

Article

Analysis and Prospective Use of Local Mineral Raw Materials to Increase the Aesthetic and Recreational Value of the Vyzhyvka River (Western Ukraine)

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Abstract

Macrophytes are important components of aquatic ecosystems performing essential ecological functions. Their species composition and density reflect the ecological status of water bodies. The optimal ratio of morphological types of macrophytes is an important condition for preventing eutrophication. The aim of the study is to analyse the species composition, distribution, and density of macrophytes in the Vyzhyvka River (Ukraine) in a seasonal aspect (2023–2024) under constant physical and chemical characteristics of water. To assess the seasonal dynamics of water quality, changes in indicators in three representative areas were analysed. The MIR method of environmental indexation of watercourses was used to assess the ecological state of the river. The water quality in the Vyzhyvka River at all test sites corresponds to the second class of the “good” category with the trophic status of “mesotrophic”. This is confirmed by the identified species diversity, which includes 64 species of higher aquatic and riparian plants. Among the various morphological types of macrophytes, submerged rooted forms account for only 10.56% of the total species composition. To ensure a functional balance between submerged and other forms of macrophytes, a scientifically based approach is proposed, which involves the use of mineral raw materials of local origin, in particular, mining and quarrying wastes rich in silicon, calcium and other mineral components. The results obtained are of practical value for water management, environmental protection, and ecological reclamation and can be used to develop effective measures to restore river ecosystems.

Keywords: macrophytes; ecological status; river ecosystem; aquatic vegetation; hydro-chemical parameters; MIR index; eutrophication; bioengineering technologies



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1. Introduction

The increasing pressure on the planet's freshwater resources due to intensified water use, rising pollution levels, and the effects of climate change has led to a widespread awareness of the key role of freshwater for sustainable development and the urgent need to improve water management mechanisms. At the same time, river ecosystems are among the most vulnerable to anthropogenic changes, as they accumulate significant amounts of pollutants of industrial, domestic, and diffuse origin [1]. In Ukraine, the state of freshwater ecosystems is further deteriorating under the influence of the effects of military operations. Studies have shown that hydromorphological disturbances in the Irpin River basin caused by military events could have led to an increase in the environmental burden on aquatic ecosystems, not only locally but also throughout the country [2].

Excessive intake of pollutants and nutrients into water bodies causes a decrease in the concentration of dissolved oxygen due to the intensification of the development of microbial communities and aquatic vegetation, which is a typical sign of eutrophication processes. This leads to massive growth of algae, plankton blooms, degradation of fish and other aquatic organisms, as well as accumulation of suspended particles and increased water turbidity. In addition to environmental impacts, such changes significantly reduce the recreational and aesthetic value of water bodies, worsening conditions for recreation and reducing the attractiveness of coastal areas and the economic efficiency of ecotourism development. The degradation of the aquatic environment also contributes to the development of pathogenic microorganisms, which increases the risk of spreading infectious diseases associated with water use [3].

Although traditional methods of contaminant removal, such as membrane bioreactors, activated sludge plants, rotating biological contact devices, and other biological treatment mechanisms are used in water treatment, most of them are costly and inefficient in terms of environmental sustainability [4]. In this regard, there is a growing interest in nature-based approaches to water environment purification. One of the most promising areas is the introduction of phytoremediation technologies based on the use of higher aquatic vegetation. This approach is considered to be an environmentally safe and cost-effective bioengineering tool for reducing the concentration of pollutants in the aquatic environment through biofiltration processes [5]. Due to their developed root system and large surface areas, macrophytes are particularly effective in aquatic phytoremediation.

Macrophytes are higher aquatic plants that grow in the water column or on the bottom of water bodies and are clearly visible to the naked eye. Based on morphological and functional characteristics, they are divided into four groups: emergent, floating-leaved, submerged, and free-floating forms [6]. Emergent macrophytes have roots anchored in bottom sediments and form above-water structures, which helps to stabilise the substrate [7]. Floating-leaved species absorb nutrients mainly through their root system, while photosynthesis is carried out by the leaves on the surface. Submerged macrophytes are completely submerged in water, sensitive to light and dissolved oxygen concentration, and absorb nutrients through both their roots and vegetative organs. Free-floating species are not anchored in the substrate and move freely across the surface of the water body [8].

Macrophytes are key components of freshwater ecosystems, actively participating in the processes of energy transformation, nutrient cycling, and sedimentation [9]. They provide a wide range of ecosystem services, including oxygen production, support of trophic networks, secretion of biologically active compounds, and creation of habitats for aquatic organisms. They also play an important role in regulating the penetration of light into the water column, which affects photosynthetic processes and phytoplankton productivity, as well as in stabilising the temperature regime and ensuring the transparency of the aquatic environment [10].

In addition to their ecological functions, macrophytes are of significant importance to society due to their recreational and aesthetic properties. Of particular value is their ability to naturally purify water—they participate in the filtration of pollutants, help reduce eutrophication, and maintain the ability of water bodies to clean themselves [11,12]. The absorption of a wide range of organic and inorganic pollutants from the aquatic environment by macrophytes has been confirmed by numerous studies [13–15]. Scientific data also indicate the prospects of using macrophytes in wastewater treatment systems to improve the overall treatment efficiency and reduce the risk of environmental contamination by antibiotic residues [16]. Other authors [17] have achieved over 97% removal of chemical oxygen demand (COD), ammonia, and phosphorus from wastewater.

Macrophytic vegetation helps to reduce water pollution through several physical, chemical, and biological processes. In particular, one of the key mechanisms is the absorption and accumulation of pollutants through the root system, followed by transport and retention in aboveground organs such as leaves and stems, which is in line with the principles of phytoremediation technologies [18]. Another way is rhizofiltration, when the roots of some species, such as *Arundo donax*, secrete compounds that can chemically fix heavy metals or stimulate the development of microflora involved in their immobilisation [19]. An important role is played by phytodegradation, in which microorganisms associated with the root zone (for example, in *Scirpus grossus* and *Phragmites australis*) break down organic matter through microbial transformation [20]. In addition, macrophytes contribute to the deposition of particles in water by reducing hydrodynamic activity, creating a natural barrier that facilitates the sedimentation of suspended particles that may contain pollutants [21]. The effectiveness of these processes is largely determined by such adaptive properties of macrophytes as intensive biomass formation [22], developed root morphology with a large absorption area [23], and a high level of resistance to toxicants [24].

In recent years, various regions of the world have been researching the biological monitoring of river ecosystems using macrophytes as bioindicators. Several water quality assessment systems based on macrophytes have been developed in Europe: the biological macrophyte index in France [25]; trophic and reference indices in Germany [26]; and the average trophic rank in Great Britain [27], which has been adapted in other countries. These methods are limited because they are based on the dependence of macrophytes on nutrients (phosphorus, nitrogen), while the influence of other factors (hydrology, substrate) is difficult to separate, which reduces the accuracy of assessments and requires improvement of methodologies.

Despite certain limitations of existing methods for assessing water quality using macrophytes, one of the most widely used and proven methods is the one developed in Poland in 2007. This approach, based on the calculation of the Macrophyte Index for Rivers (MIR), provides a comprehensive and reliable assessment of the ecological status of aquatic ecosystems based on the analysis of the quantitative and qualitative composition of freshwater plants. In the course of its application, the method has been improved based on the results of numerous studies and intercalibration within the framework of the EU Water Framework Directive, which has increased its accuracy and adaptability to various environmental conditions [28].

This method has also found practical application in Ukraine. In particular, the macrophyte approach was used to determine the species composition of aquatic and coastal plants and assess the ecological status of surface waters in the upper reaches of the Prypiat River (Turia and Tsyri Rivers) [29], the Luha River within the city of Volodymyr (Volyn Oblast) [30], and the Psyol River, a left tributary of the Dnipro River (Black Sea Basin) [31].

Most studies focus on individual populations of aquatic plants, while the role of macrophyte communities in improving water quality has not been sufficiently studied [32].

Monocultures increase the risk of secondary pollution due to the decomposition of biomass with the release of nutrients. Stable and diverse macrophyte communities ensure the continuous removal of pollutants and maintain ecological balance. For example, the author [27] showed that a combined system of *Phragmites karka* and *Eichhornia crassipes* reduced COD by 95%, while individual cultures reduced it by only 39% and 92%, respectively. The optimal ratio of macrophyte morphological types is key to minimising eutrophication.

The presence and distribution of macrophytes in aquatic ecosystems are determined by the interaction of physical, chemical, biological, and morphological factors. Physical factors, in particular water light penetration, affect photosynthesis and plant dominance [33]. Increased eutrophication, in particular excess phosphorus and nitrogen, reduces transparency and displaces submerged macrophytes, promoting the dominance of phytoplankton or free-floating forms [34]. Phytoplankton dominates in large water bodies, free-floating macrophytes in small ones, and submerged plants maintain ecological stability under low eutrophication. The chemical composition of water and bottom sediments regulates the availability of nutrients, biological factors influence species composition, and the morphology of the environment (substrate type, hydromorphology) determines the conditions for plant rooting [35].

Rooted macrophytes (emergent and submerged) have the highest productivity due to their ability to absorb resources from water and the atmosphere [36] and are key to maintaining water quality and the functioning of river ecosystems [37]. They take root in oxygen-deficient sediments and, thanks to their physiological characteristics, supply oxygen to microorganisms in the rhizoplane and rhizosphere, creating local aerobic zones [38]. Strong fibrous stems, such as those found in *Zizania latifolia* and *Phragmites australis*, transport oxygen and metabolites to the rhizosphere, supporting plants and forming oxygen micro-niches [39]. In these zones, close interactions between plants and microbiota occur, which increase the availability of nutrients and the resistance of plants to pathogens [40]. Maintaining the density of root macrophytes is critical for the stability of river ecosystems.

Optimal conditions for the development of root macrophytes are largely dependent on the pH of the water environment. Van Onsem and Triest [41] found that pH is one of the few abiotic factors that significantly affect the species composition and abundance of macrophytes (in contrast to total phosphorus, dissolved phosphorus, nitrogen concentration, and water depth, which had less of an impact).

The physical and chemical properties of water and bottom substrate significantly affect the viability of root macrophytes; therefore, various methods of improving the environment are used to restore river ecosystems [42]. In particular, the use of iron can stimulate the germination and growth of macrophytes (e.g., *Vallisneria spiralis*) and the activity of rhizosphere microbiota [43]. However, high iron concentrations ($>5.0 \text{ mg/dm}^3$) inhibit these processes, and the effect of a single application is unstable. Due to the costs and risks of toxicity, alternatives should be sought.

Another approach to maintaining the required level of basal macrophyte coverage in aquatic ecosystems is introduction, which is implemented by three main methods: sowing, direct transplantation, or sampling with subsequent cultivation and planting. However, sowing is often hampered by the limited availability of viable seeds [44], while direct transplantation can lead to significant environmental losses at collection sites due to the removal of large numbers of plants. Although there are successful examples of cultivation followed by introduction [45], it requires careful consideration of factors such as water depth and flow velocity to minimise biomass loss due to hydrodynamic drag. At the same time, the artificial cultivation of basal macrophytes or their introduction into new environments to ensure a high level of water coverage is accompanied by significant costs

for materials, installation, and maintenance. Given this, the large-scale introduction of hydrophytes in river ecosystems is rare.

Most problems can be solved using inexpensive and environmentally friendly local materials that increase the physical stability of the root system of macrophytes and the biogeochemical stability of ecosystems. For example, zeolite and expanded clay enrich water with silicon, a key element for the development of root macrophytes, which stimulates biomass accumulation and increases the ecological efficiency of plants [46]. Silicon improves nitrogen and phosphorus uptake, optimises photosynthesis, and replaces part of the carbon structures, reducing lignin content, which increases plant resistance to mechanical damage [47]. Silicon compounds are naturally present in water in concentrations of 1–30 mg/dm³, sometimes up to 50% of anions in groundwater. The main source of silicon is the chemical leaching of aluminosilicates under the influence of CO₂, H⁺ or OH[−] ions, as well as the biochemical decomposition of flora and fauna residues.

One way to increase the density of root macrophytes in nutrient-poor rivers is to add limestone as a source of calcium. Calcium promotes the accumulation of nutrients in biomass and sediments, limiting the development of phytoplankton and free-floating macrophytes, providing better light conditions for the growth of submerged plants [48]. Limestone also regulates the pH of the water by neutralising hydrogen ions and increasing the buffer capacity of the system, which contributes to the stability of conditions for macrophytes [33]. The choice of substance to improve growth depends on the hydrochemical status of the water body and the objectives, so a comprehensive assessment of water quality, nutrients, and sediments should be carried out before application.

The purpose of the research was to assess the balance of the aquatic ecosystem of the Vyzhyvka River through the study of the species composition of macrophytes and the analysis of hydrochemical indicators of water quality in different seasons of the year. The research task was to develop recommendations on the possibility of regulating the chemical composition of water in individual sections of the river to support groups of rooted submerged macrophytes, which provide significant efficiency in the processes of self-purification of aquatic ecosystems. The emphasis of the research task was placed on the search for natural geomaterials that can optimise the balance of nutrients in the river water to maintain its good condition.

The scientific novelty of the work lies in identifying the patterns of distribution of morphoecological groups of macrophytes depending on the qualitative composition of the Vyzhyvka River water and substantiating the influence of chemical characteristics of the aquatic environment on the structural and functional organisation of aquatic vegetation. For the first time, the results of hydrochemical analysis and assessment of the species composition of macrophytes were integrated for a comprehensive determination of the state of the aquatic ecosystem, which allowed the development of environmentally and economically feasible recommendations for adjusting the chemical composition of water using geomaterials—waste from the mining industry. The use of such materials contributes to an increase in the content of silicon and calcium in water, creates favourable conditions for the development of submerged rooted macrophytes, reduces the risks of eutrophication, and ensures stabilization of the ecological balance of the river, opening up new opportunities for the restoration of aquatic ecosystems with minimal impact on the environment.

The practical value of the results lies in the development of a scientifically sound approach to optimising the structure of macrophyte vegetation by targeted introduction of rocks to achieve an ecological balance between surface and root forms. The results obtained can be used in water management activities, environmental protection practices, as well as to improve the recreational and aesthetic condition of water bodies and the development of ecological tourism.

2. Materials and Methods

2.1. Geographical Characteristics of the Vyzhyvka River Basin

The Vyzhyvka River was chosen for the study—a right tributary of the Pripyat River (Dnieper basin), flowing within the Starovyzhivskyi district of the Volyn region. The watercourse is a typical example of small plain rivers of the region and has representative hydrological characteristics. The length of the river is 21 km, and the area of the catchment basin is 155 km² [49]. The slope of the riverbed is on average 1.3 m/km. The Vyzhyvka is fed by numerous nameless streams. The Vyzhyvka riverbed and its streams are characterised by moderate meandering and calm flow. The river basin also contains melioration channels with straightened sections of the riverbeds. The width of the valley varies from 50 to 300 m, and the floodplain part is approximately 100–200 m wide. During spring floods and heavy rainfall, the floodplain is usually flooded to a depth of 1.0–1.5 m. The river banks are mostly low and gentle, with areas of moderately steep slopes 1.0–1.5 m high. In many places, the banks are covered with shrub vegetation and have a peaty structure.

According to hydrological characteristics, the Vyzhyvka River belongs to watercourses with a mixed type of supply, where snow supply dominates. Snow and rainwater form up to 70% of the annual runoff, while the contribution of groundwater supply is about 30%. The hydrological regime of the Vyzhyvka is characterised by significant fluctuations in water levels and seasonal spills during spring floods and summer-autumn rains. The average annual amplitude of water level fluctuations is 0.5–1.5 m. During spring floods, the water level usually rises by 10–20 cm per day, and in some years, up to 30 cm. The duration of floods is 10–20 days. According to the size typology, the Vyzhyvka is classified as a small river with a catchment area of up to 500 km². According to the geological typology, its basin is predominantly organic with significant areas of peatlands [49].

2.2. Geological and Structural Features of the Vyzhyvka River Basin

The Vyzhyvka River flows through the territory of the Volyn Oblast, which belongs to the Volyn–Podilsky Plate—the southwestern edge of the East European Platform. The geological structure of the region is associated with the buried crystalline basement of the Ukrainian Shield, which lies at different depths. Within the framework of tectonic zoning, the western slope of the shield, the Kovel protrusion and the Lviv Palaeozoic depression are distinguished here. On the Palaeozoic rocks, there are layers of the Cretaceous system (limestones, marls) and Paleogene formations (sands, clays, sandstones), which are covered by anthropogenic loess-like loams [50].

The geological composition of the Vyzhyvka basin is represented mainly by sedimentary rocks—clays, loams and sands, which form channel and floodplain areas. Peat deposits associated with periodic flooding are widespread in the floodplain. The presence of carbonate rocks, in particular chalk and limestone, contributes to the development of karst processes in some areas of the basin. There is no active economic activity directly within the Vyzhyvka basin. The river retains its natural hydrological regime and is not subject to significant anthropogenic load, which allows it to be considered as a representative example of relatively undisturbed aquatic ecosystems in the region, despite the widespread distribution of limestone, basalt, and granite deposits in Volyn, which determine active industrial mining in the surrounding areas.

2.3. Selection of Test Sites and Representative Observation Points

The water sampling points were determined taking into account the reference to the state monitoring observation points, which are characterised by different levels of anthropogenic load and meet the representativeness criteria for assessing the impact of point and diffuse sources of pollution. Three test sites were selected for the study: the

village of Komariv (site No. 1), the village of Nova Vyzhva (site No. 2), and the village of Yakushiv (site No. 3), which are schematically presented in Figure 1. In all three test sites, the riverbed has undergone technical modification; in particular, in site No. 3, the banks are reinforced with concrete slabs.

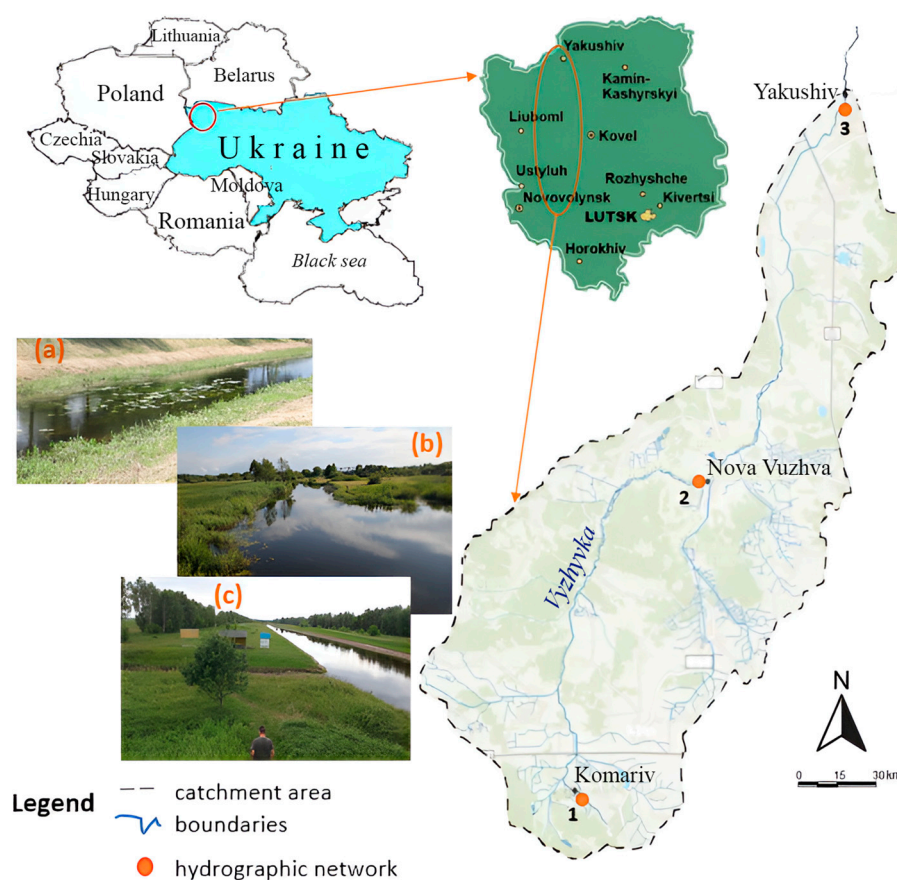


Figure 1. Layout of test plots in the Vyzhyvka River basin and view of them: (a) village of Komariv, Site No 1; (b) village of Nova Vyzhva, Site No 2; (c) village of Yakushiv, Site No 3.

The numbering of test plots and corresponding representative sampling points is given in Table 1.

Table 1. Characteristics of test plots of phytoindication studies and representative sections for sampling water of the Vyzhyvka River.

Site No	Test Site Name	Coordinates	Distance from the River Mouth, km	River Width, m	Depth, m	Current Velocity, m/s	Representativeness Justification
1	Village of Komariv	51°11′08.5″ N 24°15′30.2″ E	69.98	13.1	1.35	0.15	Background level, river outlet
2	Village of Nova Vyzhva	51°24′29.8″ N 24°25′23.1″ E	36.5	24.5	2.93	0.28	Control level, the middle part of the river bed
3	Village of Yakushiv	51°41′05.7″ N 24°35′31.8″ E	6.38	15.8	1.49	0.25	Control level, section of the river bed within the mouth of the river

2.4. Study of the Seasonal Dynamics of Water Quality Changes in the Vyzhyvka River

To track the seasonal dynamics of surface water quality in the Vyzhyvka River, an analysis of changes in the absolute values of water quality indicators in representative sections was carried out in 2023–2024. The results were presented in the form of graphs showing the distribution of median values of physical and chemical indicators within the interquartile range (25–75%) and fluctuations between minimum and maximum values. Statistical significance was assessed by Student's *t*-test ($p \leq 0.05$) [51]. Water samples were collected serially in representative sections at quarterly intervals, which allowed us to obtain data on the chemical composition of water within each hydrological season. A total of 38 samples were collected in compliance with regulatory requirements [52]. All samples were obtained at a depth of 0.5 m below the water surface using clean polyethylene bottles, pre-washed with hydrochloric acid and distilled water. Sampling was carried out until noon in the daylight hours, after which the samples were sealed and labelled and delivered to the sanitary and hygienic laboratory for further hydrochemical analysis on the same day [53]. The analysis was carried out by groups of substances, according to their functions in hydroecosystems [54]: water mineralisation (total mineralisation, chloride (Cl^-) and sulphate (SO_4^{2-}) concentrations); physicochemical parameters (suspended solids content, pH, dissolved oxygen (DO) concentration, permanganate (POX) and bichromate (BOX) oxidisability); indicators of organic pollution and nutrient content (BOD_5 , concentrations of ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-) nitrogen, orthophosphate (PO_4^{3-}), and total phosphorus (TP)).

2.5. Phytoindication of Water Quality in the Vyzhyvka River

To achieve the study objective, the Macrophyte River Assessment Methodology [28] was chosen, the main objective of which is to determine the ecological status of rivers based on the quantitative and qualitative characteristics of aquatic and coastal plants. The methodology takes into account such parameters as the number of indicator species, their projected coverage, as well as indices that characterise the trophic state of the ecosystem, in particular the trophic index *L* and the weighting factor *W*. The *L*-index varies from 1 (for waters with developed eutrophic processes) to 10 (for oligotrophic waters). The weighting factor *W* reflects the level of ecological tolerance of species: a value of 1 corresponds to eutrophic species, and a value of 3 to stenotopic species.

Based on these indicators, the Macrophyte Index of Rivers (MIR) is calculated, which is used to assess the ecological status of water bodies in accordance with the requirements of the EU Water Framework Directive [28]. The index is calculated using a list of 153 species of macrophyte bioindicators.

The methodology of macrophyte assessment of rivers allows determination of the watercourse degradation degree, in particular that caused by water pollution with nutrients. The choice of this approach for application in Ukraine is based on the high level of correspondence between the floristic lists of the studied river sections and the set of indicator macrophyte species used to calculate the MIR.

By the chosen methodology, at the preparatory stage, cartographic materials of the Volyn region were processed at various scales with a high level of accuracy and test sites for phytoindicative research were selected. At the second stage, field surveys of the test sites were conducted to determine the width, depth, and speed of the river flow. The surveys were carried out in areas that corresponded to representative water sampling sites (Table 1). The third stage involved a geobotanical description of macrophytes. Macrophytes were surveyed on river sections over 100 m long, taking into account underwater, free-floating and emergent taxa. Additionally, four abiotic parameters were recorded: current velocity, shade level, substrate type, and average depth.

Macrophytes were identified at the species level. The degree of coverage of each taxon was estimated as a percentage using a nine-point scale according to Holmes et al.'s methodology [55], where 1 corresponded to 0.1%; 2 to 0.1–1%; 3 to 1–2.5%; 4 to 2.5–5%; 5 to 5–10%; 6 to 10–25%; 7 to 25–50%; 8 to 50–75%; and 9 to more than 75%. The assessment also covered macrophytic species growing or rooting in riparian areas of the channel that are under water for more than 85% of the annual cycle. Sampling was carried out at each test site from early June to late August in 2023–2024, taking into account the specifics of the vegetation phases of different taxa. Some of the plants were identified directly in the field, while others were identified in the laboratory. The modern literature sources were used to establish species affiliation, and the scientific names of macrophytes were given by The Plant List and Euro+Med PlantBase databases [56].

The MIR was calculated based on the results of field studies using the following formula:

$$\text{MIR} = \frac{\sum_{i=1}^N L_i \times W_i \times P_i}{\sum_{i=1}^N W_i \times P_i} \times 10, \quad (1)$$

where MIR is the value of the macrophyte index of the river at the sampling site; N is the number of species at the sampling site; L_i is the value of the index for the i -th taxon; W_i is the weighting factor for the i -th taxon; and P_i is the coverage factor for the i -th taxon, determined on a 9-point scale [28].

The calculated values of the MIR were used to assess the ecological status of the rivers in the study; the index values range from 10, which corresponds to a high level of eutrophication and degradation of the watercourse, to 100, which is typical for water bodies with the best ecological status. For plain rivers, the maximum MIR values usually do not exceed 60 [57]. Specific groups of indicator species correspond to each type of river. The determined values of the MIR index were classified according to five water quality classes according to the criteria of the EU Water Framework Directive.

3. Results and Discussion

3.1. Analysis of the Seasonal Dynamics of Water Quality in the Study River

The Vyzhyvka River flows mainly within natural landscapes and has no industrial facilities or significant sources of pollution in the immediate vicinity. Its catchment area covers a sparsely populated area, and the impact of anthropogenic load is minimal, which creates conditions for maintaining a relatively stable hydrochemical regime. To study the seasonal dynamics of water quality in the Vyzhyvka River, samples were taken at three texture sites, the results of which were averaged due to the slight variation between them. The visualisation is presented in the form of boxplot graphs showing the distribution of values by season: winter (Win), spring (Spr), summer (Sum), and autumn (Aut) (Figures 2 and 3). Several physicochemical parameters were analysed to assess the water quality of the Vyzhyvka River.

According to the results of hydrochemical analysis, the highest values of total water salinity in the Vyzhyvka River were recorded in summer (230–240 mg/dm³), which is likely due to more intensive evaporation and, accordingly, an increased concentration of dissolved salts. The lowest values were observed in winter and autumn, about 200 mg/dm³. Despite seasonal fluctuations, the overall variation remained relatively stable throughout the year.

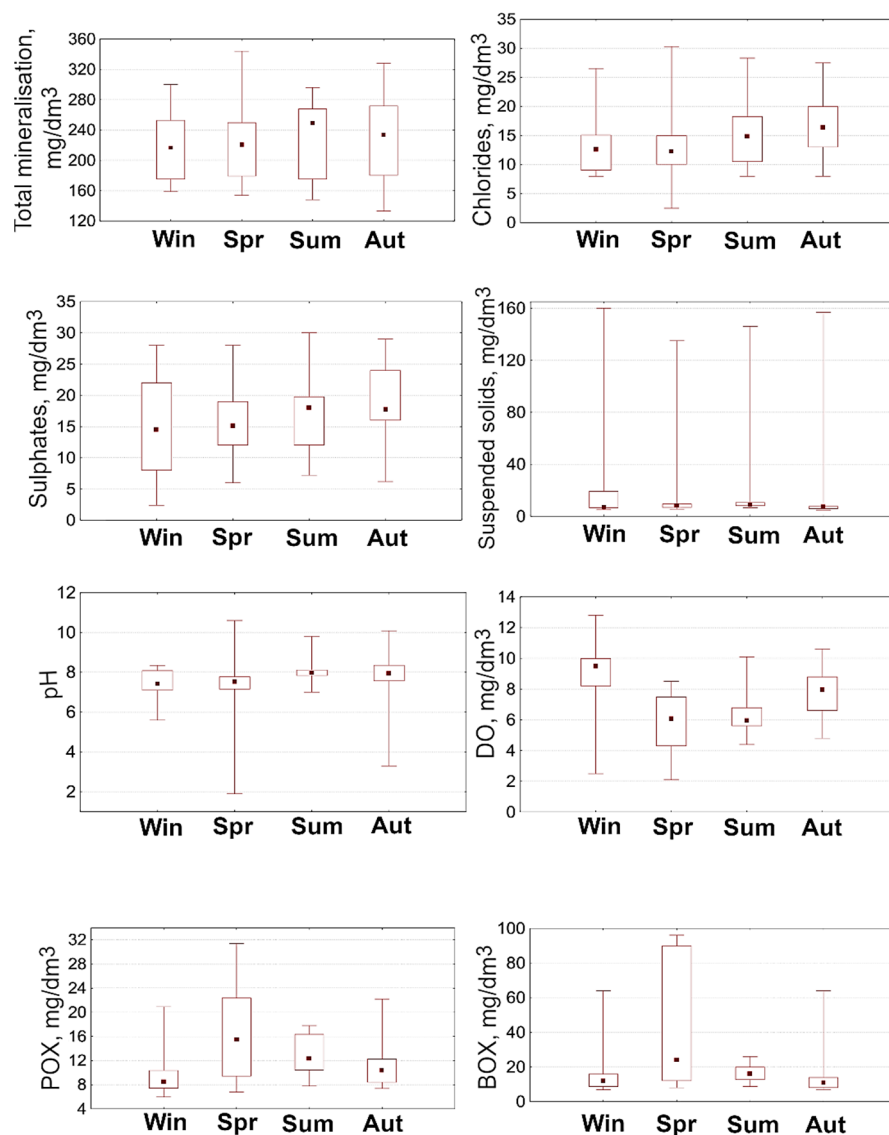


Figure 2. Seasonal dynamics of physical and chemical parameters of water in representative sections of the Vyzhivka River (2023–2024).

Chloride values remained stable during all seasons and amounted to 10–12 mg/dm³, indicating the absence of local anthropogenic load or industrial discharges. A similar situation is observed for SO₄^{2−}: in winter, spring, and summer, the median values range from 17–20 mg/dm³, while in autumn, there is a slight increase to 22–24 mg/dm³. The overall range of fluctuations throughout the year is 10–30 mg/dm³. Thus, the seasonal variation in SO₄^{2−} content is insignificant, and all the values obtained remain within the natural background.

The highest concentrations of suspended solids were observed in spring, which is likely due to active snowmelt and intensified erosion processes that cause intense surface runoff. In winter and autumn, the concentrations remained very low (median value of 2 mg/dm³), and in summer, there was a slight increase to 5 mg/dm³. Thus, the seasonal dynamics of suspended solids clearly reflect natural hydrological processes, and the total content remained within the range expected for small rivers in a temperate climate zone.

The reaction of the water environment of the Vyzhivka River remained stable throughout the entire observation period, being within the neutral-low-alkaline range (pH 7.0–8.5), which is considered optimal for most aquatic organisms [34] and is a characteristic feature of a relatively clean water environment. In the spring, a slight increase in pH values to

8.5 was observed, which is probably due to the intensification of biological processes, in particular photosynthesis. The lowest average values were recorded in autumn (7.0), while the overall pH variation ranged from 7.0 in winter to 8.5 in summer.

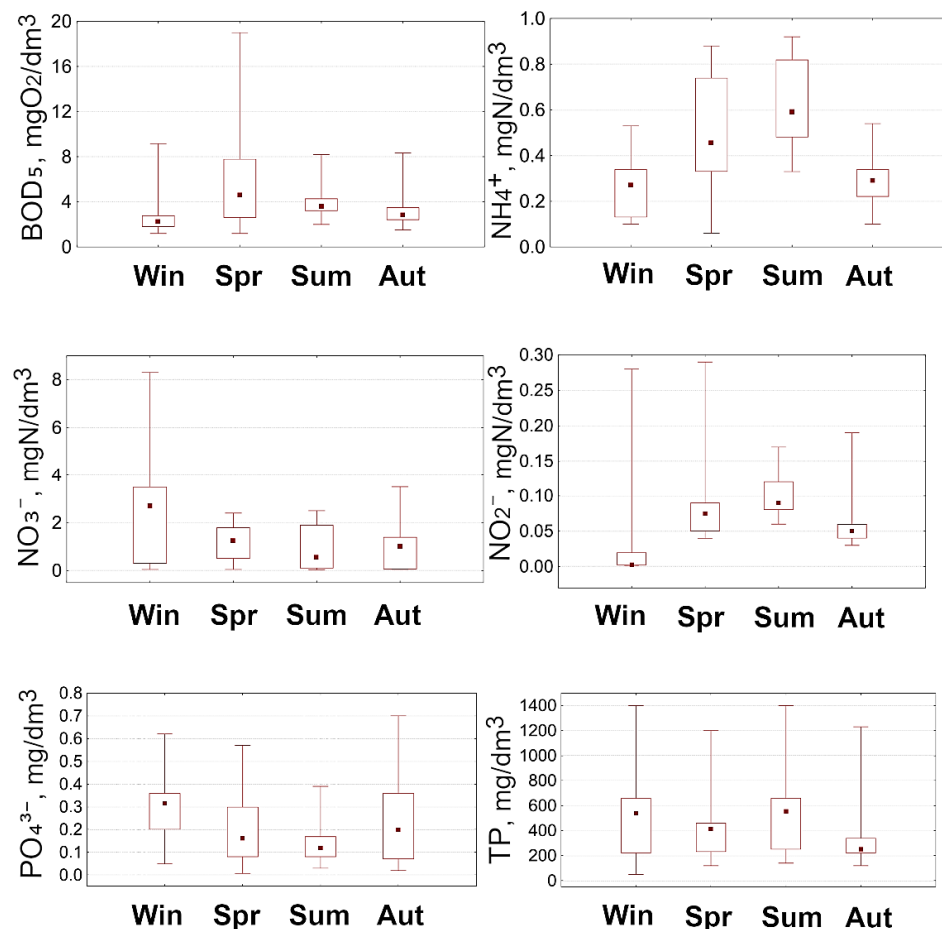


Figure 3. Indicators of organic pollution and nutrient content in the water of the Vyzhivka River (2023–2024).

An increase in the reaction of the aquatic environment towards alkalinity ($\text{pH} > 7$) can significantly affect the structure of aquatic ecosystems, in particular, macrophyte species that are sensitive to changes in chemical parameters. As noted by Lacoul and Freedman [58], pH is one of the leading abiotic factors that determine the composition and functioning of aquatic vegetation. Similar observations are presented in the work of Ljevanačić-Mašić [59], which emphasises the crucial importance of acid–base balance for the formation of macrophyte biocenoses. Svitok et al. [60] found that in watercourses with a pH above 8.4, the level of species richness of the macrophyte layer with free-floating leaves was significantly reduced compared to areas with less alkaline conditions. The authors attribute the reason for this phenomenon to the peculiarities of the metabolism of aquatic plants: some species can assimilate carbon only in the form of dissolved CO_2 . When the pH rises above 8.3, the availability of carbon dioxide decreases due to a shift in chemical equilibrium towards the hydrocarbonate form, which is less efficiently used in photosynthesis by certain taxa [60].

The lowest content of DO in the water of the Vyzhivka River was recorded in spring ($4\text{--}6\text{ mg/dm}^3$), which is associated with an increase in water temperature, intensification of biochemical processes of oxygen consumption and a decrease in turbulence. The highest DO concentrations were observed in winter ($9\text{--}10\text{ mg/dm}^3$) and autumn ($6\text{--}7\text{ mg/dm}^3$). According to the average seasonal values of this indicator, the water of the Vyzhivka

River belongs to the first quality class (very good category), which indicates its ecological condition. Low levels of DO are an important indicator of water body pollution and can negatively affect the state of aquatic ecosystems [61]. DO is a critical indicator of the ecological state of water, as it is essential for the existence of aquatic organisms. Many species of macrophytes are sensitive to a decrease in oxygen concentration in hydrosystems. Oxygen enters the water through diffusion from the atmosphere, as well as through the photosynthetic activity of aquatic plants that produce oxygen as a by-product [62].

BOD₅ is an indicator of the amount of oxygen consumed by microorganisms during the oxidation of organic compounds in water [63]. Other studies [61] show that aquatic plants contribute to the reduction in BOD₅ and chemical oxygen demand (COD), which improves water quality. In the Vyzhyvka River, the lowest BOD₅ values were observed in summer, autumn and winter (2–3 mg/dm³), while the highest values were recorded in spring (4.5–5 mg/dm³). The increase in BOD₅ levels in spring indicates an increased biological load, in particular the decomposition of organic materials.

The content of nitrogen compounds (NH₄⁺, NO₃[−] and NO₂[−]) is an important indicator of the trophic state of a water body and an indicator of anthropogenic load [64]. In the Vyzhyvka River, the NH₄⁺ concentration shows a clear seasonal trend: the minimum values were recorded in winter (0.1 mg N/dm³), while in summer, the median concentrations increased to 0.25–0.28 mg N/dm³. The peak in spring reached 0.35 mg N/dm³. This increase may be due to the active ammonification of organic matter at high temperatures and enhanced biodegradation. In autumn, the concentration decreases to 0.15 mg N/dm³.

The concentration of NO₃[−] in the water of the Vyzhyvka River remains relatively constant throughout the year, which indicates a stable trophic state of the water body. In winter, the median value is about 0.55 mg N/dm³ with maximum peaks of up to 0.75 mg N/dm³. In spring and summer, the concentrations are kept within the range of 0.4–0.5 mg N/dm³, and in autumn, the indicators remain at around 0.4 mg N/dm³. This stability of the nitrate background indicates that there is no significant anthropogenic impact, including inputs from agricultural landscapes or untreated domestic wastewater, which is typical for non-urbanised or poorly transformed basins. According to the ecological classification of nitrate nitrogen, the water in the Vyzhyvka River belongs to the first quality class (very good category). It has been established [65] that macrophytic vegetation can contribute to the reduction in nitrate concentrations in the aquatic environment, as it can produce organic matter that is used by denitrifying bacteria as a source of carbon for the reduction in nitrate to molecular nitrogen.

NO₂[−], an intermediate form of nitrogen in the nitrification and denitrification processes, also has seasonal fluctuations. In winter, low values were observed (0.05–0.08 mg N/dm³), and in spring, the median increased to 0.15 mg N/dm³ with peaks of up to 0.2 mg N/dm³, which is likely due to the activation of microbiological processes. In summer and autumn, the values stabilise within the range of 0.07–0.1 mg N/dm³. Elevated ammonium concentrations can have a toxic effect on aquatic vegetation, in particular on macrophytes. This is confirmed by the literature [66], which indicates the sensitivity of many species to ammonium nitrogen. The study [67] recorded a decrease in the biomass of *Myriophyllum spicatum* L. at a NH₄⁺ concentration of 0.847 mg/dm³, which indicates the negative impact of excessive ammonium loading.

Phosphorus compounds are key biogenic elements involved in the processes of eutrophication of aquatic ecosystems. The results of the study of the PO₄^{3−} content in the water of the Vyzhyvka River revealed seasonal dynamics, which indicate their predominantly natural origin. In winter, the concentration was 0.1–0.12 mgP/dm³, which corresponds to the II class of water quality, a good category. In the spring, a sharp increase to a median value of 0.3 mgP/dm³ was recorded with individual peaks of up to 0.6 mgP/dm³, which is

likely to be due to surface runoff during snowmelt. In summer, the PO_4^{3-} level decreased to 0.1 mgP/dm^3 , and in autumn, it remained stable with a median of $\approx 0.15 \text{ mgP/dm}^3$.

TP concentrations showed similar dynamics: winter values were at $0.1\text{--}0.12 \text{ mgP/dm}^3$; in spring, the median reached 0.4 mgP/dm^3 with a variation of up to 0.6 mgP/dm^3 ; and in summer and autumn, the indicator stabilised at $0.15\text{--}0.2 \text{ mgP/dm}^3$. According to the water quality classification, such concentrations of TP also correspond to class II, good quality. The high spring values are of natural origin. Scientific research [68] shows that an increase in phosphate content promotes the growth of aquatic vegetation, in particular macrophyte species such as *Lemna minor* and *Ceratophyllum demersum*, which confirms the potential impact of phosphorus compounds on the trophic state of the reservoir.

The generalised results of the study indicate that the ecological status of the Vyzhyvka River is classified as “good”. This is confirmed by the moderate content of nutrients, stable physical and chemical characteristics, and low levels of organic pollution. The data obtained indicate the natural seasonal dynamics of water quality in the absence of significant anthropogenic impact.

3.2. Taxonomic Diversity, Species Composition and Cover Density of Macrophytes

In June–August 2023 and 2024, geobotanical surveys were conducted in the Vyzhyvka River basin, and the ecological status of the river was assessed using the Modul Macro-Phyte MMP method. The classification table for four types of rivers used in the Polish methodology [28] was used for the calculation.

Based on surveys of the Vyzhyvka River, 64 macrophyte species belonging to 23 families were identified. Near the village of Komariv, 23 species were recorded, 17 of which are indicators of ecological status. These included floating-leaf plants such as *Nuphar lutea* (yellow water lily), emergent species like *Sagittaria sagittifolia* (common arrowhead), submerged plants including *Elodea canadensis* (Canadian elodea), and free-floating species such as *Glyceria maxima* (large glyceria) (Figure 4).

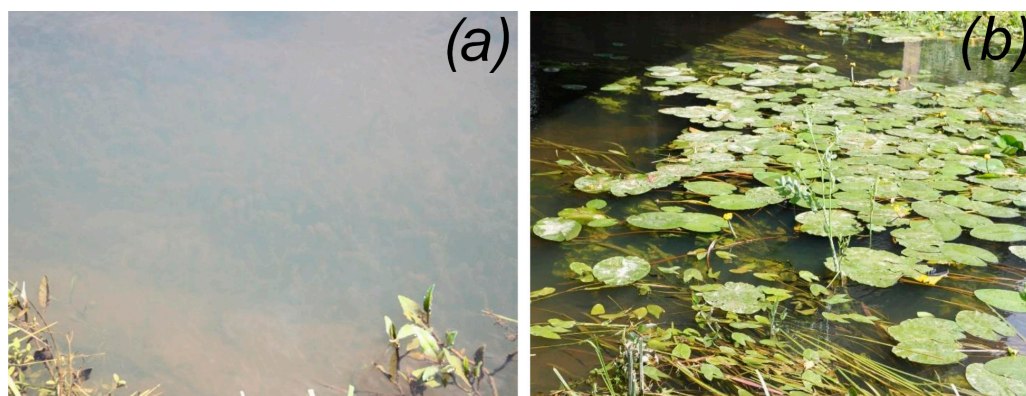


Figure 4. Macrophytes of the Vyzhyvka River at site 1 near Komariv village: (a) *Elodea canadensis* Michx.; (b) *Nuphar lutea* (L.) Smith.; and *Sagittaria sagittifolia* L.

The macrophyte index for the entire observation period (2023–2024) ranged from 34.5 to 42.6, which corresponds to the “good” category according to the MMP methodology (Table 2).

In plot 2, 22 macrophyte species were identified, 21 of which are indicators of ecological status. The species composition was dominated by floating-leaf species such as *Nuphar lutea* (yellow water lily), emergent forms like *Stratiotes aloides*, and coastal plants including *Glyceria maxima* (Figure 5).

Table 2. MOR calculation for the Vyzhyvka River, near Komariv village, site 1.

No.	Species Name	Trophic Index, Li	Weight Coefficient, Wi	June 2023		August 2023		June 2024		August 2024	
				Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi
1	<i>Cicuta virosa</i> L.	5	2	0.1	2	0.1	2	1	2	1	2
2	<i>Sium latifolium</i> L.	7	1	1	2	1	2	1	2	2	3
3	<i>Myosotis scorpioides</i> L.	4	1	0.1	2	<0.1	1	2	3	2	3
4	<i>Rorippa amphibia</i> (L.)	3	1	1	2	1	2	1	2	1.3	3
5	<i>Ceratophyllum demersum</i> L.	2	3	1	2	1	2	2	2	1	2
6	<i>Veronica beccabunga</i> L.	3	1	<0.1	1	<0.1	1	<0.1	1	-	-
7	<i>Nuphar lutea</i> (L.) Smith.	4	2	30	6	30	6	30	6	30	6
8	<i>Persicaria amphibia</i> (L.)	4	1	2	3	3	4	3	4	3	4
9	<i>Lysimachia nummularia</i> L.	-	-	1	-	1	-	1	-	1	-
10	<i>Ranunculus aquatilis</i> L.	-	-	<0.1	-	-	-	<0.1	-	-	-
11	<i>Myriophyllum spicatum</i> L.	3	2	1	2	-	-	1	2	2	3
12	<i>Alisma gramineum</i> Lej.	-	-	1		1	-	1		1	
13	<i>Sagittaria sagittifolia</i> L.	4	2	10	5	10	5	10	5	11	6
14	<i>Lemna minor</i> L.	2	2	3	4	4	4	2	3	2	3
15	<i>Spirodela polyrrhiza</i> (L.) Schleid	2	2	5	5	3	5	2	3	2	3
16	<i>Hydrocharis morsus-ranae</i> L.	6	2	5	5	4	4	3	4	3	4
17	<i>Elodea canadensis</i> Michx.	5	2	10	6	10	6	10	5	10	5
18	<i>Vallisneria spiralis</i> L.	-	-	<0.1	-	<0.1	-	<0.1		<0.1	-
19	<i>Carex riparia</i> Curtis	4	2	1	2	1	2	2	3	2	3
20	<i>Eleocharis palustris</i> (L.) Roem. & Schult.	6	2	<0.1	1	<0.1	1	<0.1	1	<0.1	1
21	<i>Juncus effusus</i> L.	-	-	0.5	-	0.5	-	0.5	-	-	-
22	<i>Glyceria maxima</i> (Hartm.) Holmb.	3	1	5	4	5	4	5	4	5	5
23	<i>Phragmites australis</i> (Cav.) Steud.	-	-	4	-	4	-	4	-	4	-
Macrophyte index (17 indicator species)		On average 37.9—good		42.6—good		38.47—good		34.5—good		36.6—good	
				2023—39.9 (good)				2024—36.0 (good)			



Figure 5. Macrophytes of the Vyzhyvka River at site 2: (a) water cuttlefish (*Stratiotes aloides* L.); (b) *Glyceria maxima* (Hartm.).

During 2023–2024, the macrophyte index ranged from 36.2 to 42.4, which corresponds to the “good” condition category (Table 3).

Table 3. Calculation of MIR for the Vyzhyvka River, near the village of Nova Vyzhva, site 2.

No.	Species Name	Trophic Index, Li	Weight Coefficient, Wi	June 2023		August 2023		June 2024		August 2024	
				Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi
1	<i>Equisetum palustre</i> L.	5	2	1	2	1	2	0.1	2	<0.1	1
2	<i>Cicuta virosa</i> L.	6	2	1	2	1	2	1	2	1	2
3	<i>Sium latifolium</i> L.	7	1	1	2	1	2	1.5	2	1.5	2
4	<i>Myosotis scorpioides</i> L.	4	1	1.5	3	1.5	3	4	4	2	3
5	<i>Mentha aquatica</i> L.	5	1	1	2	1	2	2	3	3	4
6	<i>Nuphar lutea</i> (L.) Smith.	4	2	10	5	10	5	12	6	12	6
7	<i>Persicaria amphibia</i> (L.) S.F. Gray	4	1	1	2	1	2	1	2	1	2
8	<i>Rumex aquaticus</i> Huds.	-	-	0.2	-	0.2	-	0.2	-	0.2	-
9	<i>Caltha palustris</i> L.	6	1	1	2	-	-	1	2	-	-
10	<i>Ranunculus circinatum</i> Spach	5	2	<0.1	1	-	0.1	2	-	-	-
11	<i>Acorus calamus</i> L.	2	3	4	4	4	4	4	4	4	4
12	<i>Alisma plantago-aquatica</i> L.	4	2	1	2	1	2	1.5	2	1.5	2
13	<i>Sagittaria sagittifolia</i> L.	4	2	7	5	7	5	7	5	7.5	5
14	<i>Lemna minor</i> L.	2	2	2	3	1.5	3	3	4	4	4
15	<i>Lemna trisulca</i> L.	4	2	1.5	3	1	2	2	3	2	3
16	<i>Spirodela polyrhiza</i> (L.) Schleid.	2	2	1	2	1	2	1	2	1	2
17	<i>Hydrocharis morsus-ranae</i> L.	6	2	2	3	2	3	3	4	4	4
18	<i>Stratiotes aloides</i> L.	6	2	5	4	5	4	5.5	5	5.5	5
19	<i>Carex acuta</i> L.	5	1	1	2	1	2	1.5	2	1.5	2
20	<i>Carex acutiformis</i> Ehrh.	4	1	1	2	1	2	1	2	1	2
21	<i>Scirpus lacustris</i> L.	4	2	1	2	1	2	1	2	1	2
22	<i>Glyceria maxima</i> (Hartm.) Holmb.	3	1	5	4	5	4	5	5	5	5
Macrophyte index (21 indicator species)		On average 39.6—good	40.8—good		36.2—good		42.4—good		40.5—good		
			2023—38.3 (good)				2024—40.9 (good)				

The species composition of higher aquatic plants at site 3 of the Vyzhyvka River, near the village of Yakushiv, was dominated by species with floating leaves, particularly *Nuphar lutea* (yellow water lily) and semi-submerged plants, among which *Sagittaria sagittifolia* (common arrowhead) prevailed. A significant part of the vegetation cover also consisted of free-floating species such as *Lemna minor* (small duckweed), *Spirodela polyrhiza*, and *Carex acuta* (slender sedge), which were frequently observed during the surveyed periods with high cover density (Figure 6).

The macrophyte index ranged from 37.3 to 38.2, which indicates a consistently “good” state of the ecosystem of this site (Table 4).

Cicuta virosa L. was occasionally observed in all sections of the Vyzhyvka River. Species such as *Myosotis scorpioides* L., *Ranunculus aquatilis* L., *Vallisneria spiralis* L., and *Eleocharis palustris* (L.) were also rarely observed, mainly in the upper part of the riverbed. In all sections, abundant species with high cover densities included *Lemna minor* L., *Sagittaria sagittifolia* L., and *Spirodela polyrhiza* (L.) Schleid.



Figure 6. Macrophytes at site 3 of the Vyzhyvka River, near the village of Yakushiv: (a) *Nuphar lutea* (L.) Smith, *Carex acuta* L.; (b) *Lemna minor* L.

Table 4. Calculation of MOR for the Vyzhyvka River, near the village of Yakushiv, site 3.

No.	Species Name	Trophic Index, Li	Weight Coefficient, Wi	June 2023		August 2023		June 2024		August 2024	
				Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi	Projective Coverage, %	Coverage Factor, Pi
1	<i>Cicuta virosa</i> L.	6	2	<0.1	1	0.1	1	<0.1	1	<0.1	1
2	<i>Sium latifolium</i> L.	7	1	1	2	1	2	1	2	1	2
3	<i>Myosotis scorpioides</i> L.	4	1	1	2	0.5	2	2	3	0.1	2
4	<i>Ceratophyllum demersum</i> L.	2	3	1	2	1	2	1	2	0.7	2
5	<i>Nuphar lutea</i> (L.) Smith.	4	2	5	4	5	4	6	5	10	6
6	<i>Persicaria amphibia</i> (L.) S.F. Gray	4	1	1	2	1	2	1	2	2	3
7	<i>Lysimachia nummularia</i> L.	-	-	1	-	1	-	1	-	1	-
8	<i>Ranunculus circinatum</i> Spach	5	2	<0.1	1	-	-	<0.1	1	-	-
9	<i>Myriophyllum spicatum</i> L.	3	2	1	2	1	2	0.2	2	0.2	2
10	<i>Alisma plantago-aquatica</i> L.	4	2	<0.1	1	<0.1	1	0.1	2	0.1	2
11	<i>Sagittaria sagittifolia</i> L.	4	2	2.5	3	3	4	4	4	5	4
12	<i>Lemna minor</i> L.	2	2	2	3	2	3	2	3	2	3
13	<i>Lemna trisulca</i> L.	4	2	1	3	1	3	2	3	2	3
14	<i>Spirodela polyrrhiza</i> (L.) Schleid	2	2	1	2	1	2	2	3	1	2
15	<i>Hydrocharis morsus-ranae</i> L.	6	2	2	3	3	4	2	3	3	4
16	<i>Elodea canadensis</i> Michx.	5	2	1	2	1	2	1	2	1	2
17	<i>Carex acuta</i> L.	5	1	0.5	2	0.5	2	2	3	2	3
18	<i>Glyceria maxima</i> (Hartm.) Holmb.	3	1	2	3	3	4	2	3	2	3
19	<i>Typha latifolia</i> L.	2	2	1	2	1.5	2	1.5	2	1.5	2
Macrophyte index (18 indicator species)		On average 37.7—good		37.6 —good	38.2 —good		37.3 —good	37.8 —good		2023—37.7 (good)	
										2024—37.7 (good)	

Water quality at all test sites was classified as good, with a mesotrophic trophic status, indicating favourable environmental conditions for the development of higher aquatic plants along the entire river course. This is confirmed by the diverse flora comprising 64 species of higher aquatic and coastal plants, 29 of which serve as indicators of ecological status. These species belong to 31 genera, 20 families, 14 orders, 3 classes (*Equisetopsida*, *Liliopsida*, and *Magnoliopsida*), and 2 divisions (*Equisetophyta* and *Magnoliophyta*) (Table 5).

Table 5. Taxonomic composition of macrophytes of the Vyzhyvka River.

Class	Family	Number of Species	Participation, %
Division <i>Equisetophyta</i>			
<i>Equisetopsida</i>	<i>Equisetaceae</i>	1	2.78
Division <i>Magnoliophyta</i>			
<i>Magnoliopsida</i>	<i>Apiaceae</i>	2	5.56
	<i>Boraginaceae</i>	1	2.78
	<i>Brassicaceae</i>	1	2.78
	<i>Ceratophyllaceae</i>	1	2.78
	<i>Haloragaceae</i>	1	2.78
	<i>Lamiaceae</i>	1	2.78
	<i>Numphaceae</i>	1	2.78
	<i>Plantaginaceae</i>	1	2.78
	<i>Polygonaceae</i>	2	5.56
	<i>Primulaceae</i>	2	5.56
	<i>Ranunculaceae</i>	2	5.56
<i>Liliopsida</i>	<i>Acoraceae</i>	1	2.78
	<i>Alismataceae</i>	3	8.33
	<i>Araceae</i>	3	8.33
	<i>Hydrocharitaceae</i>	4	11.11
	<i>Cyperaceae</i>	5	13.89
	<i>Juncaceae</i>	1	2.78
	<i>Poaceae</i>	2	5.56
	<i>Typhaceae</i>	1	2.78
Total		36	100

The flora of the Vyzhyvka River includes only one species of *Equisetopsida*—*Equisetum palustre*, which accounts for 2.78% of the total species number. The division *Magnoliophyta* comprises 35 species (97.22%). Among the class *Magnoliopsida*, there are 11 families (55% of the total families), including 15 species (41.66% of macrophytes). The biodiversity within *Magnoliopsida* is limited to 1–2 species per family (Table 5). The class *Liliopsida* consists of 8 families represented by 20 species (55.56%). Thus, while most families belong to *Magnoliopsida*, *Liliopsida* prevails in species number.

Thus, the overwhelming majority of the flora of the Vyzhyvka River is made up of floating plants represented by species of the *Liliopsida* class, including the *Hydrocharitaceae* family (four species, 11.11%). A small part of the flora is formed by semi-submerged plants of the *Magnoliopsida* class, which includes such families as *Cyperaceae* (13.89% of the total number of species) and *Alismataceae* (three species each, 8.33%). Other families include one to two species, including representatives of floating leaves and submerged species. Of all the macrophyte taxa listed, the genus *Nuphar* had the highest species diversity. Several species were recorded along the Vyzhyvka River, with yellow pitcherwort (*Nuphar lutea*) dominating. This species does not survive in waters with low nutrient levels and high flow velocities [69]. In addition, free-floating plants, such as large glyceria (*Glyceria maxima*), are also present in the river, indicating that there are ecologically favourable conditions for their growth.

According to the analysis of life forms [56], the macrophyte flora of the Vyzhyvka River consists mainly of herbaceous polycarpics, among which hemicryptophytes and cryptophytes predominate, accounting for 52.78% and 47.22%, respectively (Table 6).

Table 6. Biomorphological structure of macrophytes in the Vyzhyvka River.

	Life form Characteristics	Number of Species	Participation, %
I	Hydrophytes or true aquatic plants:	11	30.56
	Free-floating forms	4	11.66
	Submerged rooted forms	4	10.56
	Species with floating leaves	2	5.56
	Submerged non-rooted forms	1	2.78
II	Helophytes or air-water plants:	8	22.22
	Low-growing helophytes	5	13.89
	High-growing helophytes	3	8.33
III	Moisture-loving coastal forms (hygrohelophytes)	11	30.55
IV	Hygrophytes (coastal moisture-loving species)	6	16.67

The biomorphological structure of the macrophytes of the Vyzhyvka River includes four main life forms: aquatic macrophytes (including free-floating, submerged and floating-leaved species), helophytes or air–water plants, moisture-loving riparian forms (hygrohelophytes), and bank hygrophytes.

The aquatic macrophytes (hydrophytes) of the Vyzhyvka River include 11 species (30.56% of the total number of flora species), which are classified into four groups according to their life forms. Free-floating species make up the largest percentage (11.66%) and are represented by representatives of the families Araceae (*Spirodela polyrrhiza*) and Hydrocharitaceae (*Hydrocharis morsus-ranae*). *Hydrocharis morsus-ranae* is highly adaptable to various environmental conditions, which allows it to successfully inhabit a wide range of aquatic environments. This species can form dense masses in which leaves and roots are intertwined, potentially leading to reduced light penetration to lower water levels. This situation can hurt other species of root macrophytes, limiting their growth and biodiversity. In addition, these mats can reduce water flow, limit the availability of nutrients and dissolved gases to other plants, and reduce DO concentrations, which can have an impact on aquatic life, including fish, and overall ecosystem function [70].

The group of submerged rooted macrophytes includes four species (10.56%), of which three belong to the Hydrocharitaceae family (including *Elodea canadensis*) and one to the Haloragaceae family (*Myriophyllum spicatum*). An increase in the number of *Elodea canadensis* can significantly change the ecological balance of aquatic environments. The intensive spread of this species can cause eutrophication processes, and at the end of the growing season, its decomposition leads to secondary eutrophication [71]. This activates bacterial metabolism, which results in anaerobic conditions that contribute to a decrease in the level of dissolved oxygen in water. Under such conditions, mineralisation processes slow down and fermentation end products accumulate, which can be toxic to other aquatic plants. The widespread distribution of *Elodea canadensis* has a negative impact on local aquatic flora, significantly reducing biodiversity in ecosystems where this species has become dominant.

Species with floating leaves are represented by *Nuphar lutea* and *Persicaria amphibia* (5.56%). The macrophyte *Nuphar lutea* (L.) Smith, known as the yellow pitcher, is a typical representative of aquatic plants with distinct leaf duality. The floating leaves of this plant create a dense cover on the water surface, which significantly reduces the penetration of light into the underwater environment, limiting the photosynthetic activity of underwater macrophytes. However, the submerged leaves of *Nuphar lutea* continue to play an important role, unaffected by seasonal changes. Although its photosynthetic activity is not as pronounced as that of surface leaves, submerged leaves remain an important component of the plant's biomass during the growing season. Studies [72] have shown that the submerged leaves of *N. lutea* have significant engineering potential in the context of plant interaction with water flows. It contributes to a local reduction in flow velocity, which in turn stimulates the processes of sedimentation and deposition of organic and inorganic particles, including organic matter that enriches bottom sediments.

Submerged rootless macrophytes are represented by only one species, *Ceratophyllum demersum* (2.78%). This plant has no root system and absorbs nutrients mainly through finely divided leaves. *C. demersum* is characterised by rapid growth in aquatic ecosystems with low light levels. Due to its ability to actively vegetatively reproduce, *Ceratophyllum demersum* can quickly form significant biomass covers, which allows it to adapt to different environmental conditions and actively colonise new territories [73].

Helophytes, or emergent (air–water) plants, account for 22.22% of the total number of species (eight species). Among them, five species (13.89%) belong to low-growing helophytes, represented by the families Alismataceae, Cyperaceae, and Ranunculaceae. Tall helophytes include three species (8.33%) and belong to the families Poaceae and Typhaceae. Moisture-loving coastal macrophytes (hygrophilous riparian species) constitute the most numerous group among aquatic vegetation, comprising 30.55% of the species composition (11 species). This group includes representatives of the families Apiaceae, Acoraceae, Brassicaceae, Cyperaceae, Plantaginaceae, Polygonaceae, and Ranunculaceae. The group of hygrophytes, i.e., semi-aquatic species capable of partially entering the aquatic environment, includes six species (16.67%) and is represented by the families Equisetaceae, Boraginaceae, Lamiaceae, Primulaceae, and Juncaceae.

3.3. Use of Geogenic Minerals to Stimulate the Development of Submerged Macrophytes in the Vyzhyvka River

The water body under study is currently not used for recreational purposes and does not serve an aesthetic function, but it meets sanitary and epidemiological requirements. At the same time, an analysis of macrophyte diversity in the Vyzhyvka River revealed an imbalance in the distribution of morphoecological groups, in particular, a low proportion of submerged root forms compared to other types of aquatic vegetation. Despite the classification of the water as “good”, such structural asymmetry may indicate potential threats to the stability of the ecosystem in the medium and long term.

Given the growing need to develop recreational areas near populated areas, especially in western Ukraine, which is receiving a significant number of internally displaced persons from regions where fighting continues, it is important to find solutions that combine environmental efficiency and social expediency. In this context, it is advisable to apply bottom-up regulatory mechanisms aimed at improving the physical and chemical conditions of the environment to stimulate the development of submerged aquatic vegetation and enhance the ecological and recreational value of the water body.

One promising and economically sound solution is the use of natural minerals, in particular mining and quarry waste containing silicon, calcium and other biophilic components. These substances are non-toxic, do not deteriorate water quality, do not inhibit the functioning of the biocenosis, and at the same time can stimulate the development of

root macrophytes, stabilise bottom sediments, and reduce the bioavailability of nutrients. In addition to improving the quality of the aquatic environment, this strategy addresses the problem of industrial waste disposal, which is relevant for regions with a long history of mineral extraction. In particular, residues generated during the cutting and processing of geomaterials can be converted into by-products with high environmental potential that comply with the principles of clean production and a closed-loop economy. Unlike expensive technologies, such as the use of lanthanum-modified bentonite, which requires significant capital investment and energy consumption, the use of geogenic minerals is considered a financially accessible alternative [74].

The environmental effectiveness of this approach has already been demonstrated in studies conducted in the Ustyia River (Rivne, Ukraine) [75] and has the potential for application in the Vyzhyvka River basin. The authors proposed a combination of chemical and physical methods for restoring water bodies using regionally abundant natural minerals—carbonates and quartz-glaucinite sand, which improve water quality by stabilising pH, and filtration properties and reducing pollutant concentrations. Experimental data confirmed that the use of these materials contributes to the improvement of the ecological state of river ecosystems and creates the conditions for their aesthetic and recreational restoration, with the possibility of adapting coastal areas for public spaces.

Near the Vyzhyvka River basin, there are enterprises specialising in the extraction and processing of mineral raw materials suitable for ecological use in aquatic ecosystems. In particular, PJSC “Ternopil Quarry” is one of the leading producers of limestone products in Ukraine. The enterprise develops limestone deposits with their subsequent processing into construction and technical materials, and the annual production capacity reaches 2 million tons. The Ivano–Dolinsky quarry provides the extraction of aluminosilicates, in particular bentonite, kaolin and crushed basalt, which can be used in environmental remediation measures, in particular to stabilise bottom sediments and stimulate the development of submerged aquatic vegetation. An important source of silicon-containing raw materials is also a granite quarry located in the Rokytniv district of the Rivne region. A general view of the extraction sites of natural materials, as well as their geographical location, is shown in Figure 7.

Given the availability of mineral resources within the Vyzhyvka River basin, it is advisable to consider the environmentally safe use of quarry waste as a potentially effective and economically viable means of maintaining the favourable ecological status of the reservoir. Limestone, granite, and basalt waste contains silicon, calcium, and other elements that participate in the biogeochemical processes of water bodies. Their introduction can contribute to the stabilisation of bottom sediments, reduce the bioavailability of phosphates, and improve conditions for the development of submerged macrophytes—an important element of ecological balance.

Studies [76] have shown that the addition of silicon improves the morphological and physiological properties of macrophytes, in particular *Schoenoplectus* spp., increasing tissue strength and reducing herbivory. Another study [77] showed that the addition of calcium hydroxide contributes to a reduction in phosphate concentration and phytoplankton production, while the presence of macrophytes has a positive effect on the structure of zooplankton, enhancing biocontrol.

Aluminosilicates are natural minerals that effectively absorb excess nutrients, reducing eutrophication in water bodies. They improve conditions for the growth of submerged macrophytes and stabilise bottom sediments by binding fine particles, reducing their mobility and the risk of resuspension [78]. This helps to maintain water transparency and the necessary level of light for photosynthesis. Aluminosilicates also act as a buffer, stabilising pH and creating favourable conditions for plants that are sensitive to fluctuations

in acid–base balance [79]. Their use should be combined with biomanipulation, which regulates trophic links to limit phytoplankton [80], as well as with the management of bottom sediments by introducing stabilising materials (clay, lime, crushed basalt) and controlling their properties.



Figure 7. General view of natural material extraction sites and their geographical location.

Bentonite is a sedimentary rock whose main component is montmorillonite (over 80% by weight; 60–80% bentonite clay) [81]. Its typical chemical composition includes 64.63% SiO_2 , 13.70% Al_2O_3 , 2.72% Fe_2O_3 , 3.94% CaO , 2.26% MgO , 0.16% K_2O , and 2.32% Na_2O [82]. Bentonite clay has high sorption capacity and water retention properties due to hydroxyl groups and negative charge, which ensures effective adsorption of cations, in particular heavy metals and organic compounds. Its use in water bodies helps to reduce turbidity, stabilises bottom sediments, and improves conditions for the growth of aquatic vegetation. In a study [83], bentonite had a positive effect on the development of *Vallisneria spiralis*: at bentonite/sediment ratios of 1:1 and 1:5, biomass growth was 18.78% and 11.79%, respectively. The activation of rhizosphere microbiota and changes in the physical and chemical characteristics of the sediment were also noted. One of the factors stimulating the growth of macrophytes was the release of nutrients from bentonite.

Crushed basalt, as a primary magmatic rock, is considered a promising mineral resource for improving the chemical composition of the aquatic environment and stimulating the growth of submerged plants. Studies [84] have shown that among geogenic substrates, basalt provides the most intense release of biophilic elements (Ca, Mg, Mn, Si), contributing to the formation of enriched biomass. Its effectiveness as a mineral fertiliser has also been confirmed in terrestrial ecosystems, in particular on *Urochloa brizantha* [85], where the application of basalt powder improved the agrochemical properties of the soil (increase in pH, macroelement content, reduction in phytotoxic Al), and increased plant productivity. Thus, crushed basalt shows potential as an environmentally safe mineral source of nutrients, capable of increasing soil fertility and stimulating plant growth in various types of ecosystems.

Limestone is a sedimentary rock, the basis of which is the minerals calcite and aragonite, various crystalline forms of calcium carbonate. It is advisable to use it to increase the buffer capacity and stabilise the pH of the aquatic environment. In addition, limestone particles can serve as a substrate for the rooting of submerged macrophytes, promoting their growth. According to the study [86], the limestone barrier created along the coastline contributed to the increase in the species diversity of coastal vegetation and improved conditions for the development of macrophytes, in particular *Schoenoplectus lacustris* and *Glyceria maxima*, which showed a high ability to absorb phosphorus a year after planting. At the same time, a stable decrease in the concentration of phosphorus in the water was recorded, which confirms the effectiveness of limestone as a natural filter in surface runoff treatment systems and maintaining the water's ecological balance.

The use of limestone for surface water treatment is an effective measure aimed at regulating the acid–base balance, in particular, increasing the pH of the environment and reducing the concentrations of phosphates and heavy metals [87]. Due to its slow dissolution in water, limestone provides a gradual change in chemical properties without the risk of toxic effects on aquatic biota [88]. Its dissolution products, in particular carbonate ions, can serve as a source of inorganic carbon for photosynthetic processes, and also contribute to the formation of poorly soluble forms of heavy metals, reducing their environmental hazard [89].

The pH level of the aquatic environment is one of the key factors affecting the structure of aquatic vegetation. Submerged basal macrophytes can use bicarbonates as a carbon source; therefore, their productivity increases in conditions of increased alkalinity. Dissolution of limestone contributes to an increase in the concentration of these ions, which creates favourable conditions for the development of submerged species [90]. Increasing pH also limits the competitive capabilities of free-floating macrophytes, as their metabolic activity decreases at pH > 9.5, and nutrient uptake, particularly phosphate and nitrate, becomes less efficient [91]. In addition, in alkaline environments, the bioavailability of trace elements such as iron, manganese, and phosphorus decreases due to their precipitation as poorly soluble compounds [92].

Mining and quarry wastes have significant potential to improve the conditions for the development of basal macrophytes in aquatic ecosystems. Due to their ability to absorb pollutants, buffer pH and regulate the content of nutrients in the aquatic environment, mineral materials can create a stable and favourable environment for macrophytes. The use of these materials in ecological restoration processes provides new opportunities for maintaining aquatic biodiversity and improving the condition of degraded river ecosystems.

Regulation of the optimal ratio of macrophytes in river ecosystems can significantly improve water quality, reducing eutrophication, suppressing the development of undesirable aquatic vegetation and contributing to the restoration of natural balance. At the same time, this has not only ecological, but also important recreational and aesthetic significance. It is precisely water spaces with well-balanced aquatic vegetation that have an attractive appearance, contribute to the formation of a favourable microclimate and become centres for recreation, walks and sports. Modern projects for the revitalisation of urban rivers involve not only improving water quality but also creating multifunctional public spaces, where ecosystem balance is combined with comfort and accessibility for residents [75]. Thus, the ecological restoration of rivers by regulating the structure of aquatic vegetation opens up new opportunities for the development of ecotourism and strengthening the connection between man and the natural environment.

The research results are applicable not only for the improvement of natural rivers. They can also be used for green structures, integrating living plants and building structures. This is promising technology for the improvement [92,93] of the outdoor [94,95] and indoor

environment, rainwater management [96–98], recovery of historical heritage [99,100], food production [101], etc. Usually, we use green roofs, green walls, vertical greening, etc. But there are some green roofs combined with artificial water features. An example is the Park Baku Residence in Baku, Azerbaijan (Figure 8), with artificial rivers.

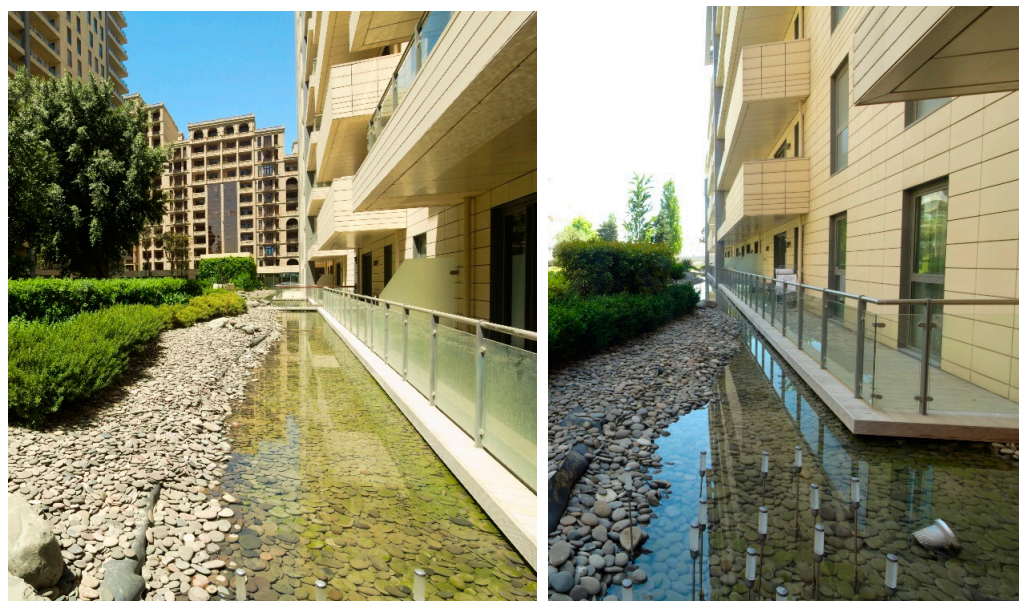


Figure 8. A natural river in the Park Baku Residence, Baku, Azerbaijan (author’s pictures).

The rivers have controlled depth and speed. The main purposes of them are the aesthetic improvement and ecoregulation—stress mitigation by interaction with nature. Such objects can increase the estimation by the green certification standards, including the Ukrainian SOU OEM 08.002.41.032 [102]. As is known, water can absorb air pollutants. Thus, we can improve the artificial rivers’ functions for cleaning the air environment by introducing the appropriate macrophytes. Their cleaning function is also important for the longer usage of the circulating water. There are some challenges, for example, the need for enough nutrients without breaking pumps, low depth, etc. It is possible to use most of the minerals in Section 3.3 for the bottom of the river, as they release the nutrients very slowly at the microelement level. Therefore, this direction will be the topic for future research.

4. Conclusions

The results of a comprehensive hydrobiological and hydrochemical study of the Vyzhyvka River in Ukraine confirmed its good ecological status. Throughout the year, the main physical and chemical indicators remained within natural background levels, indicating an absence of significant anthropogenic impact. According to the MIR index, all surveyed sections of the river are classified as Class II quality with a mesotrophic trophic status. The phytoindication analysis identified 64 species of macrophytes, with coastal life forms being the most dominant: hygro-helophytes (30.6%), helophytes (22.2%), and hygrophytes (16.7%). In contrast, the share of hydrophytes stands at only 30.6%, including four free-floating species, four submerged rooted species, two that have floating leaves, and one submerged unrooted species. This distribution pattern suggests a limited presence of submerged rooted forms, which are essential for regulating water transparency, binding sediments, and facilitating nutrient cycling. The low abundance of root-bound submerged macrophytes may be linked to a deficiency in key biogenic elements, particularly silicon and calcium. Although the overall ecological status of the river is assessed as good, the imbalance in life forms indicates potential risks to the ecosystem’s stability in the medium

and long term. Therefore, a practical recommendation is proposed: to use locally sourced mineral raw materials (such as aluminosilicates, limestone, and geomaterials obtained from mining waste) as natural amendments to improve conditions for the growth of root forms. Further research should focus on experimentally testing the impact of various geomaterials on the development of macrophytes, especially root-bound submerged species, while considering their ecological sensitivity. Additionally, it is important to study the interactions between silicon and other nutrients to optimise the approach to the eco-technical improvement of water bodies. The results obtained from this research can serve as a foundation for developing an effective environmental strategy for managing aquatic ecosystems.

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