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Environmental assessment of water resources in the tourist zones of Ivano-Frankivsk region: A case study

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ABSTRACT

This article presents the results of a comprehensive environmental assessment of surface water quality in the tourist regions of the Ivano-Frankivsk oblast, with a case study of the upper Prut River within the city of Yaremche. Given the intensification of seasonal recreational activities in the Carpathian region, special attention is paid to the ecological condition of mountain water bodies and their natural self-purification capacity. The study applied modern mobile express methods using a multifunctional portable water-quality meter (AZ 8603K) to conduct in situ measurements of key hydrochemical parameters, including total mineralization, pH, and dissolved oxygen (DO) concentration. Field sampling was carried out at ten control points along a 90-meter river section downstream from the Probiy waterfall – a zone of high turbulence and anthropogenic pressure. The data revealed a sharp decrease in mineralization (from 700 to 251 mg/L) and a simultaneous increase in DO (from 40.9 to 93.3 mg/L) within the first 30 meters, demonstrating the efficiency of turbulent aeration, dilution, and gravitational sedimentation. To quantitatively describe this self-purification process, an exponential decay model $M(x) = 450 \cdot e^{-0.07}x + 250$ was developed, capturing the spatial attenuation of mineralization and confirming stabilization beyond the initial turbulent zone. In parallel, an emission-based approach was used to estimate pollutant loads (BOD_5, nitrogen, phosphates) from both the permanent population (23,165 residents) and annual tourist flows (approx. 1 million visitors). The results indicated that the seasonal tourist load generates up to 43 times higher pollutant emissions than local residents, underscoring the critical environmental vulnerability of high-tourism mountain basins. A comparative analysis of field results with systematic state monitoring data (State Agency of Water Resources of Ukraine) confirmed the reliability of mobile diagnostics and highlighted the need for adaptive water quality management in regions with seasonal ecological stress. The findings demonstrate the feasibility of integrating mobile express monitoring, mathematical modelling, and emission forecasting into national water governance frameworks. The study provides scientifically grounded recommendations for improving environmental safety in tourist areas, including the modernization of wastewater treatment infrastructure, the development of mobile purification units, and stricter regulation of diffuse pollution sources.

Keywords: hydrochemistry, mobile diagnostics, self-purification, recreational load, emission modelling, eco-vulnerability, aeration, decay model, adaptive.

INTRODUCTION

Preservation of ecological balance and the achievement of sustainable development in tourist regions are defined as strategic imperatives of contemporary environmental policy in both national and global dimensions (European Environment Agency, 2025; Verkhovna Rada of Ukraine, 1995). Water resources occupy a pivotal position within this framework, as they function simultaneously as integral structural components of natural ecosystems and as determining factors of regional socio-economic dynamics (Strokal, 2021; Shumilova et al., 2023). Their role is particularly significant in the sphere of tourism, recreation, and local economic growth, where the quality and stability of aquatic systems directly influence public health, biodiversity maintenance, and the attractiveness of recreational landscapes (Zelinska, et al., 2021; Prykhodko et al., 2023).

Intensification of recreational activity in mountain territories is accompanied by growing anthropogenic pressures that substantially transform hydrochemical regimes of rivers and springs (Kravchynskyi et al., 2021). Under such conditions, natural mechanisms of self-purification are weakened, resilience of aquatic ecosystems is reduced, and the overall ecological potential of territories declines (Odnorih et al., 2020; Kijowska-Strugala et al., 2021). The Carpathian region illustrates this problem with particular clarity, as seasonal tourism surges create episodic but highly concentrated loads on fragile headwater systems (Matiyiv, et al., 2022). Effective response to these challenges presupposes systematic, spatially differentiated monitoring of water quality, incorporating both advanced analytical instrumentation and mobile diagnostic methods capable of capturing short-term fluctuations (Malovanyy et al., 2019; Kopei et al., 2020).

Empirical research confirms that recreational activities provoke marked variations in the concentrations of nitrates, phosphates, dissolved organic matter, and heavy metals, altering the functional stability of aquatic systems (Mandryk et al., 2020; Kinash et al., 2019). Investigations in the upper Prut River basin demonstrate the multifactorial impact of point-source emissions and diffuse runoff, which together create a complex hydroecological situation in Carpathian tourist centres (Korchemlyuk et al., 2019; Arkhypova et al., 2022). At the global and continental level, water contamination remains one of the most acute challenges to human well-being and ecological sustainability (Directive 2000/60/EC). According to the World Health Organization (2024), more than two billion people regularly consume polluted water, which increases the prevalence of cholera, dysentery, typhoid, and other waterborne infections. Despite the objectives of the United Nations Sustainable Development Goal 6, which envisages universal access to safe water and sanitation by 2030, real progress is uneven, particularly in developing states where infrastructure, governance, and environmental resilience remain insufficient (United Nations, 2023; European Environment Agency, 2025).

Health consequences of water pollution are profound and multidimensional (Khilchevskyi & Karamushka, 2022). Lin et al. (2022) note that diarrheal diseases annually claim approximately 485,000 lives, predominantly among children under five. Long-term exposure to toxic elements, particularly arsenic, substantially increases the probability of oncological pathologies, cardiovascular complications, and developmental disorders (Hasan et al., 2019). Chapman and Sullivan (2022) argue that one of the most significant barriers to effective water governance lies in the scarcity and fragmentation of reliable monitoring data. Absence of systematic observation of physicochemical and biological parameters creates so-called "blind spots," undermining timely management interventions and reducing the capacity of ecosystems for natural recovery. Consequently, monitoring systems must not only record concentration levels but also trace contamination pathways, evaluate efficiency of remediation measures, and form a basis for predictive ecological modelling.

The vulnerability of mountain regions is accentuated by the synergistic interaction of anthropogenic load and climate-induced variability of hydrological regimes. In the Carpathians, seasonal changes in runoff, intensified precipitation extremes, and rising air temperatures aggravate hydroecological instability. Vyshnevskyi and Donich (2021) highlight statistically significant shifts in climatic parameters that diminish the self-purification capacity of riverine ecosystems. Lowland reaches are particularly exposed during summer low-flow periods, when pollutant accumulation intensifies and dilution mechanisms are impaired. Adaptive models of water governance that integrate real-time monitoring and seasonal risk assessment emerge as indispensable prerequisites for ecological security.

Technological modernisation has introduced mobile rapid assessment techniques as efficient instruments for field diagnostics of hydrochemical parameters. Hansson and Pettersson (2016) and Jin and Whitehead (2018) emphasise that such approaches enable prompt evaluation of water quality in remote or tourism-intensive areas, where traditional laboratory analyses are limited by logistical constraints. Integration of mobile express methods with institutional monitoring frameworks provides a comprehensive analytical foundation, allowing the assessment of self-purification mechanisms, particularly in hydrodynamically active zones (Martinez-Haro et al., 2015).

Intensive recreational development in the Ukrainian Carpathians is accompanied by infrastructural limitations that amplify ecological risks. According to research by Klymchuk et al. (2022), a considerable share of tourist facilities in the Yaremche region operate without effective wastewater treatment systems, which contributes to diffuse groundwater contamination and deterioration of spring water quality. The study reveals altitude-dependent differences in the concentration of heavy metals and demonstrates that only half of tourism enterprises use protected underground sources, while the rest rely on unregulated surface water. Such findings reinforce the need for systematic laboratory observations in combination with mobile rapid diagnostics to strengthen environmental control in mountain tourism clusters. Despite the intensification of hydroecological research, processes of turbulent self-purification in areas of hydraulic disturbance such as waterfalls remain insufficiently explored. These microzones, characterised by aeration, turbulent mixing, and gravitational sedimentation, play a crucial role in restoring hydrochemical equilibrium and stabilising oxygen regimes. The Prut River within Yaremche provides a representative natural laboratory for studying the interaction of seasonal recreational load, diffuse pollution sources, and natural mechanisms of hydrochemical balance restoration. On this basis, the present study sets the objective of conducting a multi-parameter ecological assessment of the Prut River by means of mobile hydrochemical diagnostics, evaluating the role of natural self-purification processes, and formulating adaptive principles of water quality governance in tourism-dependent regions of the Ukrainian Carpathians.

EXPERIMENTAL PART

Water quality testing was carried out using modern portable devices, in particular the multifunctional Water-qualitymeter AZ 8603K, which allows field measurements of acidity (pH), electrical conductivity (mineralisation) and dissolved oxygen (DO) concentration. This device allows for rapid measurement of key hydrochemical indicators, including:

- acidity (pH) – an indicator of the acid-alkaline balance of water, reflecting the activity of hydrogen ions in the aquatic environment;
- mineralisation (electrical conductivity) – determines the total content of dissolved salts, including calcium, magnesium, sodium, chloride, sulphate and bicarbonate ions;
- DO concentration – a critically important indicator for assessing the ecological quality of water, reflecting the ability of the aquatic environment to support the life of hydrobionts.

The aim was to assess the effectiveness of the natural self-purification processes of the Prut River within the tourist centre of Yaremche. Samples were taken at 10 control points located 0–90 metres below the Probii waterfall. The rapid analysis method provided timely information on the actual state of the aquatic environment in the study area, which is particularly relevant in the context of the ever-increasing number of tourists and the growing pressure on infrastructure. All measurements were carried out in accordance with current standards for field hydrochemistry and hydroecological monitoring of surface waters in accordance with the provisions of DSTU 4287:2004 (Derzhspozhyvstandart

Table 1. Water quality indicators for the Prut River from the Probi waterfall (0–90 m)

№	Distance, m	Location	Coordinates (latitude, longitude)	Mineralization, mg/L	Dissolved oxygen, mg/L	Purification by mineralization, %	Purification by oxygen, %
1	0	Probiy Waterfall (initial point)	48.439425, 24.539593	700	40.9	0.0	0.0
2	10	Prut River, 10 m downstream	48.438123, 24.540404	525	58.2	25.0	42.3
3	20	Prut River, 20 m downstream	48.438600, 24.539700	380	70.3	45.71	71.88
4	30	Prut River, 30 m downstream	48.438123, 24.540404	251	93.3	64.14	128.12
5	40	Prut River, 40 m downstream	48.437800, 24.540800	260	95.1	62.86	132.52
6	50	Prut River, 50 m downstream	48.437500, 24.541100	275	97.0	60.71	137.16
7	60	Prut River, 60 m downstream	48.437200, 24.541400	310	96.3	55.71	135.45
8	70	Prut River, 70 m downstream	48.436900, 24.541700	308	95.5	56.00	133.50
9	80	Prut River, 80 m downstream	48.436600, 24.542000	320	95.0	54.29	132.27
10	90	Prut River, 90 m downstream	48.436300, 24.542300	380	96.0	45.71	134.72

Ukrainy, 2004). Water samples were taken from the Prut River, which flows through major tourist centres such as Yaremche (Table 1). Water quality standards for recreational and domestic water bodies (in Ukraine) are shown in Table 2. In order to objectively quantify the self-purification processes of the Prut River over a 90-metre stretch from the Probiy waterfall, purification coefficients were calculated based on two key hydrochemical indicators: mineralisation and dissolved oxygen concentration. The calculations were performed in accordance with the classical formula for determining the relative change in the concentration of a substance in an aqueous medium:

$$K_{\text{purif}} = \frac{C_{\text{start}} - C_i}{C_{\text{start}}} \times 100\% \quad (1)$$

where: C_{start} – concentration of the indicator at the starting point (0 m), C_i – concentration at a selected point of the river profile.

For dissolved oxygen, where the concentration tends to increase due to turbulent saturation, the formula takes the form:

$$K_{purif} = \frac{DO_i - DO_{start}}{DO_{start}} \times 100\% \quad (2)$$

where: DO_{start} – dissolved oxygen concentration at the starting point, DO_i – dissolved oxygen concentration at a selected point of the river profile.

The initial concentrations were 700 mg/l for mineralisation and 40.9 mg/l for dissolved oxygen. Further calculations show an intense decrease in mineralisation in the first 30 metres, corresponding to a 64.14% purification in this section, after which the indicator gradually increases, which probably indicates remineralisation or secondary enrichment of water due to runoff from the banks and bottom. At the same time, the concentration of dissolved oxygen increased throughout the profile, reaching 96.0 mg/l at a distance of 90 metres, which corresponds to a purification of over 130%.

The dynamics confirm the high level of turbulent oxygen saturation in the studied area, which indicates the effectiveness of natural self-purification processes in the upper reaches of the Prut River (Figure 1).

To ensure a comprehensive assessment of the ecological status of the Prut River within the urban limits of Yaremche—a locality subject to intensive seasonal recreational activity—a comparative analysis was conducted between primary field measurements obtained through mobile hydrochemical diagnostics and the results of systematic state environmental monitoring (Ivano-Frankivsk Regional State (Military) Administration, 2023). This comparative approach is essential for assessing both short-term local deviations in water quality and the consistency of field-based rapid measurements

Table 2. Water quality standards for recreational and domestic water bodies

Parameter	MAC / Standard Value	Source / Note
Mineralization	up to 1000 mg/L (total mineralization)	DSTU 4077:2001
Dissolved oxygen	not less than 4–6 mg/L	DSTU 4808:2007

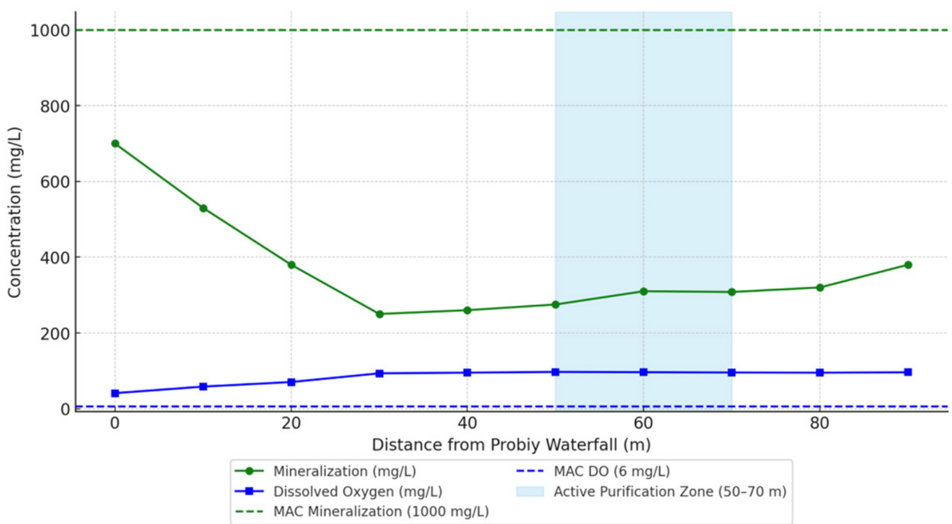

Figure 1. Water indicators with visualisation of the active self-cleaning zone

with standardized laboratory protocols (Arkhypova et al., 2025). Such dual-level evaluation not only enhances the reliability of in situ assessments but also provides a deeper understanding of the spatiotemporal dynamics of hydrochemical indicators under conditions of anthropogenic load

To establish a reliable basis for comparison, the study utilised data from the national surface water monitoring network managed by the State Agency of Water Resources of Ukraine. Specifically, the monitoring data were obtained from the hydrological observation site (Prut River, 896 km, Yaremche, left bank), which is officially included in the regional monitoring framework. The latest available sampling date for this station was 24 September 2024, corresponding closely with the timeframe of the present field-based survey, ensuring adequate temporal consistency between datasets.

The official monitoring protocol at this location includes a broad spectrum of hydrochemical indicators reflecting both anthropogenic influence and natural background conditions. Among the parameters systematically measured are suspended particulate matter (SS), total nitrogen (TN), sulphates (SO_4^{2-}), chlorides (Cl^-), ammonium ions (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-), and phosphates (PO_4^{3-}). Furthermore, key ecological indicators – namely DO and five-day biochemical oxygen demand (BOD_5) – are used to evaluate the metabolic balance and self-purification potential of the aquatic system. These variables are widely accepted in international practice as core metrics for determining eutrophication risk, nutrient dynamics, and the degree of organic contamination in surface water ecosystems. Importantly, all monitored values at the observation point remained within the regulatory thresholds defined by Ukrainian and international environmental standards for surface waters designated for recreational and domestic use. In particular, the levels of dissolved oxygen were consistently above the minimum ecological thresholds (≥ 6 mg/L), and BOD_5 values did not indicate significant organic contamination. These results confirm the general ecological stability of the monitored river segment at the time of sampling and validate the use of mobile express methods for real-time water quality screening in tourism-impacted regions. (Table 3).

According to official data provided by the State Agency of Water Resources of Ukraine, the concentration of DO in the Prut River at the designated observation point (Prut River, 896 km, Yaremche, left bank) on the date of the latest sampling – 24 September 2024 – was recorded at 8.9 mg/L. This value lies well within the permissible ecological range for surface waters used for recreational and domestic purposes, in accordance with national standards that prescribe a minimum threshold of 4.0–6.0 mg/L for maintaining aquatic ecosystem functionality and biological diversity.

In contrast, the results of field-based rapid measurements carried out during this study revealed substantially higher concentrations of dissolved oxygen, with peak values reaching 96.0 mg/L at certain sampling points. At first glance, such elevated oxygen levels may appear anomalous; however, their interpretation must be contextualized within the specific hydrodynamic conditions of the sampling site. Measurements were taken directly downstream from the Probiy waterfall, a zone characterized by pronounced vertical water displacement, turbulent mixing, and intensive aeration. These processes significantly enhance gas exchange between the atmosphere and the water column, promoting supersaturation with molecular oxygen – a well-documented phenomenon in lotic environments subject to cascade and plunge-pool hydrodynamics.

Table 3. Water quality monitoring (Prut River, Yaremche, 24 September 2024) according to data from the State Agency of Water Resources of Ukraine

Indicator	Actual value	MPC (MAC)*	Exceedance of norm
Total nitrogen, mg/dm³	0.99	–	None
Biochemical oxygen demand (BOD_5), mgO_2/dm^3	1.6	3	None
Suspended solids, mg/dm³	15	15	None
Dissolved oxygen, mgO_2/dm^3	8.9	4	None
Sulphate ions, mg/dm³	54	100	None
Chloride ions, mg/dm³	14	300	None
Ammonium ions, mg/dm³	0.03	0.5	None
Nitrate ions, mg/dm³	0.29	45	None
Nitrite ions, mg/dm³	0.009	3.3	None
Phosphate ions (polyphosphates), mg/dm³	0.015	3.5	None

Rather than indicating any technical measurement error or systemic environmental disturbance, the observed supersaturation in DO serves as empirical evidence of the effective natural self-purification mechanisms operating in mountain river systems under turbulent flow conditions. These mechanisms are particularly active in the upper reaches of river basins where vertical gradients, substrate roughness, and flow acceleration generate aeration zones with high ecological value.

The consistency between field and official monitoring results – despite differences in sampling location and hydrodynamic context – underscores the validity and scientific reliability of mobile express methods for ecological diagnostics. Such methods are especially valuable in hard-to-access or dynamic environments where stationary monitoring infrastructure is limited. The comparative analysis not only confirms the favourable environmental status of the studied river segment but also highlights the methodological complementarity of centralized laboratory testing and decentralized field-based observations.

In addition to the pointwise comparison, a broader temporal analysis was conducted based on monthly dissolved oxygen data for the year 2024, as published by the State Water Agency. This analysis revealed seasonal fluctuations in DO concentrations, ranging from a minimum of 8.3 mgO_2/dm^3 in July to a maximum of 13.2 mgO_2/dm^3 in March, as illustrated in Figure 2. Notably, at no point during the year did DO levels fall below the regulatory threshold, suggesting that even during the warmest and most hydrologically vulnerable months, the river retains sufficient oxidative capacity to sustain ecological stability.

These seasonal dynamics are consistent with established hydroecological theory: lower DO values in summer are attributed to elevated water temperatures, increased biological oxygen demand, and reduced solubility of gases, while higher values in late winter and early spring coincide with cooler temperatures, reduced metabolic activity, and enhanced turbulence from snowmelt-driven flows. Such patterns provide additional validation of both the resilience of the Prut River ecosystem and the predictive reliability of national monitoring frameworks in capturing intra-annual variations in key environmental indicators.

Taken together, the findings support the integration of mobile express measurements into national environmental surveillance strategies and affirm the importance of hydrodynamic context in interpreting oxygen metrics in river systems.

The longitudinal analysis of DO concentrations over the course of the 2024 calendar year reveals a distinct and predictable seasonal dependence, which reflects the fundamental interaction between hydrometeorological variables and the oxidative status of freshwater ecosystems. According to official data from the State Agency of Water Resources, DO levels in the Prut River exhibit bimodal peaks during the transitional seasons – specifically in spring (March–May) and autumn (October–December). During these periods, measured concentrations were

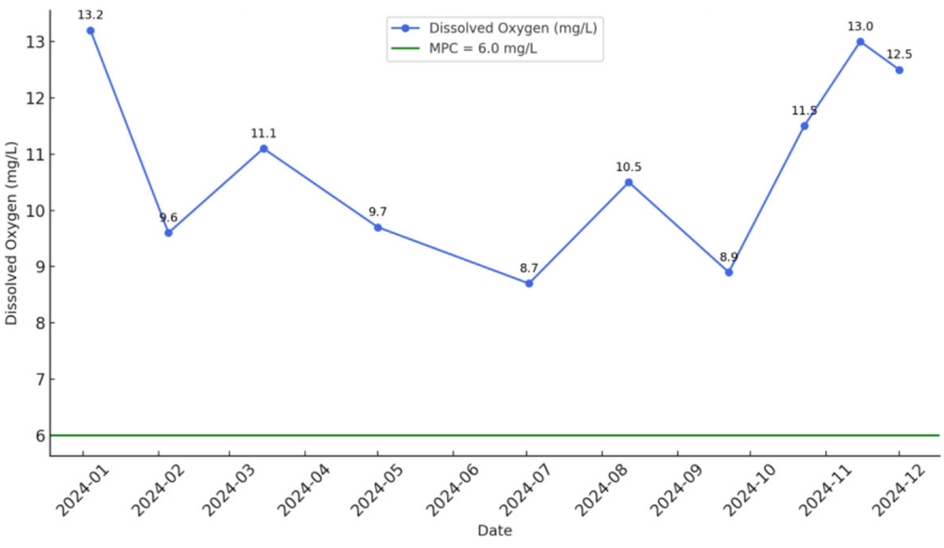

Figure 2. Dynamics of dissolved oxygen in the Prut River within the city of Yaremche according to data from the Western Region Water Monitoring Laboratory (2024). The green line indicates the maximum permissible level (MPC = 4.0 mgO_2/dm^3). Source: https://monitoring.davr.gov.ua/

consistently elevated, reaching a maximum of 13.2 mgO_2/dm^3 in March.

This seasonal increase in oxygenation can be attributed to several interrelated factors. Firstly, lower water temperatures during spring and autumn enhance the solubility of oxygen, as gas solubility in water is inversely proportional to temperature. Secondly, increased hydrological turbulence, driven by snowmelt runoff in spring and rainfall in autumn, promotes vertical and horizontal mixing within the water column, thereby facilitating more efficient atmospheric gas exchange. Thirdly, reduced biological oxygen demand (BOD) during cooler periods, due to slower microbial metabolism and lower phytoplankton activity, contributes to maintaining higher background oxygen levels.

Conversely, during the summer months (June–August), a slight but discernible decline in DO concentrations was observed, with the annual minimum of 8.3 mgO_2/dm^3 recorded in July. This seasonal dip is consistent with well-documented hydroecological processes, whereby elevated temperatures decrease the solubility of dissolved gases and simultaneously intensify biological oxygen consumption, especially under conditions of heightened primary productivity and microbial decomposition. In addition, reduced discharge volumes and slower flow velocities in summer further limit turbulent mixing and exacerbate thermal stratification, thereby reducing oxygen renewal rates in surface waters.

Despite this decline, the minimum recorded DO levels remained well within the ecological safety range, thus confirming that the Prut River retains its oxidative stability even under seasonal stress. These results provide strong empirical support for theoretical models of oxygen regime dynamics in temperate mountain rivers and further validate the role of continuous state monitoring in capturing short- and medium-term fluctuations in ecosystem function.

In parallel with the oxygen dynamics, the study also focused on characterizing the self-purification capacity of the river in terms of mineralisation attenuation. To this end, a regression model employing exponential smoothing was developed based on empirical data collected across a 90-meter transect downstream of the Probiy waterfall in Yaremche. The observed spatial profile of mineralisation indicated a sharp and nonlinear decrease in salt concentration during the first 30 meters of flow, followed by a transition to a relatively stable plateau.

This pattern is characteristic of diffusion-turbulent interactions within high-energy fluvial environments, where mechanical mixing, gravitational settling of suspended solids, and rapid dilution converge to enhance water quality. The turbulent aeration induced by the waterfall acts as a hydraulic disturbance that facilitates instantaneous vertical homogenization, while downstream transport allows for progressive chemical stabilization as the river approaches a new hydrochemical equilibrium.

The exponential nature of the decline supports the hypothesis that the dominant regulatory processes are governed by first-order kinetic decay and turbulent dispersion, which are typical for open-channel flows with high Reynolds numbers and significant head differentials. As such, the derived model provides not only a quantitative description of observed mineralisation behavior, but also a theoretical framework for understanding self-cleaning dynamics in mountainous river systems.

The mathematical model takes the form:

$$M(x) = a \cdot e^{-bx} + c \quad (3)$$

where: $M(x)$ – water mineralisation (mg/l) at a distance of x metres from the waterfall; a, b, c – model parameters that determine the shape of the curve (empirically selected based on data); e – base of the natural logarithm (approximately 2.718); x – distance in metres from the point of water discharge.

The developed model is based on the need for a quantitative description of self-cleaning processes in river systems after hydrodynamic disturbance caused by waterfall. In the case of the Prut River within the city of Yaremche, a rapid decrease in water mineralisation is recorded in the section after the Probiy waterfall, indicating the action of intense dilution and precipitation mechanisms. To formalise the observed dynamics, an exponential decay analytical function was chosen, which allows modelling the decrease in the concentration of mineralised substances depending on the distance from the source of disturbance.

From the point of view of mathematical modelling, such systems with a sharp initial decrease in concentration and a gradual approach to equilibrium are best described by an exponential decay function, which is analytically suitable for expressing such nonlinear patterns.

The primary mechanism contributing to the change in hydrochemical composition is turbulent dilution, which occurs as a result of water falling from a height. When water comes into contact with air at high speed and with high kinetic energy, zones of intense mixing are formed, leading to effective oxygen saturation of the water and simultaneous dilution of dissolved salts, which explains the rapid decrease in mineralisation in the first few metres after the waterfall, as evidenced by empirical data and corresponding to the function profile e^{-bx}.

Another important factor is the gravitational settling of suspended substances, particularly particles with a high specific weight. When the flow velocity changes abruptly after passing a waterfall, the flow slows down, creating conditions for undissolved fractions to settle to the bottom. The greatest effect of sedimentation occurs in the initial section (up to 30 metres), after which the process becomes less pronounced, which corresponds to the gradual levelling of the concentration curve in the model.

In addition, the effects of molecular and turbulent diffusion, which ensure the redistribution of dissolved substances in the water column, should be taken into account. As it moves away from the source of disturbance (waterfall), the system approaches conditions of local hydrochemical equilibrium, within which concentration gradients decrease and mineralisation stabilises at a certain background level. In the model, this is reflected by the asymptote ccc, which reflects the residual level of salts that does not change with distance.

Thus, the use of an exponential function in modelling the dynamics of mineralisation of the Prut River after hydraulic disturbance is scientifically sound and ecologically relevant. The model not only accurately describes empirical data, but also makes it possible to predict changes in water quality in cases of increased tourist load, changes in climatic conditions or anthropogenic impact. Its analytical form allows formalising and integrating natural self-purification mechanisms into general water management models. Based on the selection of the best approximating equation using the least squares method (in Excel) for the given data, the following parameters were obtained:

$$M(x) = 450 \cdot e^{-0.07x} + 250 \quad (4)$$

where: $C(x)$ – mineral concentration at a distance of xxx from the starting point (mg/l); a = 450 – amplitude of initial mineralization decrease; b = 0.07 – cleaning speed coefficient (reduction); c = 250 – asymptotic value of mineralization, below which the indicator does not decrease (baseline).

Based on the model, a graph was constructed showing the decay of mineralization with distance from the source of turbulent disturbance (Figure 3). The curve demonstrates logical hydrochemical behavior - a rapid decrease in mineralization to approximately 30 m, after which the concentration stabilizes, which may indicate the limit of the effective action of turbulent aeration and mixing. The selection of the exponential functional form to describe mineralisation dynamics downstream of

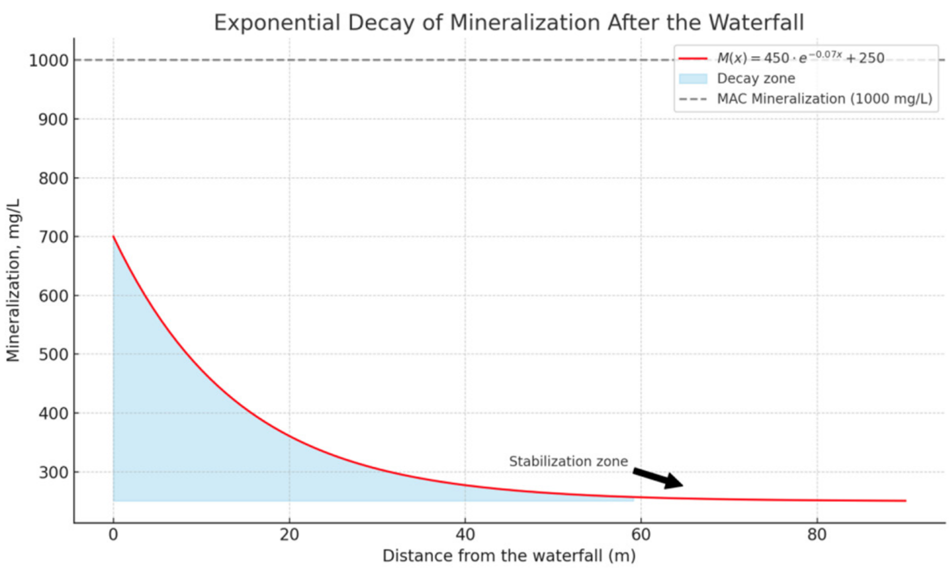

Figure 3. Mineralization fading with distance from the source of turbulent disturbance

the waterfall is underpinned by the intrinsic physical and hydrodynamic characteristics of mountain river systems. Within the initial tens of metres following the turbulent drop, the flow undergoes gravitational sedimentation of suspended solids, accompanied by intensive mechanical mixing and atmospheric oxygenation. These processes, driven by the high energy gradient, result in a rapid transformation of the hydrochemical parameters. As the flow exits the zone of maximum turbulence, a gradual transition toward quasi-equilibrium background conditions is observed. The resulting behaviour aligns with the classical exponential decay function, exhibiting a fast initial decline in parameter values followed by asymptotic convergence toward a steady state, indicative of the system's natural self-regulation capacity.

The mathematical model derived from this observed pattern provides a robust tool for evaluating the effectiveness of natural self-purification mechanisms, projecting potential shifts under increased anthropogenic pressure, and informing localized water protection strategies, especially in regions experiencing high tourist activity (Hydrologic Modeling, 2018). Owing to its analytical structure, the model is amenable to integration within environmental monitoring frameworks, spatial planning algorithms, and adaptive water management systems, thereby enhancing both predictive accuracy and policy relevance (Kolesnik et al., 2017).

Complementing this modelling approach is the calculation of pollutant emissions into surface water bodies, which constitutes an integral component of systematic environmental diagnostics and long-term sustainability forecasting of aquatic ecosystems. In the context of the Ivano-Frankivsk region, where the Prut River basin encompasses multiple high-intensity recreational zones, the application of an emission-based methodology is particularly justified. Traditional water quality observation, while informative, often fails to establish clear cause-and-effect relationships between contamination sources and hydroecological outcomes ((Ivano-Frankivsk Regional State Administration, 2022). In contrast, quantitative emission estimations—i.e., the measurement of the actual mass of pollutants entering the aquatic environment—offer a more diagnostic and management-oriented perspective.

Specifically, the Prut River sub-basin encompassing Yaremche, Mykulychyn, and Bukovel is subject to a dual anthropogenic load: a baseline constant pressure from permanent residents and a highly variable seasonal load resulting from tourism, which intensifies markedly during peak periods. During these times, the influx of visitors may double or triple the local population, placing excessive stress on existing water abstraction, wastewater collection, and treatment infrastructure. This, in turn, promotes the accumulation of both solid and dissolved pollutants in the aquatic system. Notably, a considerable proportion of tourist establishments in this region remain disconnected from centralized sewage networks, discharging partially treated or untreated effluents directly into the environment. These non-point (diffuse) pollution sources, due to their spatial dispersion and lack of formal regulation, present significant challenges for environmental governance and enforcement.

Therefore, the integration of functional modelling, emission-based accounting, and mobile field diagnostics constitutes a comprehensive strategy for addressing the cumulative environmental risks posed by unregulated tourism growth in mountain river basins. Such an approach facilitates more effective ecological forecasting, supports the implementation of mitigation policies, and contributes to the sustainable development of tourism-intensive territories.

Calculation formula:

$$E = \frac{N \cdot e \cdot (1 - \eta) \cdot 365}{1000} \quad (5)$$

where: E – annual pollutant emissions, tonnes/year; N – population (persons); e – specific emission of a substance per person per day, g/day; η – cleaning efficiency coefficient (from 0 to 1) 365 – the number of days in a year; 1000 – conversion factor for grams to tonnes.

Submitted data:
- permanent population: 23,165 people,
- tourists per year: 1,000,000 people.

Specific emissions:
- BOD_5 – 60 g/day
- Total nitrogen – 9.9 g/day
- Phosphate ions (polyphosphates) – 0.15 g/day
- treatment efficiency: 70% (untreated fraction – 30%)
- number of days in a year: 365
- conversion of grams to tonnes: /1000

The results of the calculations are shown in Table 4. The conducted estimations clearly indicate a substantial disparity in pollutant emissions into surface water bodies between the permanent

Table 4. Calculation results

Indicator	Permanent population (t/year)	Tourists (t/year)
BOD_5	152,194.05	6,570,000.00
Total nitrogen	25,112.02	1,084,050.00
Total phosphorus	380.49	16,425.00

residents and seasonal tourist population within the Yaremche territorial community. This pronounced imbalance serves as a strong indicator of the ecological vulnerability of the region under conditions of seasonally intensified anthropogenic pressure, particularly during peak tourist periods.

According to the modelling results, the annual anthropogenic load generated by the permanent population of 23,165 individuals amounts to approximately 152.2 tonnes of biochemical oxygen demand (BOD_5), 22.32 tonnes of total nitrogen, and 6.34 tonnes of phosphate compounds. These calculations are based on standard emission coefficients and assume the average performance of local wastewater treatment infrastructure.

In contrast, the annual tourist flow, which reaches 1,000,000 individuals, contributes a disproportionately high pollutant load, potentially resulting in 6.570 tonnes of BOD_5, 963.6 tonnes of total nitrogen, and 273.75 tonnes of phosphates. These estimates reflect per capita daily discharge norms for unregulated tourism-related wastewater and account for a 70% treatment efficiency, meaning that 30% of all pollutants bypass proper treatment and are directly discharged into natural aquatic systems.

The comparative analysis reveals that the pollution load attributable to the tourist population is approximately 43 times greater than that of the permanent population. This disparity is attributed not only to the greater absolute number of visitors but also to the temporal concentration of tourist activities – often within a few peak months – resulting in short-term but extremely intense pressure on local water supply and sanitation infrastructure.

Such episodic yet high-magnitude pollution loads substantially increase the risk of eutrophication, disruption of aquatic biocenoses, and functional degradation of river ecosystems. Furthermore, the elevated concentrations of organic and nutrient pollutants (particularly nitrogen and phosphorus compounds) compromise the efficacy of water treatment processes and negatively affect the recreational and ecological value of the water bodies.

These findings substantiate the urgent necessity of implementing a holistic and adaptive water management system in tourism-intensive areas of the Carpathians. Key strategic directions should include:

- the modernisation and expansion of centralised wastewater treatment facilities to accommodate seasonal fluctuations;
- the establishment of riparian buffer zones and constructed wetlands to intercept surface runoff;
- enhanced monitoring and control mechanisms for non-point (diffuse) pollution sources from decentralised tourist infrastructure;
- and the integration of dynamic forecasting models to account for projected seasonal loads in water management planning and environmental policy.

Adopting such a multifaceted approach will ensure not only the preservation of water quality and ecosystem resilience, but also the sustainability of tourism-driven economic development in mountainous regions with heightened ecological sensitivity.

DISCUSSION

The results of the experimental field study demonstrate a consistent reduction in water mineralisation levels in the Prut River downstream from the zone of pronounced hydrodynamic disturbance, specifically the Probiy waterfall located in Yaremche. Hydrochemical transformation within this segment is effectively described by an exponential decay model developed on the basis of in situ measurements of dissolved solid concentrations. The constructed model confirms the existence of a well-defined natural dilution zone spanning the initial 30 metres beyond the waterfall, where a marked decrease in mineralisation is observed. The reduction is attributable to the synergistic effect of intensive aeration, gravitational sedimentation, and turbulent mixing of the flow. Beyond this threshold, the mineralisation curve demonstrates a near-horizontal trajectory, indicating the onset of hydrochemical equilibrium. Such dynamics are typical for mountain fluvial systems characterised by steep gradients and coarse substrates, where turbulence plays a significant role in enhancing solute dispersion and sedimentation processes.

A critical analytical component of the study involved the estimation of pollutant emission loads discharged into the aquatic environment. Utilising standardised daily emission coefficients – 60 grams of BOD_5, 9.9 grams of total nitrogen, and 0.15 grams of phosphate compounds per capita – the cumulative annual load from the resident population of the Yaremche community, comprising 23,165 individuals, was calculated to be approximately 152 tonnes of BOD_5, 22 tonnes of nitrogen, and 6 tonnes of phosphate compounds.

In contrast, the anthropogenic pressure associated with the annual tourist flow, officially reported at around one million individuals, generates substantially higher pollutant emissions. The estimated contributions from this category reach over 6.570 tonnes of BOD_5, 963 tonnes of nitrogen, and 274 tonnes of phosphates per year. The disparity reflects the intensity and temporal concentration of recreational activity, which imposes a disproportionately high burden on local water management infrastructure during peak seasons.

The analysis underscores the leading role of tourism-related emissions in shaping the hydroecological profile of the region. Findings justify the necessity of implementing seasonally adaptive wastewater management mechanisms capable of mitigating peak loads. Integration of such approaches is essential for preserving the ecological functionality of mountain river systems and maintaining the balance between environmental protection and sustainable regional development.

The findings obtained in the present study demonstrate a high degree of correlation with previously published results by Boichuk et al. (2021), who investigated the anthropogenic transformation of hydrochemical conditions in the Prut River basin within the territorial boundaries of Yaremche. The referenced authors reported consistently elevated concentrations of organic matter and biogenic elements, particularly during periods of increased recreational activity. The seasonal nature of these fluctuations was highlighted as a critical factor influencing the ecological stability of fluvial systems in mountain regions with active tourism infrastructure.

Comparable patterns were also documented in the work of Kondratyuk (2021), who conducted a detailed hydroecological analysis of the Styr River. That study employed mathematical modelling to identify and spatially localise zones of excessive anthropogenic load within urbanised sections of the river. Modelling outputs facilitated the delineation of ecologically vulnerable sites and provided quantitative support for the implementation of targeted pollution mitigation strategies. The methodological framework used underscores the practical utility of simulation tools in the development of adaptive water management approaches in heavily impacted aquatic environments.

Further reinforcement of these findings is provided by Lukyanets et al. (2021), whose research focused on spatial-temporal variability in runoff and water quality across multiple riverine catchments. Particular emphasis was placed on the causal relationships between seasonal fluctuations in hydrological parameters and the intensification of diffuse (non-point source) pollution. Their conclusions align with the observed dynamics in the Prut River, supporting the hypothesis that the combination of natural climatic variability and human-induced pressures serves as a key driver of chemical transformation in mountain watercourses.

Collectively, these referenced studies substantiate the validity of the methodological approaches adopted in the current research and reinforce the interpretation of seasonal and spatial pollutant variability as a function of anthropogenic stress, hydrometeorological conditions, and geomorphological context. The integration of comparative hydrological assessments and modelling techniques is therefore essential for robust diagnosis of ecological risks and informed environmental decision-making in tourism-intensive regions.

A growing body of empirical evidence indicates that small river basins located within regions of intensive recreational exploitation demonstrate heightened sensitivity to anthropogenic impacts. In particular, the comparative hydroecological assessments presented by Tsaryk, et al., 2022) provide valuable insights into the ecological vulnerability of aquatic systems in the western part of Ukraine. Their research, conducted across a range of tourist-influenced catchments, reveals the accumulation of biogenic and organic pollutants in surface waters, especially in cases where decentralised or absent sewage treatment infrastructure exacerbates the scale and dispersion of contamination. The authors highlight that diffuse sources of pollution, typical for mountainous tourist areas, lead to the degradation of water quality and diminish the natural capacity of river systems for self-purification.

Additional empirical evidence reinforcing the conclusions of the present study can be found in the research conducted by Bosak et al., (2019), which comprehensively assessed the ecological condition of riverine systems within the Slavske district of the Lviv region – a territory similarly characterised by high tourist activity in a mountainous landscape. Their findings demonstrated that the unregulated expansion of recreational infrastructure and the seasonal influx of visitors contribute significantly to the disruption of aquatic ecosystems. Notably, the study observed elevated levels of biogenic elements such as nitrates and phosphates, an increase in suspended particulate matter, and destabilisation of hydrochemical parameters, particularly during peak tourism months. These alterations indicate a shift in the ecological balance of the river systems, exacerbated by the limited self-purification capacity of mountain streams and the absence of adequate wastewater treatment infrastructure. The authors emphasised the critical need for spatially explicit ecological monitoring frameworks that prioritise buffer zones around tourism-intensive areas. Such measures are essential not only for identifying early signs of ecological stress but also for informing adaptive management strategies that aim to reconcile environmental protection with the socioeconomic objectives of regional tourism development. This body of evidence aligns with the outcomes of the current study and underscores the necessity for systemic governance approaches to mitigate the cumulative hydroecological impacts of tourism in fragile mountain regions

In a broader, international context, the study conducted by Liao et al. (2017) offers a comparative perspective. Their analysis of river systems in southern China established a statistically significant relationship between the intensity of land use – particularly urban and tourism development – and the accumulation of contaminants in bottom sediments. The research demonstrated that increased anthropogenic pressure not only elevates nutrient and heavy metal concentrations in aquatic ecosystems but also disrupts the sedimentary balance, thereby accelerating degradation processes.

The convergence of empirical data at both regional and global scales highlights a structurally recurring phenomenon: territories where tourism acts as a dominant sector of economic activity are characterised by a disproportionately high susceptibility to hydroecological destabilisation (Perschke et al, 2023). This is particularly evident in mountainous and foothill regions, where riverine systems, due to their geomorphological structure, possess limited hydrodynamic buffering capacities and reduced self-purification potential. Such environments respond acutely to even moderate levels of seasonal anthropogenic pressure, resulting in alterations to flow regimes, increases in nutrient and organic pollutant loads, and eventual disruption of aquatic ecosystem functioning (Wang et al, 2023).

The outcomes of the present study substantiate this global pattern in the context of the Ukrainian Carpathians, demonstrating that the combined application of hydrochemical field diagnostics and emission-based modelling constitutes a methodologically sound and scientifically grounded approach for identifying ecological stress zones. Through this integrative methodology, it becomes possible not only to quantify pollutant loads associated with different categories of anthropogenic sources (permanent vs. seasonal population), but also to forecast their spatial and temporal impacts on water quality under conditions of fluctuating recreational activity. Such a dual-layered analytical framework enables a more nuanced understanding of ecosystem vulnerability thresholds and enhances the capacity for evidence-based environmental planning (Water Strategy of Ukraine for the period until 2050, 2022).

In areas such as the Yaremche municipality, where river systems perform a dual role—as essential components of the natural landscape and as critical infrastructural assets underpinning the tourism economy – the imperative for adaptive water governance becomes particularly pronounced. The seasonal influx of tourists imposes episodic but intense pressures on water supply and wastewater infrastructure, leading to spikes in biochemical oxygen demand, nutrient concentrations, and the potential for eutrophication, especially in low-flow periods. In such contexts, standard administrative approaches to water resource management are insufficient, necessitating the transition towards spatially differentiated and adaptively responsive strategies.

The formulation of localised water protection policies must be underpinned by a robust empirical foundation, including real-time hydrochemical data collection, integration of high-resolution modelling tools, and cross-referencing with international benchmarks such as the EU Water Framework Directive and the Sustainable Development Goals (particularly SDG 6: Clean Water and Sanitation). In particular, the development of dynamic predictive models that incorporate both climatic and anthropogenic stressors is vital for anticipating critical load exceedances and formulating targeted mitigation scenarios.

Moreover, institutional and community-level capacity-building is required to ensure that the scientific evidence generated through such studies is effectively translated into policy action. This includes enhancing regulatory enforcement in protected areas, incentivising sustainable tourism practices, and improving access to decentralised wastewater treatment technologies, especially in remote or high-altitude settlements lacking centralised infrastructure (Resolution of the Cabinet of Ministers of Ukraine, 2018).

The evidence presented confirms that mountain territories experiencing tourism-driven development must adopt a paradigm shift in water governance – from reactive remediation to proactive, anticipatory management – grounded in spatially explicit data, interdisciplinary modelling, and stakeholder-inclusive decision-making. Only through such an integrated and context-sensitive approach can the ecological sustainability of riverine environments be safeguarded while maintaining the long-term viability of the regional recreational economy.

CONCLUSIONS

The conducted research provides a comprehensive quantitative characterisation of the anthropogenic impact on the hydroecological system of the upper course of the Prut River within the administrative boundaries of Yaremche. This segment represents a hydrological corridor of high strategic significance for maintaining the ecological sustainability and recreational capacity of the Ivano-Frankivsk region. The selected territory functions as a convergence zone between environmentally sensitive aquatic habitats and infrastructure associated with mass tourism, thereby serving as a representative example of socio-ecological interaction under stress.

Application of a spatially explicit mathematical modelling framework allowed for the identification of mineralisation gradients resulting from turbulent hydraulic perturbation in the vicinity of the Probiy waterfall. The derived exponential decay function characterises the rate of natural attenuation of dissolved solids and supports the hypothesis regarding the effectiveness of natural self-purification mechanisms—namely, turbulent aeration, gravitational sedimentation, and hydraulic dilution – within the initial 30 metres downstream. Such patterns are indicative of dynamic physicochemical transformation zones typical for high-gradient fluvial systems with intensified vertical mixing.

In parallel, emission flux modelling based on demographic and functional load indicators was used to estimate the mass of pollutants entering the aquatic environment from residential and tourism-related sources. The results revealed a multiple-fold increase in organic and nutrient loadings during periods of peak recreational activity, highlighting a disproportional burden on ecosystem assimilative capacity. The predominant share of contamination originated from non-point sources, particularly decentralised accommodation units, including small hotels, guesthouses, and seasonal rentals lacking connection to centralised sanitation networks.

The methodological innovation of this research lies in the dual integration of hydrodynamic simulation and pollutant emission quantification, which together enabled a systemic assessment of hydrochemical stressors at various spatial and temporal scales. The resulting approach is applicable for diagnosing zones of ecological instability and for constructing evidence-based decision-support instruments in the field of integrated watershed governance.

To strengthen the resilience of fluvial ecosystems in mountainous regions exposed to seasonal recreational pressures and long-term anthropogenic transformations, the implementation of a regionalised hydroecological early warning system is strongly recommended. Such a system should be conceptualised as an integrated information-analytical platform capable of continuous, real-time monitoring and forecasting of water quality dynamics at various spatial and temporal scales. Its core components must include automated sensor networks deployed at critical hydrological nodes, enabling the high-frequency registration of physicochemical indicators such as temperature, pH, conductivity, turbidity, DO, and BOD_5. In parallel, satellite-based remote sensing technologies should be utilised to monitor land cover changes, surface water extent, vegetation indices, and sediment transport patterns, thereby enhancing the capacity for spatial diagnostics.

Advanced hydrological and hydrochemical models – calibrated with empirical data from field stations – must be integrated into the system architecture to simulate water flow dynamics, pollutant dispersion trajectories, and assimilation potential under varying hydrometeorological conditions. The inclusion of machine learning and statistical data analytics modules will enable anomaly detection, early identification of pollution events, and predictive assessments of ecological risks. Such a multifaceted infrastructure should not function solely as a reactive mechanism, but also serve as a proactive tool for scenario modelling, strategic planning, and adaptive management of hydroecological resources.

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