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River Diversity Under Pressure: Benthic Invertebrates Reveal Urban Stream Syndrome and Guide Mitigation

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Abstract

Urban rivers provide vital ecosystem services, benefiting both nature and people, yet they are heavily impacted worldwide, exhibiting similar symptoms collectively known as the Urban Stream Syndrome (USS). This study assessed the ecological health of the Someșul Mic River, located in Cluj-Napoca, Romania's second-largest and rapidly developing city, through the lens of benthic invertebrate communities, recognized for their strong bioindicator value. Six sites along the main river course and four adjacent sites on tributaries and an artificial canal were analyzed. Our findings revealed the presence of USS at all sites; however, contrary to expectations, the mainstem sites showed higher water quality and greater taxonomic and functional diversity of zoobenthos. The primary drivers of this pattern were the proportion of coarse sediments and flow velocity, with river width playing a lesser role. Based on these results, eight mitigation strategies were proposed, aligned with the river ecosystem services. Their implementation could improve the ecological condition across the river, floodplain, and catchment levels, involving both scientists and the general public. Overall, the study provides a management-oriented framework for future river restoration initiatives in a growing city and a comparative reference for urban river assessments.

Keywords: mainstem vs. adjacent sites; Cluj-Napoca (Transylvania; Romania); taxonomic & functional diversity; drivers; bioassessment; mitigation; ecosystem services

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1. Introduction

The progressive anthropization of natural environments began with the establishment of early human settlements near water bodies, which served as essential resources for sustenance and hygiene [1]. Over time, water systems became transport routes, raw material sources, and waste receptors, and today this intensified interaction between the anthroposphere and urban aquatic systems exerts cumulative stress, leading to the alteration and degradation of both components [2–4]. The iconic profile of urban environments is often shaped by their natural water bodies—rivers, lakes, coasts, or wetlands—whose networks have been progressively incorporated into the expanding urban canvas, in a reciprocal relationship where cities reshape aquatic systems through channelization, embankments, and hydromorphological alterations [5]. Over time, natural water networks have been transformed into utilitarian systems shaped to meet the functional demands of urban development, serving purposes ranging from recreation and transport to industry and irrigation [2,6]. The parallel evolution of water supply, drainage, and wastewater treatment infrastructures has integrated these systems into the urban hydrological network, enabling the recycling and reintegration of treated water to protect ecosystems and sustain water resources.

Urbanization represents a major driver of anthropogenic pressure, encompassing increased greenhouse gas emissions, waste management challenges, and extensive transformations in land use and urban morphology [7]. Urbanization is a prevailing global trend, with over half of the world's population already concentrated in urban centers and their catchment areas, a figure projected to exceed two-thirds by 2050 [8,9].

Smart cities represent a possible model of urban development that integrate digital technologies, communication systems, and data analytics to improve quality of life, service efficiency, and sustainability [10]. Although definitions differ, they are generally understood as cities that transform traditional services and infrastructures through information and communication technologies. Core elements include smart infrastructure, mobility, energy, healthcare, and technology systems, supported by foundational tools such as the Internet of Things (IoT) and big data [11]. By linking physical, technological, social, and economic infrastructures, smart cities strive to create greener, safer, more efficient, and more inclusive urban environments. Although the smart city concept explicitly addresses climate change and environmental degradation [10], urban biodiversity is rarely included in the metrics used to prioritize project initiatives. Yet cities play a key role in biodiversity conservation [12], while urban biodiversity enhances climate resilience, supports human health, and fosters positive attitudes toward nature [13].

In this context, Blue-Green Infrastructure (BGI) in cities - an interconnected network of natural and semi-natural areas, such as rivers, wetlands, parks, and green corridors, integrates water and vegetated systems to enhance biodiversity, ecosystem services, and urban resilience [14]. Despite the proven benefits of urban BGI, its implementation remains challenging worldwide [15], particularly in developing countries like Romania, where blue infrastructure is underrepresented in local policies and strongly shaped by the morphological and historical characteristics of cities [16].

Urban waters are among the most heavily modified ecosystems, transformed by urbanization, land cover change, industrialization, and large-scale engineering to maximize human water use [17,18]. These alterations gave rise to the concept of Urban Stream Syndrome (USS), which describes specific hydrological, chemical, and biological degradation observed in urban rivers [19]. USS refers to rivers characterized by four major features: increased flow variability, hydromorphological alterations, high pollutant loads, and the predominance of tolerant taxa [18–21]. Additional criteria have later been proposed to describe these highly impacted ecosystems, including alterations of riparian communities, ecosystem-level processes, rubbish accumulation [22], and the ecosystem services provided by the river [23].

Surface water quality is primarily assessed through biotic components of ecosystems—namely benthic invertebrates, algae, macrophytes, and fish —using standardized and legally mandated methods, e.g., the Water Framework Directive 2000/60/EC in Europe [24–26]. Benthic invertebrates are key components of river food webs and reliable bioindicators, due to their limited mobility, short life cycles, sediment–water interface habitat, and diverse tolerance to pollutants [27]. Benthic invertebrates are most useful for assessing responses to urbanization due to their well-documented and consistent community shifts [19]. Accordingly, numerous studies assessing water quality in urban rivers rely on zoobenthic community characteristics such as abundance or taxonomic diversity [28–30], or on functional traits and multi-metric indices [31–33].

The present study focuses on Cluj-Napoca, Romania's second largest city after the capital, Bucharest, with nearly 400,000 inhabitants including its metropolitan area (2021 Population and Housing Census, National Institute of Statistics, https://insse.ro, accessed on 2 October 2025). The Someșul Mic River, formed upstream at the confluence of the Someșul Cald and Someșul Rece rivers, flows west to east through the city. It drains a catchment of 3,733 km² and has a total length of 100 km, about one quarter of which lies within the metropolitan sector [34]. The region holds major socio-economic importance, having experienced rapid urbanization in recent years, with the Someșul Mic River corridor identified as the main axis for the future development of the Cluj-Napoca Metropolitan

Area [35]. Previous studies on river ecosystems from the city of Cluj-Napoca included both environmental analyses [36–38] and data on biotic communities, like diatoms and invertebrates [39–42] or fish [43].

The present study has two main objectives: (1) to investigate the ecological health of the Someșul Mic River, a key component in the sustainable development of a rapidly expanding urban region, and (2) to propose mitigation solutions for the problems revealed by data analyses. Our working hypothesis was that the river exhibits typical symptoms of an urban stream (USS), particularly along its main course and within the city center, while tributaries bring cleaner water that helps improve overall quality (1.1). To assess the USS, we examined the primary drivers of benthic invertebrate abundance and diversity, a community selected for its essential role in ecosystem functioning and its high bioindicator value (1.2). Based on the key findings, targeted solutions were identified and linked to the ecosystem services provided by the urban Someșul Mic River, with the dual aim of informing similar research in comparable regions and supporting decision-makers in future remediation programs (2).

This study provides an applied perspective by using benthic invertebrate data—taxonomic richness, biotic indices, and functional diversity—to propose realistic mitigation strategies that can restore the river role as a supporting system for the city.

2. Materials and Methods

2.1. Sampling and Environmental Parameters

Ten stations were selected for benthic invertebrate sampling, consisting of six **mainstem sites** along the principal course of the Someșul Mic River within the city of Cluj-Napoca (SUV, SDV, SUN, SDN, SUC, SDC) and four **adjacent sites**, including two on major tributaries (Valea Gârbăului VGB and Nadăș NAD) and two on Canalul Morii (CM1 and CM2) (Table S1, Figure 1). Canalul Morii, an artificial branch of the Someșul Mic River flowing roughly parallel to it for about 7 km, was created following the City Council decision from 1558, to divert the river water closer to the town through an excavated channel [44].

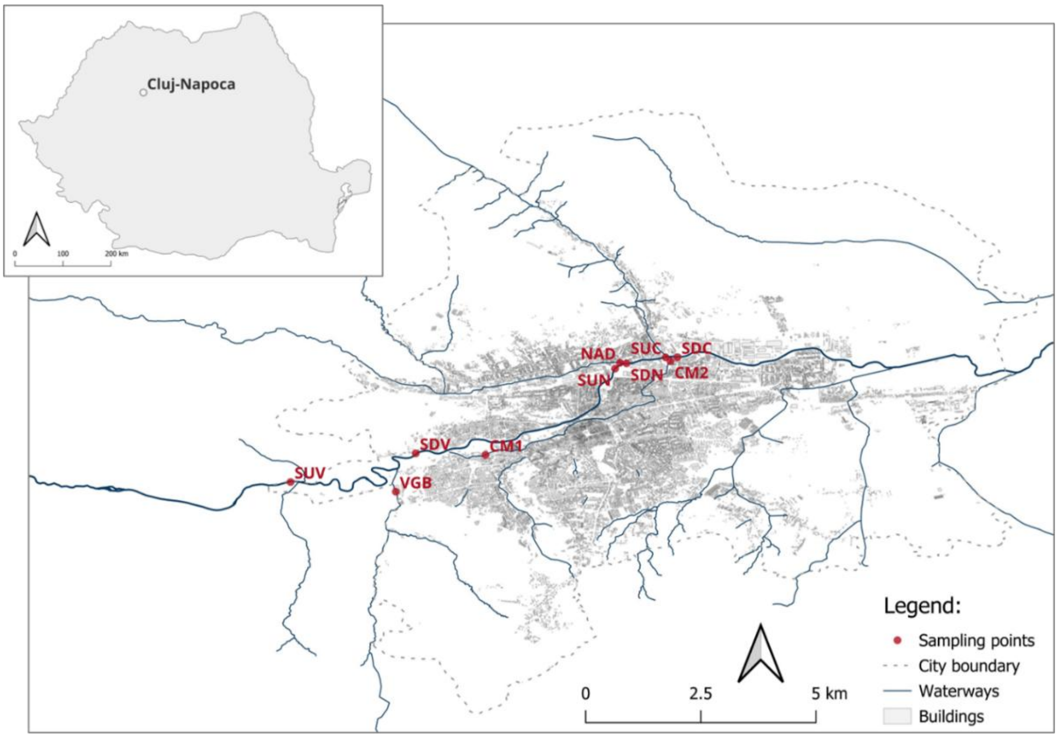

Figure 1. Location of the ten sampling sites considered for the present study (from upstream to downstream: SUV - Someșul Mic River – upstream of the confluence with Valea Gârbăului Tributary; VGB - Valea Gârbăului

Tributary; SDV - Someșul Mic River, downstream of the confluence with Valea Gârbăului Tributary; CM1 - Canalul Morii waterway, site 1; SUN - Someșul Mic River – upstream of the confluence with Nadăș Tributary; NAD - Nadăș Tributary; SDN - Someșul Mic River – downstream of the confluence with Nadăș Tributary; SUC - Someșul Mic River – upstream of the Canalul Morii Outfall; CM2 - Canalul Morii waterway, site 2; SDC - Someșul Mic River – downstream of the Canalul Morii Outfall); upper left corner: location of the city of Cluj-Napoca in Romania (map source: QGIS 3.44.2 [45]).

Numerous environmental parameters were measured in the field using portable instruments: dissolved oxygen and water temperature with a HI98193 portable oximeter, water conductivity and pH with a Hanna HI98130, flow velocity with Geopacks 4.3 flowmeter, and phosphate and nitrate concentrations with HI3817BP portable test kits (Table S1). Other field measurements included river width and depth, distance to the nearest built area, and the composition of different bed sediments, based on which the river was classified as riffle or riffle/pool according to [46] (Table S1). The adjacent sites were characterized by high water conductivity values and elevated concentrations of phosphates. The six mainstem stations exhibited greater widths and depths, higher flow velocities, and a higher proportion of boulders and pebbles in the sediments (Figure 2).

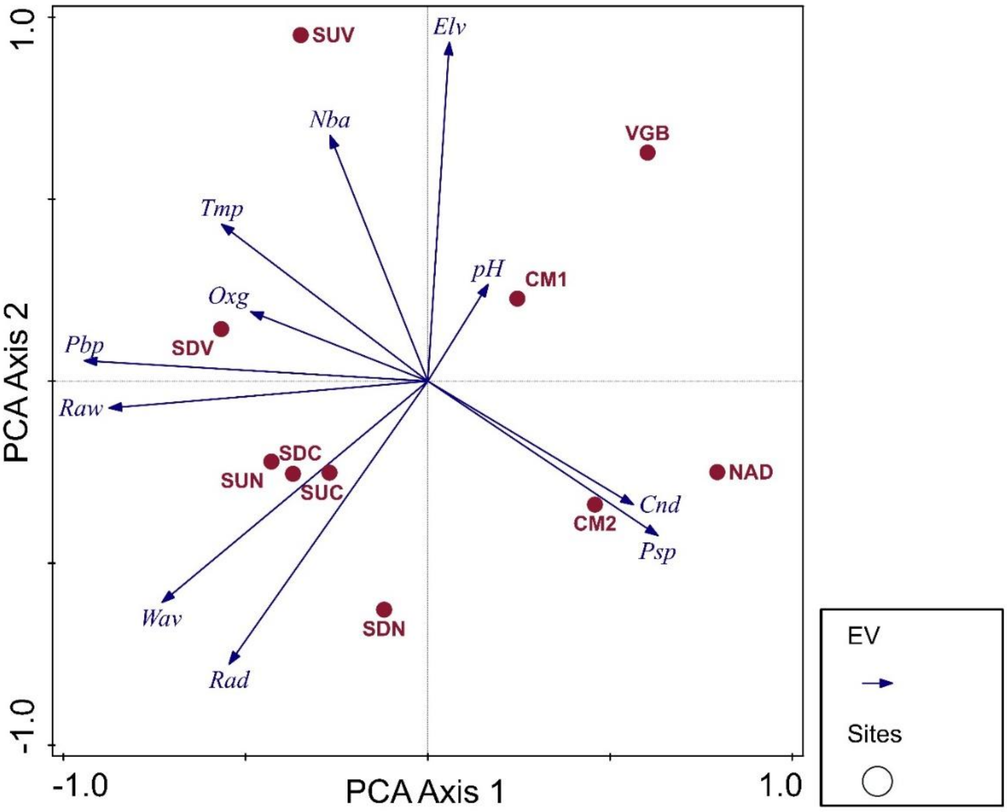

Figure 2. Principal Component Analysis (PCA) plot showing the ordination of the sampling sites based on the following abiotic parameters: Cnd – Water conductivity (μS/cm); Elv – elevation (m a.s.l.); Nba – Nearest built area (m); Oxg – Dissolved oxygen (mg/L); Pbp – Percentage of boulders and pebbles in sediments (%); Psp – Phosphates (mg/L); Rad – river average depth (m); Raw – river average width (m); Tmp – water temperature (°C); Wav – water average velocity (m/s); explained variation (cumulative, axis 1 & 2): 61.35 (site abbreviations as in Table S1).

2.2. Laboratory Analyses on Benthic Invertebrates

Semiquantitative samples were collected using 250-μm mesh kick nets, with five replicates taken at each station, totaling a sampled area of 3125 cm², in accordance with standardized methods (e.g., [47]). Samples were preserved in the field with 96% ethanol, then washed in the laboratory using

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sediment sieves, manually sorted under Nikon SMZ 800 stereomicroscopes and Nikon YS100 microscopes, and identified to different taxonomic levels (Table S2) using standard identification keys (e.g., [48]).

Three functional traits were used to distinguish guilds within the benthic invertebrate communities: (i) body size (following [48]), (ii) dispersal ability, and (iii) feeding habit (Table S2). Body size separated taxa into large and small forms, while dispersal ability distinguished mobile taxa (with a winged stage enabling high dispersal) from sedentary taxa (lacking an aerial phase). Parasites associated with aerial hosts were also included in the mobile guild, as their dispersal potential is mediated by their winged hosts [49]. Feeding habits were classified into eight distinct trophic guilds (i.e., functional feeding groups FFG): (1) scrapers, feeding by grazing organic and mineral substrates; (2) shredders, consuming macrophytes or coarse detritus; (3) suspension feeders (filtering collectors), ingesting algal cells and fine particulate organic matter; (4) sediment feeders (gathering collectors), exploiting fine particulate organic matter deposited on the streambed; (5) engulfing predators (swallowers), consuming whole organisms or body parts; (6) piercing predators, extracting cell and tissue fluids; (7) piercing herbivores, sucking the contents of algal cells; and (8) parasites, exhibiting parasitic feeding strategies (Table S2). FFG assignment was performed following [48,50–53].

2.3. Indices and Statistical Analyses

Basic ecological indices were calculated for the benthic invertebrate communities: frequency, expressed as the percentage of samples in which each taxon was present; relative abundance, expressed as the proportion of individuals of each taxon within the community; and the index of dominance ID [54], representing the percentage contribution of the two most abundant taxa in each community. Taxonomic diversity was assessed by means of species richness, Shannon–Wiener diversity H′ [55], and the effective number of taxa, exp(H′), expressing diversity in terms of equally abundant species [56] (Table S3). The effective number of taxa ranges from 1 to the actual species richness (under perfect evenness) and offers the advantage of enabling direct site comparisons and a more intuitive interpretation than the Shannon–Wiener index, which is expressed in entropy units [56].

Water quality was assessed using two biotic indices based on aquatic invertebrates: the Extensive Biotic Index, EBI [57] and the Modified New Walley Hawkes, MNWH [46]. EBI is based on the presence and taxonomic composition of benthic invertebrates identified at family or genus level, whereas the MNWH assigns scores to families (with Oligochaeta treated as a group) using either Presence-Only (PO) data or four abundance classes (AR, Abundance Related: 1–9, 10–99, 100–999, >1000 individuals). Both EBI and MNWH classify water quality into five categories: class I, high (EBI: 10–12; MNWH: >100); class II, good (EBI: 8–9; MNWH: 71–100); class III, moderate (EBI: 6–7; MNWH: 41–70); class IV, poor (EBI: 4–5; MNWH: 11–40); and class V, bad (EBI: 0–3; MNWH: 0–10) (Table S3).

Community trait structure was examined by considering both the mean trait values of dominant taxa (community trait mean) and the dissimilarities among taxa (functional diversity). The dissimilarity matrix was calculated using the Gower distance [58] with the 'gawdis' function in R [59,60], integrating mixed trait types: quantitative (body size), binary (dispersal ability), and fuzzy-coded, allowing intermediate trait values (FFG) [61]. Hierarchical clustering of the resulting matrix was then performed with Ward's minimum-variance method (method = 'ward.D2' in R) to construct the dendrogram. The community functional structure was analyzed by means of the Community Weighted Mean (CWM), which represents the average trait values in a community, weighted by the relative abundances of taxa, thus giving greater influence to the most abundant ones [61]. Several functional diversity indices were calculated: Functional Richness FRic, Functional Evenness FEve, Functional Divergence FDiv, Functional Dispersion FDis, Rao's Quadratic Entropy RaoQ [62] (Table S3). Because benthic invertebrate FFGs reflect food resource availability and underlying environmental conditions, their ratios were used as proxies for river ecosystem conditions, following [52,63] (Table S3). FFGs were further used to classify taxa as specialists (assigned to a single FFG) or generalists (>1 FFG), with water mites treated as specialists since larval and adult FFGs differ.

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Multivariate analyses were considered for the visualization and interpretation of datasets, using Canoco 5, version 5.15 [64]. Principal Components Analysis (PCA), an unconstrained linear ordination method [65], was applied to visualize similarities among sampling sites based on environmental factors. Constrained ordination techniques, including Redundancy Analysis (RDA, linear) and Canonical Correspondence Analysis (CCA, unimodal) [65], were employed to examine relationships between explanatory environmental variables and benthic invertebrate community attributes (abundances and Community Weighted Means). Key predictors explaining community taxonomic and trait composition were tested and selected based on the Monte Carlo permutation test (n = 999) and the simple term effects, i.e., each selected variable was considered to be independent. The p value adjusted for False Discovery Rate (FDR-adjusted p) was considered. Response curves were constructed to illustrate relationships between different environmental factors and the abundances of major benthic groups, while Van Dobben circles (t-value biplots) were used to identify taxa significantly influenced by environmental gradients [65].

Hierarchical clustering on presence/absence data was performed in R [66] using Euclidean distances. Taxonomic diversity was assessed with the *vegan* package [67]. Correlations between community and environmental parameters, based on Spearman's coefficient, and multiple linear regression with backward selection of predictors were conducted using the *PerformanceAnalytics* package [68].

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Benthic Invertebrates: Abundance, Diversity and Water Quality Indices

A total number of 37 benthic invertebrate taxa were identified in the sampling sites, including 34 families and three taxa treated as broader groups (Nematoda, Oligochaeta, and Ostracoda). Four taxa were present at all stations (oligochaetes, chironomid dipterans, isopods, and nematodes), whereas certain families of mayflies (Ephemeroptera: Ephemerellidae, Heptageniidae) and stoneflies (Plecoptera: Leuctridae) occurred at only one site (Figure S1). Similarity analysis using Euclidean distances separated the communities into two groups: mainstem and adjacent sites, based on presence/absence data (Figure S2). The percentage of oligochaetes and chironomid dipterans was high across most sampling stations, while at the adjacent sites it ranged from 55% to 75% (Figure S3). A similar pattern was revealed by the ID (Figure S4), with values consistently above 54%, indicating that only two taxa accounted for the majority of individuals in the community (Table S3).

Taxonomic diversity was lower at adjacent sites, with an effective number of about four equally common taxa, but differed only slightly from mainstem communities, where values ranged from 5.39 to 7.23 (Table S3). Similar results were observed for water quality assessed using benthic invertebrate biotic indices, which ranged between classes III and IV at the adjacent sites and between classes II and III along the mainstem (Table S3).

The percentage of boulders and pebbles in sediments correlated positively with taxa richness (0.77, $p<0.01$), diversity (0.71, $p<0.01$) and biotic indices (0.62, $p<0.05$ for EBI and 0.83, $p<0.01$ for MNWH-AR), but negatively with the percentage of Oligochaeta and Chironomidae (–0.75, $p<0.05$). As expected, taxa richness showed strong positive correlations with both biotic indices ($p<0.001$). Diversity was negatively related to water conductivity and phosphate concentration (–0.81, $p<0.01$ and –0.58, $p<0.05$, respectively), while the distance to the nearest built area correlated negatively with ID (–0.66, $p<0.05$), indicating more balanced communities further from built-up areas.

Four groups of taxa were identified within benthic invertebrate communities, based on the dissimilarity matrix constructed from functional traits (Table S2, Figure 3). Sedentary forms were clearly separated into small and large taxa, as were the mobile ones. Each group included both predatory and herbivorous / detritivorous taxa, with the exception of water mites.

Functional diversity indices indicated that taxa occupied a limited functional space (FRic < 0.25; FDis < 0.3) that was relatively evenly filled (FEve > 0.55), with dominant taxa showing extreme trait values (FDiv > 0.78), while low RaoQ values, ranging from 0.05 to 0.08, reflected small functional distances and high trait similarity among taxa (Table S3).

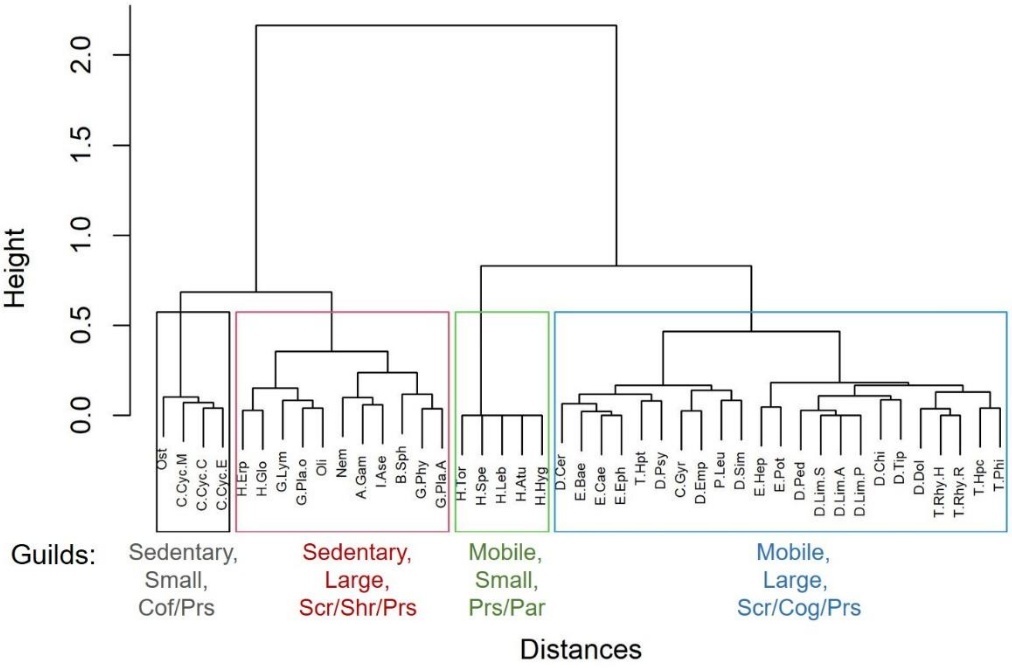

Figure 3. Dendrogram of benthic invertebrate functional traits (size, dispersal ability and FFG), constructed from dissimilarity matrix based on Gower distance; four major groups are distinguished (from left to right): sedentary small taxa (black), sedentary large taxa (red), mobile small taxa (green), and mobile large taxa (blue); Scr - scrapers ; Shr – shredders; Cof - suspension feeders (filtering collectors); Cog - sediment feeders (gathering collectors); Prs - engulfing predators (swallowers); Par – parasites; taxa abbreviation as in Table S2.

FFG generalist taxa were fewer than specialists at all sites, but they were more abundant in 9 of 10 cases. Ecosystem attributes derived from FFG ratios indicated that none of the sites were autotrophic, relying instead on allochthonous organic matter from upstream and riparian areas (Table S3). High loads of Fine Particulate Organic Matter FPOM were evident at all sites. Stable channel index values confirmed the presence of coarse stable substrates like boulders or pebbles, with higher averages at mainstem (1.72 ± 1.16 SD) than adjacent sites (0.75 ± 0.16 SD), while predator-to-prey ratios remained within normal ranges throughout.

3.2. Benthic Invertebrates: Main Drivers for Distribution and Diversity

At adjacent sites, taxa belonging to oligochaetes, crustaceans, and dipterans were prevalent, whereas mayflies, stoneflies, and caddisflies (EPT) dominated at mainstem sites (Figure 4). The key drivers of benthic invertebrate community structure were, in decreasing order of importance and significance: (i) the percentage of boulders and pebbles in sediments (explained 31.3% of the variation, pseudo-F = 3.6, p = 0.002, FDR-adjusted p = 0.006); (ii) water average velocity (27.2%, pseudo-F = 3.0, p = 0.005, FDR-adjusted p = 0.007); and (iii) river average width (26.5%, pseudo-F = 2.9, p = 0.007, FDR-adjusted p = 0.007) (Figure 4). The values of these key parameters were lower at adjacent sites, as were those of the Shannon–Wiener diversity index, which was represented as isolines in the ordination space to illustrate its variation in relation to environmental factors (Figure 4).

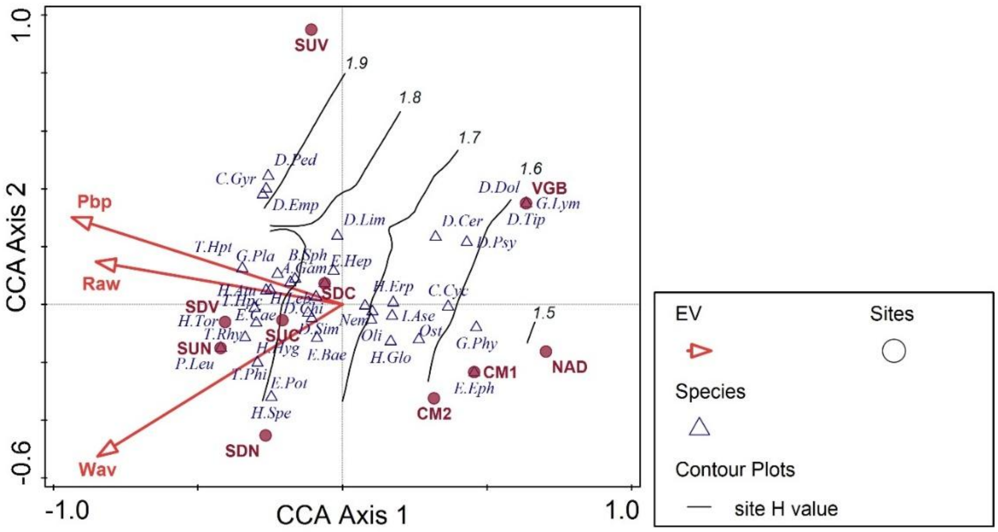

Figure 4. Canonical Correspondence Analysis CCA biplot with benthic invertebrate taxa abundances as response variables and environmental explanatory variables (Pbp – percentage of boulders and pebbles in sediments (%); Raw – river average width (m); Wav – water average velocity (m/s)), showing isolines of Shannon-Wiener diversity H′ index values across the ordination space; site abbreviations as in Table S1; taxa abbreviations as in Table S2 (adjusted explained variation is 20.89%, Monte Carlo permutation test results on all axes: pseudo-F = 1.8, p=0.025).

Response curves (Figure S5) showed that sensitive taxa (EPT) exhibited increased abundances at high percentages of boulders and pebbles and under elevated water velocities, whereas tolerant taxa (Oligochaeta and Chironomidae, OCH) displayed the opposite pattern. Van Dobben circles (Figure S6) showed that Trichoptera: Hydropsychidae increased with coarse substrates while oligochaetes declined. Ephemeroptera: Baetidae responded positively to higher flow velocity and Ephemeroptera: Caenidae to lower dissolved oxygen. Phosphate enrichment favored Gastropoda: Physidae, but reduced the abundance of several families of mayflies, leeches, and water mites.

Regression analyses revealed strong relationships between invertebrate community indices and environmental predictors (Table 1). Diversity and the proportion of EPT were positively influenced by water velocity and by distance from built areas (Adjusted $R^2 = 0.95$). Taxa richness was positively related to coarse substrates, while phosphate enrichment reduced EPT, and pH declines were linked to higher OCH values (Table 1).

Table 1. Results of multiple regression models relating community attributes (dependent variables: Eff.tx – Effective number of taxa; No.tx – Number of taxa; ID – Index of Dominance; EPT% – Percentage of Ephemeroptera, Plecoptera, Trichoptera; OCH% – Percentage of Oligochaeta and Chironomidae; MNWH-AR – Values of Modified New Walley Hawkes, Abundance-Related) to environmental predictors (independent variables: Wav – Water average velocity; Psp – Concentration of phosphates; Nba – Nearest built area; Pbp – Percentage of boulders and pebbles in sediments; Cnd – Water conductivity; Oxg – Dissolved oxygen; Raw – River average width); values represent regression coefficients (Estimates) with corresponding p-values for each predictor; model fit statistics (R^2, adjusted R^2, F-statistic, and significance) are reported below the table; values in bold: $p<0.01$.

Predictor	**Model 1: Eff.tx**	**Model 2: No.tx**	**Model 3: ID**	**Model 4: EPT%**	**Model 5: OCH%**	**Model 6: MNWH-AR**
Intercept	**4.61** **(p < 0.001)**	–2.94 (p = 0.642)	**0.57** **(p < 0.001)**	**–41.90** **(p = 0.002)**	529.75 (p = 0.013)	**43.93** **(p < 0.001)**
Wav	3.31 (p = 0.014)	–	–	**130.16** **(p < 0.001)**	–	–
Psp	–0.32 (p = 0.015)	–	0.029 (p = 0.016)	–4.46 (p = 0.011)	–	–

Nba	1.84 (p = 0.009)	–	–0.052 (p = 0.289)	**25.92 (p = 0.006)**	–	32.12 (p = 0.066)
Pbp	–	**0.32 (p = 0.006)**	–	–	–	–
Cnd	–	–	–	**0.017 (p = 0.005)**	–	–
pH	–	–	–	–	–69.23 (p = 0.023)	–
Oxg	–	–	–	–	9.33 (p = 0.076)	–
Raw	–	–	–	–	**–1.31 (p = 0.002)**	**1.22 (p = 0.002)**

Model fit:
Model 1: $R^2 = 0.88$, Adjusted $R^2 = 0.82$, $F(3,6) = 14.86$, $p = 0.0035$
Model 2: $R^2 = 0.63$, Adjusted $R^2 = 0.58$, $F(1,8) = 13.53$, $p = 0.0062$
Model 3: $R^2 = 0.65$, Adjusted $R^2 = 0.55$, $F(2,7) = 6.50$, $p = 0.0254$
Model 4: $R^2 = 0.97$, Adjusted $R^2 = 0.95$, $F(4,5) = 42.22$, $p < 0.001$
Model 5: $R^2 = 0.85$, Adjusted $R^2 = 0.78$, $F(3,6) = 11.48$, $p = 0.0067$
Model 6: $R^2 = 0.83$, Adjusted $R^2 = 0.78$, $F(2,7) = 16.71$, $p = 0.0022$

Consistent key drivers were identified in the regression analyses relating zoobenthic community trait structure to environmental parameters (Figure 5). They were, in decreasing order of explanatory power and significance: (i) the percentage of boulders and pebbles in sediments (explaining 52.1% of the variation; pseudo-F = 8.7, p = 0.006, FDR-adjusted p = 0.0105); (ii) river average width (48.6%; pseudo-F = 7.6, p = 0.007, FDR-adjusted p = 0.0105); and (iii) water average velocity (36.7%; pseudo-F = 4.6, p = 0.028, FDR-adjusted p = 0.028).

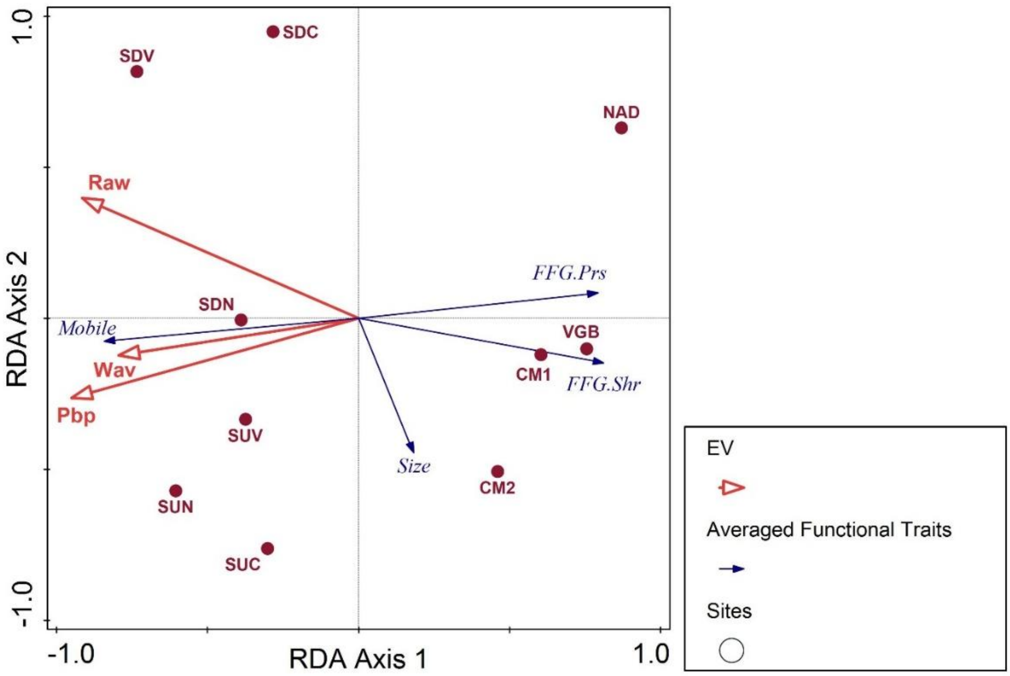

Figure 5. Redundancy Analysis RDA biplot with the values of Community Weighted Means CWM for benthic invertebrate length (Size), dispersal ability (Mobile) and the presence of predator (Prs) and shredder (Shr) functional feeding groups FFG – as response variables; and environmental explanatory variables (Pbp – Percentage of boulders and pebbles in sediments (%); Raw – river average width (m); Wav – water average velocity (m/s)); site abbreviations as in Table S1; adjusted explained variation is 44.24%, Monte Carlo permutation test results on all axes: pseudo-F = 3.4, p=0.033.

3.3. Mitigation Strategies Anchored in Key Findings

The Someșul Mic River provides a range of ecosystem services within the urban area of Cluj-Napoca. A synthesis of its provisioning, regulating, and cultural services is presented in Table 2, adapted from [30,69–71].

Table 2. Provisioning, regulating and cultural services provided by the Someșul Mic River ecosystem in the city of Cluj-Napoca.

Type	Code	Ecosystem Service
Provisioning	P1	Production of energy;
	P2	Riverfront restaurants, cafes, shops;
	P3	Changes in riverfront property values;
	P4	Recreational bathing;
	P5	Irrigation of crops (urban gardens);
	P6	Groundwater recharge.
Regulation & Maintenance	RM1	Bio-remediation made by biota (micro-organisms, algae, plants, animals);
	RM2	Filtration of toxic substances by biota (macrophytes);
	RM3	Sequestration of CO_2 by primary producers;
	RM4	Sink for organic and inorganic substances (nutrients, metals, organic pollutants);
	RM5	Regulation of water chemistry made by biota (bio-geo-chemical cycles);
	RM6	Support for pollinators;
	RM7	Maintaining viable populations and gene pool;
	RM8	Maintaining habitats (aquatic & riparian);
	RM9	Regulation of temperature and humidity (climate regulation);
	RM10	Control of erosion rates;
	RM11	Sediment transport regulation;
	RM12	Hydrological cycle - including flood regulation.
Cultural	C1	River traits that allow activities sustaining human health (walks, jogging, water sports etc.);
	C2	River traits that promote mental health (temporary getaway, tranquil location, meditation, feeling of safety etc.);
	C3	River traits that promote social activities (festivals, artistic events etc.);
	C4	River traits that allow educational & training activities (environmental awareness, nature laboratory, bird-watching, healthy value systems etc.);
	C5	River traits that allow recreational activities (recreational fishing, picnics etc.);
	C6	River traits with historical/heritage importance (water mills, historical bridges, places connected to the history of the city);
	C7	Aesthetic experiences (panoramic viewpoint, scenic beauty, natural sounds, charismatic fauna, lack of foul odors etc.).

Since urban streams share the same syndrome, but each river has its own particularities [18,21], eight targeted mitigation strategies were proposed for the Someșul Mic River in Cluj-Napoca, selected from the literature and adapted to local conditions based on the structure of benthic invertebrate communities in mainstem and adjacent sites (Table 3). The mitigation strategies span four levels: the riverbed (mitigation #1), the floodplain (#2 and #3), the catchment scale (#4, #5, and #6), and human involvement (#7 and #8) (Figure 6).

Table 3. Mitigation strategies for the Urban Stream Syndrome derived from invertebrate community patterns in the Someșul Mic River (Nbs – Nature based Solution; ES – Ecosystem Services, see Table 2).

#	Mitigation measure	Output / Details	Nbs	Targeted ES	Sources
1.	Enhancement of in-stream habitat heterogeneity	Addition of boulders, large cobbles, gravel and/or wooden structures, artificial riffles and meanders; Using combined remediation techniques, addressing pollution sources in the catchment and maintaining refugia within the riverbed are crucial for the successful recolonization of new substrates.	yes	RM1, RM3-8, C2, C4, C5	[18,72]
2.	Replacement of impervious surfaces, in/near the river with more natural substrates	Impervious surfaces (e.g., concrete riverbed / banks) disrupt the connection between river and groundwater through the hyporheic zone (which acts as a refuge and a regulator of water quality and floods); There is a direct connection between the flow of the Someșul Mic River and the groundwater level beneath Cluj-Napoca; until the late 19th century, the river served as the primary water source in the city, with its discharge directly determining the water supply; More natural substrates should be used (e.g., gravel, fascines & geotextiles, porous concrete, ripraps, mixed-techniques like lower-bank ripraps with upper-bank plantings); Positive effects: urban stormwater runoff reduction; riparian habitat heterogeneity increase; in-stream habitat heterogeneity increase; unlimited connections between riverbed and riparian communities (lateral connectivity).	yes	P6, RM1-9, RM12 C1, C2, C4, C5	[18,44,73–75]
3.	Establishment and/or maintenance of riparian vegetation	Herbs, shrub or trees, native species, living directly on the river banks or on artificial substrates (like walls), acting as riparian buffers; Positive effects: urban stormwater runoff reduction and filtration, floodplain habitat increase; constant food source in the river coming from terrestrial vegetation; increased shading leading to less extreme temperatures; decreased heat stress.	yes	P3, P6, RM1-3, RM5-12, C1-5	[18,76–79]
4.	Maintenance of a stable flow regime, downstream Florești II Dam	The Florești II Dam regulates the flow on the Someșul Mic, in Cluj-Napoca, to its confluence with the Someșul Mare. Intermittent water releases often generate hydropeaking effects in downstream sections; high flows lead to organism removal, reduction of habitat, increases in turbidity and disturbed sediments; low flows lead to reduction of habitat and food, increased concentrations of nutrients or pollutants and decreased oxygenation.	no	P1, RM4-5, RM7-9, C2-5	[1,18,80,81]
5.	Reduction of pollutant loads, at the catchment scale	Addressing pollution problems upstream of the city and within the tributary catchments is essential to secure good physico-chemical quality along the urban river reach.	yes	P2-6, RM2, RM4-5, C7	[18]
6.	Blue-Green Infrastructure BGI and Low-Impact Development LID technologies in the city	Examples of BGI and LID: permeable pavements, urban tree planting, green roofs, bioswales, rain gardens, infiltration trenches, biofilters, rain tanks etc.; Positive effects: reduction of runoff, filtering pollutants, and enhancing natural infiltration processes.	yes	P5, RM6, RM9, RM12, C1-2, C4-5	[20,82,83]

#	Mitigation measure	Output / Details	Nbs	Targeted ES	Sources
7.	Continuous research & monitoring; adaptative & ecosystem-based management & design	Smart water management: the use of sensors, Internet of Things, machine learning, big data analyses, digital twins concept - in order to monitor, detect changes, predict, support decision makers etc.; Adaptive design in urban planning, together with focus of biodiversity, multifunctionality, redundancy and modularization are strategies for increasing urban resilience capacity.	no	RM7-8, C4	[82,84–87]
8.	Citizen & stakeholder involvement	Active involvement of the general public (including citizen science) and of all stakeholders, such as: authorities (the Romanian Waters National Administration - Someș-Tisa Water Basin Administration, the Someș Water Company, Hidroelectrica S.A., Cluj-Napoca Municipality); the County Association of Anglers, various NGOs, civic activists, riparian residents etc.	no	P2-5, C1-7	[88,89]

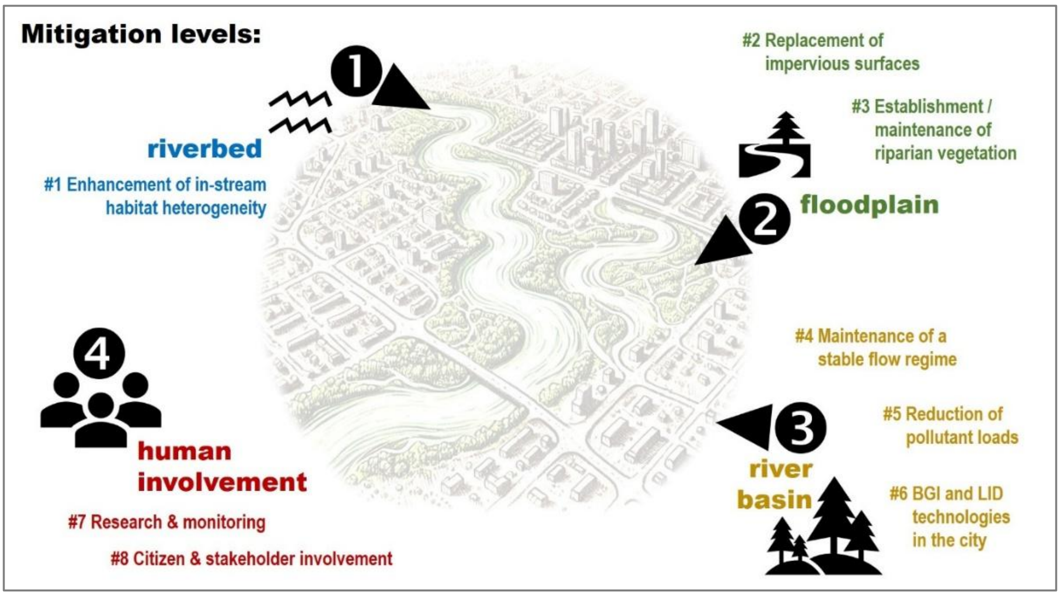

Figure 6. Conceptual representation of the four levels of mitigation solutions proposed in the present study (base image generated using OpenAI's ChatGPT, DALL·E 3 model, accessed on 4 October 2025, modified by the authors).

4. Discussion

4.1. Urban Stream Syndrome Indicated by Benthic Invertebrates

USS symptom 1: **Flow variability** in the Someșul Mic River in Cluj-Napoca results from an artificially induced regime, as the upstream Someșul Cald and Someșul Mic are regulated by reservoirs and hydropower plants with a total installed capacity of ~300 MW [34,90,91]. The Florești II Dam, located at the river's entrance into the city, further controls discharge downstream to its confluence with the Someșul Mare near Dej (https://www.hidroelectrica.ro, accessed on 3 October 2025).

USS symptom 2: **Channel alteration** is particularly evident in the city center, where the river has been straightened and the banks reinforced with concrete.

USS symptom 3: **High nutrient and pollutant loads** have been documented in the Someșul Mic River, with elevated concentrations of trace metals, organic contaminants and microplastics detected in sediments (particularly in industrial and densely populated sectors) and increased nutrient levels, such as nitrates, recorded in the water column downstream [36–38].

USS symptom 4: The **structure and diversity** of benthic invertebrate communities in urban rivers differ markedly from those in less impacted areas.

USS symptom 4.1: Our data showed **unbalanced communities**, exhibiting high dominance indices that highlighted the prevalence of two tolerant taxonomic groups—typically oligochaetes and chironomids—a pattern frequently reported in the literature [19,92–94]. Moreover, the abundance of generalist taxa exceeded that of specialists at most sampling sites, consistent with findings from other studies [95].

USS symptom 4.2: **Taxonomic diversity** of benthic invertebrates and the water quality indicated by their communities were relatively modest, although conditions were generally better at mainstem sites, which showed higher diversity and correspondingly higher ecological quality (classes II–III compared to III–IV in adjacent sites). Low diversity of benthic assemblages and water quality decline associated with increasing urbanization have been widely reported in urban rivers [32,92,93,96], and earlier studies in the present area similarly documented poor water quality and a dominance of tolerant taxa downstream of SDV [39–42].

Sediment type emerged as the main driver of community composition: higher proportions of boulders and pebbles supported greater taxonomic richness and correlated positively with diversity and biotic indices, favoring Hydropsychidae caddisflies while reducing tolerant OCH taxa. Such patterns align with previous findings linking coarse substrates to higher diversity and unstable habitats to the dominance of tolerant groups [97]. Flow velocity and stream width also played key roles, as both taxonomic diversity and the proportion of sensitive EPT taxa increased with higher velocities, especially for Baëtidae mayflies. Comparable results have been reported for stream width in the eastern USA [94] and for flow fluctuations in the UK and Portugal [92,93], where conductivity and nitrate concentrations were also identified as stressors—parameters that in this study correlated negatively with diversity.

Dissolved oxygen, by contrast, was less influential here than in other studies (e.g., [94]). Notably, Caenidae mayflies increased in abundance under lower oxygen conditions, reflecting their habitat preferences as detritus feeders in fine sediments and under stones [48]. Finally, distance to the nearest built structure was negatively correlated with dominance, suggesting more balanced, EPT-dominated communities in areas further from urban development. Similar negative effects of buildings and roads on benthic invertebrate diversity have been highlighted elsewhere [98,99].

USS symptom 4.3: **Functional diversity** was very low across both mainstem and adjacent sites, as indicated by Functional Richness and Rao’s Quadratic Entropy, though a slight increase was observed with higher proportions of coarse substrates. Substrate composition strongly influenced functional trait community-weighted means (CWM), with adjacent sites characterized by finer sediments and poorer water quality, supporting larger and more mobile taxa in terms of dispersal ability, consistent with reports linking the “non-flyer dispersion mode” to high urbanization pressure [100] and fine-particle feeders to heavily impacted systems [32]. CWM also revealed higher proportions of engulfing predators (swallowers) in adjacent stations, associated with sand and silt dominated substrates and low flow velocity, with notable examples including Dolichopodid dipterans in VGB, elevated leech abundance in CM1, and high densities of the copepod *Macrocyclops albidus* in NAD and CM2, a predator of cladocerans in river macrophyte habitats [101]. While many studies report reduced top consumers and simplified trophic structures in urban rivers [32,95], others have documented predator dominance under urbanization stress [100], with FFG–substrate relationships varying with flow and food availability [102]. In this study, stream ecosystem attributes estimated via FFGs indicated an overall normal predator-to-prey ratio, though predator prevalence in more urbanized stations needs further investigation.

Exploration of the four USS symptoms confirmed the impacted state of the urban river ecosystems in Cluj-Napoca, but the initial hypothesis was rejected, as water quality and benthic invertebrate diversity proved to be higher at mainstem sites compared to adjacent ones.

4.2. Current State of the Someșul Mic River in Cluj-Napoca and Directions for Mitigation

The urban water cycle includes interconnected networks— the natural waterways, potable water supply, stormwater drainage, domestic and industrial wastewater discharge, and the treatment network that returns water to the natural system—functioning through tightly regulated, interdependent layers [103]. The functionality of Cluj-Napoca entire water system—encompassing both surface and subsurface networks—can only be maintained through coordinated management processes (investments, initiatives, and action–response plans) among all institutional stakeholders. The Someșul Mic River, the central axis of Cluj-Napoca urban water system, is undergoing a major transformation. Once undervalued, it has become a key element in sustainable urban development [35], now envisioned as a blue-green corridor integrating the entire urban and metropolitan landscape.

As part of the city's strategy for the *European Capital of Culture* competition, the establishment of a joint administrative and academic body—the *Water Council*—was proposed to integrate representatives of public authorities and the scientific community into a unified management framework. Within the same program, the Romanian Order of Architects suggested organizing a design competition for the redevelopment of the Someșul Mic River along its urban stretch. Adopted by the Cluj-Napoca Municipality, this initiative led to the *Rethinking Someș* project (2015–2023), which resulted in a comprehensive structural and landscape transformation of the river corridor. The result was a clear definition of the Someșul Mic River corridor as a genuine blue–green urban park, extending for approximately 7 km downstream from the city western entrance, and an additional 2 km through the Feroviarilor and Armătura Park areas (Rethinking Someș, Cluj-Napoca, https://oar.archi/concursuri/oar/rethinking-somes-cluj-napoca/, accessed on 8 October 2025). Subsequent projects, such as the *Feroviarilor Park Rehabilitation* competition (Parcul Feroviar, Cluj-Napoca, https://oar.archi/concursuri/oar/reabilitarea-peisagera-si-reactivarea-parcului-feroviar-cluj-napoca/, accessed on 8 October 2025), further advanced this vision by integrating wetlands and new pedestrian crossings, reinforcing a sustainability-oriented urban water management approach. These initiatives have increased both the extent and quality of planted areas, improved pedestrian and cycling mobility (the river now serving as a near-continuous cycling route), and ensured public accessibility to the water. Another major project—the *Eastern Park Development* (Amenajare Parc Est, Cluj-Napoca, https://oar.archi/concursuri/oar/amenajare-parc-est-cluj-napoca/, accessed on 8 October 2025)—continues this direction, aiming to convert a vast wetland area located on a tributary of the Someșul Mic River into a public park in the coming years. In addition to large-scale infrastructural interventions, the river—and the city aquatic system as a whole—has become a key focus on the agenda of Cluj-Napoca civil society. In this context, *Someș Delivery*, a public awareness and micro-intervention program [104], engages with various river sections that deserve attention, organizing public events that bring together citizens and scientists, as well as cultural activities and cycling routes along the river. Since 2016, the river section known to locals as *Grigorescu Beach* (downstream site SDV) has hosted the *Vamos a la Playa* project, now in its seventh edition (Vamos a la Playa 2025, https://cluj.com/articole/vamos-a-la-playa-2025-plaja-grigorescu-cluj-napoca/, accessed on 9 October 2025), a ten-day community event promoting awareness of the river cultural and social value within the urban landscape.

The present study proposes mitigation strategies addressing the anthropogenic impacts on riverine biotic communities, directly linked to the key findings described above. These strategies primarily target the enrichment of riverbed substrates, given that our data indicate that coarse sediments, combined with higher flow velocity, support greater taxonomic and functional diversity of invertebrate communities. Measures aimed at reducing impervious surface areas and increasing riparian vegetation within the floodplain are the most challenging to implement, due to constraints imposed by national flood-control plans [105]. At the catchment scale, efforts should focus on minimizing pollution, maintaining a stable flow regime downstream the hydrotechnical works, and implementing BGI solutions in adjacent areas. However, spatial limitations restrict the feasibility of many BGI measures, such as constructed wetlands designed to retain stormwater runoff [79]. Finally, continuous monitoring and public involvement are essential for calibration, adaptation, and dissemination.

Restoration is a complex, long-term process [20] that should focus on restoring ecosystem processes rather than isolated habitats, yet success is not always guaranteed. The main reasons for failure include: planning restricted to river segments while ignoring watershed-scale pressures, reliance on a single method, failure to secure colonization of newly created habitats, neglect of environmental quality, and focus on improving physical complexity alone [18,72,106]. Moreover, the standard approaches commonly applied under the EU Water Framework Directive to assess biotic community parameters are often insufficiently sensitive to detect the outcomes of restoration in urban streams [78,107]. Additional regional barriers hinder cohesive urban and ecological regeneration: (1) the river passage through diverse urban fabrics (open floodplain, densely built areas, industrial zones), making integrated development challenging; (2) land ownership fragmentation, (3) nearby transport infrastructure causing pollution, and (4) fragmented institutional management. Transforming the Someșul Mic River into a blue-green urban corridor requires a collective shift toward sustainable behavior of citizens and institutions, and greater public awareness of the river ecological and cultural value.

5. Conclusions

The present study assessed the ecological status of several urban aquatic ecosystems in Cluj-Napoca, yielding several key findings.

(1.1) *Same soup, different spices:* all analyzed communities exhibited typical urban stream symptoms—low taxonomic and functional diversity and dominance of tolerant taxa. However, the initial hypothesis was invalidated, as tributaries did not supply cleaner water; instead, they displayed poorer ecological conditions than the mainstem sites.

(1.2) Our results showed that coarse substrates and higher flow velocity were the main drivers shaping the structure, taxonomic richness, and functional diversity of aquatic invertebrate communities, whereas river width, distance to nearby constructions, conductivity, and dissolved oxygen contributed to a lesser degree.

(2) Based on these findings, eight mitigation strategies were proposed and linked to the ecosystem services identified for the studied aquatic systems, encompassing in-stream, floodplain, catchment, and research & public engagement components.

Future studies should expand the research area to include additional tributaries and the rapidly growing metropolitan zone of Cluj-Napoca. Nevertheless, the present study provides a valuable tool for decision-makers in the implementation of mitigation measures and serves as a relevant example for assessing urban rivers in similar climatic regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/doi/s1, **Table S1:** The sampling site codes and names, sampling dates, coordinates and main environmental parameters measured for the analyses; **Table S2:** Presence of benthic invertebrate taxa from the sampling sites, their codes used in the analyses and the three functional traits considered: size, dispersal ability and functional feeding group (FFG); **Table S3:** Benthic invertebrate indices calculated for the present study in the sampling sites; **Figure S1:** Frequency of benthic invertebrate families (Nematoda, Oligochaeta and Ostracoda considered as groups) in the sampling sites analyzed for the present study; larger squares indicate higher frequencies, i.e., occurrence in more sites; **Figure S2:** Benthic invertebrate taxa similarity, based on presence/absence data and depicted as a dendrogram constructed with Euclidean distance; **Figure S3:** Abundance of main groups of benthic invertebrates; **Figure S4:** The Index of Dominance ID (percentage of the most abundant two taxa from the community), showing the value of the index and the dominant groups in each sampling site; **Figure S5:** Response curves for main groups of benthic invertebrates and explanatory variables: the percentage of boulders and pebbles in sediments Pbp (%) (left); and the water average velocity Wav (m/s) (right); **Figure S6:** Van Dobben circles (t-values biplots), showing the benthic invertebrate taxa that best respond to: the percentage of boulders and pebbles in sediments Pbp (%) (up left); the

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water average velocity Wav (m/s) (up right); the dissolved oxygen values Oxg (mg/L) (down left); and the phosphate concentration Psp (mg/L) (down right).

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Abbreviations

The following abbreviations are used in this manuscript:

BGI	Blue-Green Infrastructure
EBI	Extensive Biotic Index
EPT	Ephemeroptera, Plecoptera, Trichoptera
FDis	Functional Dispersion
FDiv	Functional Divergence
FDR	False Discovery Rate
FEve	Functional Evenness
FFG	Functional Feeding Groups
FRic	Functional Richness
ID	Index of Dominance
MNWH-AR	Modified New Walley Hawkes, Abundance Related
MNWH-PO	Modified New Walley Hawkes, Presence-Only
OCH	Oligochaeta, Chironomidae
RaoQ	Rao’s Quadratic Entropy
SD	Standard deviation
USS	Urban Stream Syndrome

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