single numerical value.

Synthetic water quality indices are widely applied in environmental studies to simplify the interpretation of multiple physicochemical variables and facilitate comparisons among different aquatic ecosystems (Iticescu et al., 2019; Uddin et al., 2021; Georgescu et.al., 2023; Muhammad et al., 2025; Das, 2026).

The WQI* was calculated using the following parameters: pH, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), total phosphorus (TP), and total nitrogen (TN). These indicators were selected because they represent key physicochemical variables used in the ecological assessment of surface waters and could be unequivocally assigned to the quality classes defined by Order No. 161/2006.

Chemical oxygen demand (COD) was determined during laboratory analyses and is presented in the results section; however, it was not included in the WQI* calculation because four of the five investigated samples were reported as below the analytical reporting limit (<12 mg O_2 L^{-1}).

Consequently, the corresponding ecological quality class could not be assigned with sufficient certainty, and its inclusion would have introduced additional uncertainty into the synthetic index.

Potassium (K^+) was also excluded from the WQI* calculation. According to Order No. 161/2006, potassium belongs to the group of salinity-related parameters and represents a

naturally occurring constituent rather than an indicator of anthropogenic pollution or ecological degradation. Nevertheless, K^+ concentrations were analyzed separately because they may provide useful information regarding groundwater inputs, mineral weathering processes, and local hydrogeochemical conditions.
Total nitrogen concentrations were below the analytical limit of quantification (LOQ) in all investigated samples. Since this value is substantially lower than the threshold corresponding to Quality Class I (1.5 mg L^{-1}) established by Order No. 161/2006, all TN measurements were considered to comply with Quality Class I and were assigned the corresponding numerical score in the WQI* calculation.
For each analyzed parameter, the ecological quality class was determined according to the threshold values established by Order No. 161/2006 and subsequently converted into a numerical score (Table 1).

Table 1. WQI* scoring system

Quality class	Ecological status	Value WQI
I	very good status	100
II	good status	80
III	moderate status	60
IV	poor status	40
V	bad status	20

The synthetic WQI* was calculated as the weighted average of the parameter scores using the following equation:

$$WQI^* = \frac{\sum_{i=1}^{n}(w_i \cdot S_i)}{\sum_{i=1}^{n} w_i}$$

where:

- (S_i) represents the numeral score assigned to parameter i according to its ecological quality class;
- (w_i) represents the weight assigned to parameter i;
- (n) represents the number of parameters included in the calculation.

In the present study, all parameters were assigned equal weights ($w_i = 1$), assuming that each physicochemical indicator contributes equally to the overall assessment of water quality. This approach was adopted to ensure a straightforward and objective comparison among the investigated lakes while avoiding subjective weighting of individual parameters. The proposed WQI* does not replace the official ecological classification established by Romanian legislation. Instead, it serves as a synthetic comparative index designed to integrate multiple physicochemical indicators into a single numerical value, thereby facilitating the overall evaluation and comparison of water quality among the analyzed lakes.

Statistical analysis

The obtained data were analyzed using descriptive statistical methods, including the calculation of the arithmetic mean, standard deviation (SV), and coefficient of variation (CV), in order to characterize the variability of the investigated physicochemical parameters.
To evaluate the relationships between the analyzed variables, the Pearson correlation coefficient (r) was calculated according to the following equation:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}}$$

where:

- x_i represents the observed values of the first variable;
- y_i represents the observed values of the second variable;
- $\bar{x}$ represents the arithmetic mean value of x;
- $\bar{y}$ represents the arithmetic mean value of y.

The Pearson correlation coefficient ranges from - 1 and +1 where values close to +1 indicate a strong positive linear relationship, values close to −1 indicate a strong negative linear relationship, and values around 0 indicate little or no linear correlation between the analyzed variables.

Remote sensing analysis (NDVI and NDMI)

Spatial environmental changes were analyzed using Sentinel-2 satellite imagery provided by the Copernicus Programme for the years 2015 and 2025. Based on these images, the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI) were calculated to assess vegetation dynamics and variations in surface moisture content in the area surrounding the analyzed lakes (Șerban et al., 2022).

RESULTS AND DISCUSSIONS

Physicochemical parameters

The results of the physicochemical analyses performed on the five investigated lakes are presented in Table 2. Overall, most of the

analyzed parameters exhibited only minor variations among the lakes, indicating relatively similar water quality conditions. The pH values ranged from 7.0 to 9.0, indicating near neutral conditions in most of the investigated lakes. Lake L3 (Kings Land) recorded the highest pH value (9.0), suggesting a slightly alkaline water conditions. Similar pH ranges (7.2-8.8) have been reported for post-extraction gravel pit lakes in Germany and the Netherlands, where water chemistry is largely controlled by carbonate buffering and biological productivity rather than by anthropogenic pollution (Schultze et al., 2010; Mollema et al., 2016). Likewise, Karlović et al. (2023) reported pH values ranging from approximately 7.0 to 10.7 in Croatian gravel pit lakes, with the highest values being associated with active phytoplankton communities and enhanced photosynthetic processes. Similarly, dissolved oxygen concentrations exceeding saturation levels have been observed in productive gravel pit lakes as a consequence of oxygen release during photosynthesis.

Dissolved oxygen (DO) concentrations varied between 5.65 and 13.70 mg L^{-1}, with the highest value recorded in Lake L3 (Kings Land) and the lowest in Lake L2. The DO concentration measured in Lake L3 (13.70 mg L^{-1}) substantially exceeded the theoretical oxygen saturation concentration expected at the measured water temperature (18.8°C), which is approximately 9.1 mg L^{-1} under standard atmospheric pressure, indicating oxygen supersaturation of nearly 150%. This phenomenon is commonly associated with intense photosynthetic activity by phytoplankton and submerged aquatic vegetation, which consume dissolved CO_2 while simultaneously releasing oxygen into the water column. The elevated pH value (9.0) observed in the same lake further supports this interpretation, as CO_2 uptake during photosynthesis shifts the carbonate equilibrium toward more alkaline conditions. Similar patterns of oxygen supersaturation accompanied by elevated pH values have been reported in productive gravel pit lakes and other shallow aquatic ecosystems in the Netherlands and Croatia, where high biological productivity and groundwater–surface water interactions strongly influence hydrochemical conditions (Mollema et al., 2016; Karlović et al., 2023).

The biochemical oxygen demand (BOD_5) values ranged from 3.85 to 5.12 mg L^{-1}, indicating a low to moderate biodegradable organic load in the investigated lakes. Similar BOD_5 values have been reported for European gravel pit lakes, reflecting generally good ecological conditions and limited organic pollution. Total phosphorus concentrations (TP) ranged between 0.045 mg/L and 0.070 mg/L, indicating relatively low nutrient, while total nitrogen (TN) remained below. the limit of quantification (<LOQ) in all analyzed samples. The combination of low phosphorus and nitrogen concentrations suggests limited nutrient enrichment and a low risk of eutrophication. Comparable findings have been reported for gravel pit lakes, where biological uptake by algae and microbial communities contributes to nutrient removal and the maintenance of good water quality. Research on quarry and gravel-pit lakes indicates that many such novel ecosystems may develop comparatively favorable chemical and ecological conditions, although their evolution depends strongly on hydrological connectivity, nutrient availability, lake morphology, and surrounding land use (Mollema & Antonellini, 2016; Seelen et al., 2021; Hetmański et al., 2023). In addition, Karlović et al. (2023) highlighted the potential role of gravel-pit lakes in modifying groundwater chemistry, particularly through processes associated with nitrate removal, including biological uptake and denitrification. Such processes may contribute to lower nitrate concentrations in lake water compared with the surrounding groundwater and illustrate the potential of these systems to provide natural attenuation functions.

Potassium (K^+) concentrations exhibited the greatest spatial variability among the analyzed parameters, ranging from 2.00 to 22.55 mg L^{-1}, with the highest concentration recorded in Lake L4 (Fildan). In contrast, the remaining lakes showed relatively low potassium concentrations, ranging from 2.00 to 4.90 mg L^{-1}. The elevated K^+ concentration observed in Lake L4 may reflect local geological characteristics, mineral weathering processes, groundwater inflows, or site-specific anthropogenic influences within the surrounding catchment.

Previous studies have shown that potassium concentrations in gravel pit lakes and post-

extraction water bodies are strongly influenced by the mineral composition of the excavated sediments and by groundwater–surface water interactions rather than by in-lake biological processes. Mollema et al. (2015; 2016) reported that hydrochemical conditions in gravel pit lakes are primarily controlled by geological substrates and groundwater recharge, resulting in spatial differences in dissolved ion concentrations. Jost et al. (2023) further emphasized the close hydrodynamic coupling between gravel-pit lakes and adjacent aquifers. Similarly, Hetmański et al. (2023) highlighted that the chemical composition of gravel pit lakes may vary considerably depending on local lithology, hydrological connectivity, and land-use practices in the adjacent areas.

To provide an integrated visualization of the physicochemical variability among the investigated lakes, the measured parameters are summarized in the heatmap presented in Figure 4.

Table 2. Physicochemical parameters determined of the investigated lakes and their classification according to Order No. 161/2006

Parameter	L1 (Utopia)	L2 (Valer)	L3 (Kings Land)	L4 (Fildan)	L5 (Camelot Resort)	Quality class according to Order No. 161/2006
pH	7.2	7.4	9.00	7.00	7.00	Class I/all lakes
DO (mg/L)	8.32	5.65	13.70	8.47	9.41	L1, L3, L4, L5 – Class I; L2 – Class II
COD (mg O_2 L^{-1})	<12	<12	<12	17.40	<12	L4 – Class II; others: ≤ Class II (exact class cannot be determined due to censored values)
BOD_5 (mg O_2 L^{-1})	3.85	3.95	4.21	4.58	5.12	L1–L4 – Class II; L5 – Class III
TP (mg P L^{-1})	0.067	0.051	0.045	0.048	0.070	Class I (all lakes)
TN, (mg N L^{-1})	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	-
K^+ (mg L^{-1})	2.00	4.90	3.20	22.55	4.40	Not classified (natural salinity parameter under Order No. 161/2006)
Temperature, ℃	18.20	18.30	18.80	18.70	18.80	-

Note. COD = chemical oxygen demand; BOD_5 = biochemical oxygen demand; TP = total phosphorus; TN = total nitrogen; LOQ = limit of quantification. The physicochemical parameters presented in Table 2 were determined from water samples collected during two monitoring campaigns conducted in May and October 2025.

Potassium (K^+) is not included in the ecological quality classification established by Order No. 161/2006, as it belongs to the salinity group and represents a naturally occurring constituent. For COD values reported as "<12 mg O_2 L^{-1}", an exact quality class cannot be assigned because the analytical result falls below the reporting limit but above the Class I threshold (10 mg O_2 L^{-1}). Therefore, these values may correspond to either Class I or Class II.

The classification of total nitrogen assumes that the analytical limit of quantification (LOQ) is lower than the Class I threshold established by Order No. 161/2006.

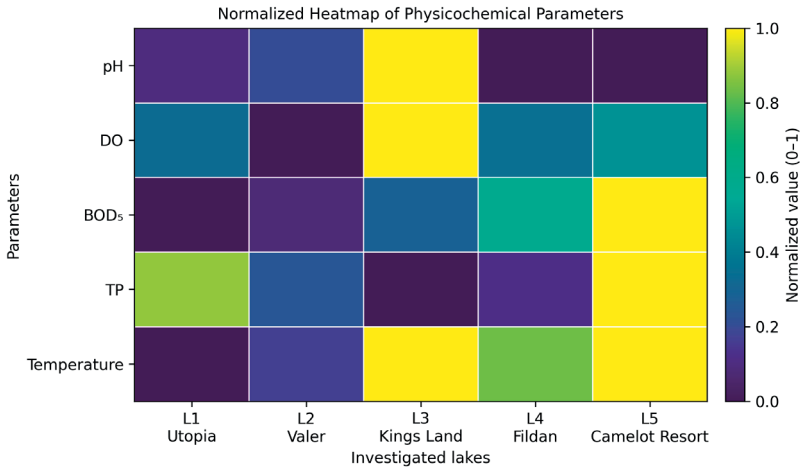


Figure 4. Heatmap of physicochemical parameters across the investigated gravel-pit lakes

The comparison of the obtained values with the threshold limits established by Order No. 161/2006 indicates that most of the analyzed parameters fall within good or very good quality classes. The physicochemical characteristics of the five investigated lakes and their corresponding ecological quality classes according to Order No. 161/2006 are presented in Table 2. Overall, the results indicate that the investigated post-extraction lakes are characterized by generally good physicochemical conditions, with most parameters corresponding to Quality Classes I and II.

The pH values generally fall within Quality Class I, with the exception of Lake L3, where the slightly alkaline value leads to classification in Quality Class II. The pH values ranged from 7.00 to 9.00, indicating neutral to slightly alkaline conditions in all lakes and corresponding to Quality Class I. Dissolved oxygen (DO) concentrations varied between 5.65 and 13.70 mg L^{-1}. Four of the five lakes (L1, L3, L4, and L5) were classified as Quality Class I, whereas Lake L2 corresponded to Quality Class II due to its lower oxygen concentration.

Chemical oxygen demand (COD) values were generally low, with concentrations below the analytical reporting limit (<12 mg O_2 L^{-1}) in four lakes. Lake L4 recorded the highest COD value (17.40 mg O_2 L^{-1}), corresponding to Quality Class II, while the exact classification of the remaining lakes could not be determined because the reported values were below the analytical threshold.

Biochemical oxygen demand (BOD_5) ranged from 3.85 to 5.12 mg O_2 L^{-1}. Lakes L1-L4 were classified as Quality Class II, indicating a low to moderate biodegradable organic load, whereas Lake L5 slightly exceeded the Class II threshold and was therefore assigned to Quality Class III.

Nutrient concentrations were generally low across all investigated lakes. Total phosphorus (TP) values ranged between 0.045 and 0.070 mg P L^{-1}, corresponding to Quality Class I for all sampling sites. Total nitrogen (TN) concentrations were below the analytical limit of quantification in all samples.

Potassium concentrations exhibited the greatest spatial variability, ranging from 2.00 to 22.55 mg L^{-1}, with the highest value recorded in Lake L4 (Fildan). However, potassium is classified as a naturally occurring salinity-related element under Order No. 161/2006 and is therefore not used for ecological status assessment. The observed variability is more likely associated with local geological conditions and groundwater–surface water interactions than with anthropogenic pollution.

Overall, the classification according to Order No. 161/2006 indicates that the investigated lakes maintain a predominantly very good to good ecological status, with only isolated deviations observed for BOD_5 in Lake L5 and COD in Lake L4. These findings suggest that the post-extraction lakes investigated in the present study have preserved favourable physicochemical characteristics and currently exhibit a low degree of anthropogenic disturbance.

Calculation of the WQI* index

The calculated WQI* values for the five investigated lakes are presented in Table 3. The index integrates the quality classes assigned to the analyzed physicochemical parameters (pH, dissolved oxygen, biochemical oxygen demand, total phosphorus, and total nitrogen) into a single comparative value, providing an overall assessment of water quality.

Table 3. Water Quality Index (WQI*) values and interpretation.

Lake	WQI*	Water quality status
L1 - Utopia	95	Very good
L2 - Valer	83	Good
L3 - Kings Land	93	Very good
L4 - Fildan	95	Very good
L5 - Camelot	90	Very good

The calculated WQI* values ranged from 83 to 95, indicating good to very good overall water quality across all investigated lakes. Lakes L1 (Utopia) and L4 (Fildan) achieved the highest index values (95), reflecting the predominance of physicochemical parameters classified within Quality Class I, with only biochemical oxygen demand (BOD_5) corresponding to Quality Class II.

Lake L3 (Kings Land) recorded a WQI* value of 93, primarily due to the excellent quality of most analyzed parameters. The slight reduction in the overall score was associated with the pH value, which was assigned to Quality Class II because of its slightly alkaline character.

The lowest WQI* value (83) was obtained for Lake L2 (Valer) and was mainly influenced by

the dissolved oxygen concentration, which corresponded to Quality Class II, while the remaining parameters were generally classified within the highest quality categories.

Lake L5 (Camelot Resort) achieved a WQI* value of 90, indicating very good overall water quality despite the biochemical oxygen demand being classified as Quality Class III. This result demonstrates that the favorable values recorded for the remaining physicochemical parameters compensated for the moderate reduction associated with BOD_5.

Overall, the WQI* assessment confirms that the investigated post-extraction lakes exhibit predominantly very good ecological conditions, with only minor differences among sites. The results further indicate that these anthropogenic water bodies have developed stable physicochemical characteristics and currently maintain a generally favourable water quality status.

Statistical analysis

The descriptive statistical analysis of the physicochemical parameters is summarized in Table 4. Overall, the results indicate relatively homogeneous water quality conditions among the five investigated lakes, although some parameters exhibited noticeable spatial variability.

Table 4. Descriptive statistics of the investigated physicochemical parameters

Parameter	Mean	Standard deviation (SD)	Coefficient of variation (CV%)
pH	7.520	0.844	11.22
DO (mg L^{-1})	9.110	2.922	32.08
COD (mg O_2 L^{-1})	10.704	6.362	59.44
BOD_5 (mg O_2 L^{-1})	4.342	0.518	11.94
TP (mg P L^{-1})	0.056	0.011	20.42
K^+ (mg L^{-1})	7.410	8.538	115.22
Temperature (°C)	18.560	0.288	1.55

Note. Total nitrogen (TN) concentrations were below the analytical limit of quantification (LOQ) in all investigated samples and were therefore excluded from the descriptive statistical analysis. Chemical oxygen demand (COD) was not included because four of the five measurements were reported as <12 mg O_2 L^{-1}, preventing the calculation of reliable descriptive statistics.

The mean pH value was 7.52 ± 0.84, indicating neutral to slightly alkaline conditions throughout the study area. Dissolved oxygen (DO) presented an average concentration of 9.11 ± 2.92 mg L^{-1}, with a coefficient of variation (CV) of 32.08%, reflecting considerable differences among lakes, mainly due to the elevated value recorded in Lake L3.

Biochemical oxygen demand (BOD_5) showed moderate variability (CV = 11.94%), with an average concentration of 4.34 ± 0.52 mg O_2 L^{-1}, suggesting relatively uniform levels of biodegradable organic matter among the investigated water bodies. Similarly, total phosphorus (TP) exhibited moderate variability (CV = 20.42%) and a mean concentration of 0.056 ± 0.011 mg P L^{-1}, indicating relatively consistent nutrient conditions across the study sites.

Potassium (K^+) displayed the highest variability (CV = 115.22%), mainly due to the elevated concentration measured in Lake L4. This pronounced variability most likely reflects local hydrogeochemical conditions rather than anthropogenic pollution, as potassium is considered a naturally occurring salinity-related parameter under Order No. 161/2006.

Water temperature remained highly uniform among the investigated lakes, with a mean value of 18.56 ± 0.29°C and a coefficient of variation of only 1.55%, indicating similar thermal conditions during sampling.

Total nitrogen (TN) concentrations were below the analytical limit of quantification (LOQ) in all investigated samples and were therefore excluded from the descriptive statistical analysis.

The Pearson coefficient indicates the direction and strength of the linear relationship between the analyzed indicators. Values close to +1 indicate a strong positive association, while values close to - 1 indicate a strong negative association. The application of the mathematical formula used to calculate the Pearson correlation coefficient resulted in the values presented in Table 5.

The relationships among the investigated physicochemical parameters are further illustrated by the Pearson correlation heatmap presented in Figure 5. Given the limited sample size (n = 5), the observed correlations should be interpreted as exploratory rather than conclusive.

The strongest positive correlation was observed between pH and dissolved oxygen (DO) (r = 0.774), suggesting that both parameters tend to increase simultaneously.

Table 5 Pearson correlation matrix for the investigated physicochemical parameters

Parameter	pH	DO	BOD_5	TP	K^+
pH	1.000	0.774	−0.297	−0.576	−0.365
DO	0.774	1.000	0.201	−0.243	−0.170
BOD_5	−0.297	0.201	1.000	0.294	0.309
TP	−0.576	−0.243	0.294	1.000	−0.418
K^+	−0.365	−0.170	0.309	−0.418	1.000

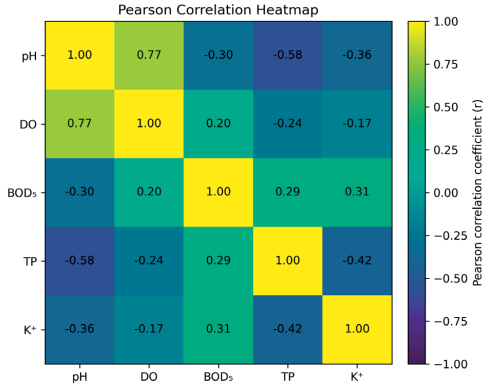


Figure 5. Pearson Correlation Heatmap of the investigated physicochemical parameters (The results should be interpreted with caution because the analysis was performed on a limited dataset - n = 5)

This relationship may be associated with enhanced photosynthetic activity, during which the uptake of dissolved CO_2 by aquatic plants and phytoplankton increases pH while simultaneously promoting oxygen production.

A moderate negative correlation was identified between pH and total phosphorus (TP) (r = - 0.576), indicating a tendency for phosphorus concentrations to decrease as pH increases. Likewise, a moderate negative association was observed between TP and potassium (K^+) (r = - 0.418). However, the ecological significance of these relationships should be interpreted with caution, as potassium is primarily influenced by local hydrogeochemical conditions rather than anthropogenic pollution.

The correlations involving BOD_5 were generally weak, with coefficients ranging between - 0.297 and 0.309, suggesting limited linear relationships with the other investigated parameters.

Similarly, dissolved oxygen exhibited only weak associations with total phosphorus (r = - 0.243) and potassium (r = - 0.170).

Overall, the correlation analysis indicates that no strong linear relationships exist among most of the investigated variables, with the exception of the positive association between pH and dissolved oxygen.

Analysis of the NDVI and NDMI spectral indices

The analysis of the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI) for the years 2015 and 2025 highlighted significant changes in vegetation cover and surface moisture conditions in the surroundings of the investigated lakes. The comparison of NDVI maps indicates an expansion of areas characterized by moderate to high vegetation density in 2025 relative to 2015, indicated progressive vegetation regeneration and ecological succession in the peri-lacustrine zones following mineral aggregate extraction activities (Șerban et al., 2022). Similary, the NDMI analysis demonstrated an increase area with higher moisture values around the lakes in 2025, reflecting the influence of the newly established water bodies on local soil moisture conditions and the surrounding environment. The creation of these anthropogenic lakes appears to have modified the local hydrological regime by increasing water availability and promoting the development of moisture-dependent vegetation (Figure 6).

Overall, the combined interpretation of the NDVI and NDMI indices suggests that the post-extraction lakes have contributed to the gradual establishment of new ecological conditions, characterized by enhanced vegetation development and improved surface moisture in the adjacent areas. These findings support the hypothesis that, beyond their anthropogenic origin, such water bodies can facilitate local ecological restoration processes and increase landscape heterogeneity.

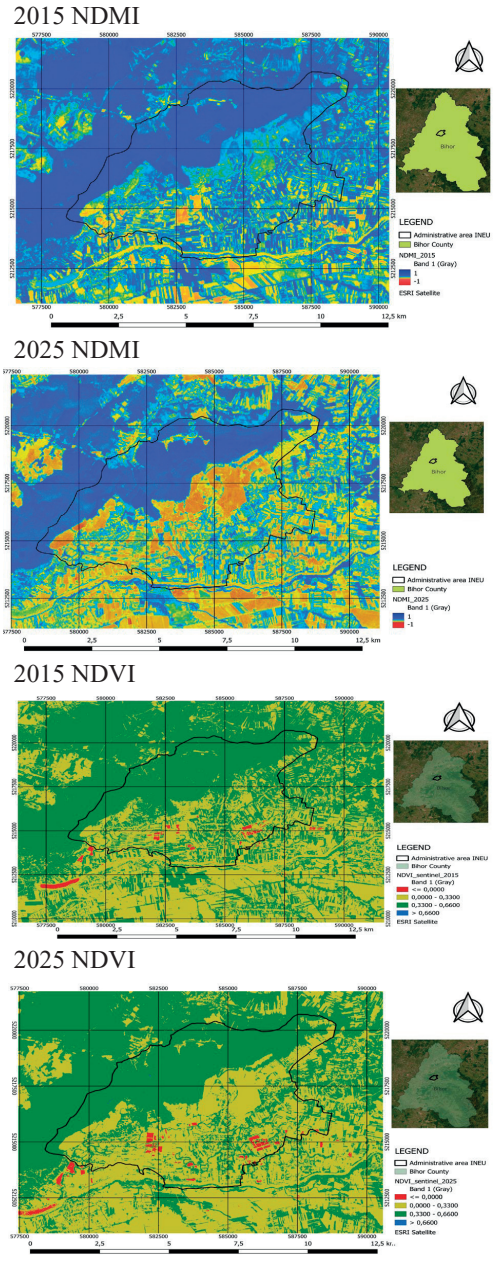


Figure 6. Spatial distribution of the NDVI and NDMI indices in 2015 and 2025, derived from Sentinel-2 imagery, illustrating changes in vegetation cover and surface moisture around the investigated lakes

CONCLUSIONS

The present study evaluated the water quality of five lakes formed as a result of mineral aggregate extraction in the Ineu area, Bihor County, through the analysis of physicochemical parameters and their integration into a synthetic water quality index (WQI*), complemented by statistical analysis and by the assessment of land -cover and moisture dynamcs using the NDVI and NDMI spectral indices

The physicochemical analyses revealed relatively homogeneous conditions among the investigated lakes, indicating an overall good water quality status. Most pH values were close to neutrality, while dissolved oxygen concentrations generally reflected well-aerated conditions, although lower values recorded in Lake L2 suggest local hydrochemical variability. Biochemical oxygen demand values corresponded to a low to moderate organic load, and total phosphorus concentrations remained low across all sampling sites, indicating limited nutrient enrichment during the monitoring period. The markedly higher potassium concentration recorded in Lake L4 compared with the other investigated lakes, suggesting the influence of local geochemical or hydrological conditions rather than a regional pattern and emphasizing the importance of site-specific controls on the ionic composition of post-extraction aquatic ecosystems.

According to the classification criteria established by Romanian Order No. 161/2006 most analyzed parameters were assigned to Quality Classes I and II, confirming the generally favorable physicochemical status of the investigated water bodies.

The calculated WQI* values ranged between 83 and 95, corresponding to good and very good water quality. The highest scores were obtained for Lakes L1 and L4, whereas the comparatively lower value recorded for Lake L2 was primarily associated with reduced dissolved oxygen concentrations. It should be emphasized that the WQI* represents a synthetic comparative indicator designed for this study and does not replace the ecological status assessment framework established under the European Water Framework Directive.

Statistical analysis confirmed moderate variability for most analyzed parameters, while dissolved oxygen and potassium exhibited higher coefficients of variation, reflecting local environmental heterogeneity among the lakes. Pearson correlation analysis revealed a positive

correlation between pH and dissolved oxygen, as well as moderate relationships between biochemical oxygen demand and nutrient concentrations, suggesting interactions among the biogeochemical processes governing water quality. The analysis of the NDVI and NDMI spectral indices highlighted changes in land cover and moisture regime between the years 2015 and 2025. The increase in NDVI values around the lakes indicates progressive vegetation development in the peri-lacustrine zones, whereas higher NDMI values suggest enhanced surface moisture conditions in adjacent areas whereas higher NDMI values suggest an increase enhanced surface moisture conditions in adjacent areas. These patterns are consistent with ongoing ecological succession and the gradual stabilization of ecosystems established after mineral aggregate extraction. Overall, the investigated lakes indicate curently exhibit good to very good physicochemical water quality and demonstrate a progressive tendency toward ecological stabilization. The development of peri-lacustrine vegetation and relatively stable hydrological conditions may support the establishment of habitats for aquatic and semi-aquatic organisms, including bird species observed in the study area, thereby increasing the ecological value of these artificial lakes. Nevertheless, the suitability of these water bodies for recreational activities or aquaculture should be verified through additional biological, microbiological, and sanitary assessments.

Several limitations should be considered when interpreting the results. The relatively small number of investigated lakes (n = 5) restricts the extrapolation of the findings to other post-extraction aquatic systems. Furthermore, physicochemical monitoring was based on two sampling campaigns conducted in 2025 and therefore may not fully capture seasonal or interannual variability. In addition, the assessment focused exclusively on physicochemical indicators and did not include the biological quality elements or hydromorphological components required for a complete ecological status evaluation under the Water Framework Directive.

Future research should incorporate long-term monitoring, a broader suite of physicochemical and biological indicators, and ecological assessment methods consistent with the Water Framework Directive to o provide a more comprehensive understanding of the evolution and ecological functioning of lakes formed as a result of mineral aggregate extraction.

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