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Sediment Chemistry and Substratum Characteristics as Determinants of Benthic Community Structure in River Jhelum: A Secondary Data-Based Review and Analytical Assessment

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Abstract
River sediment is a geochemical storage site, physical habitat, and exposure pathway for benthic organisms. This article studies how sediment chemistry and substratum variability may contribute to the presence and abundance of benthic macroinvertebrates in the River Jhelum and its Kashmir Himalayan tributaries. It differentiates direct evidence of the Jhelum from other studies concerning dominating processes. A priority was given to studies published during the years 2020 to 2025. Data across the Jhelum Basin show that benthic communities vary along the longitudinal axis of the river and within different seasons. The finer sediments that compose a habitat type, together with pH, temperature, discharge, habitat type, and the degree of disruption of natural flow regimes, are important factors influencing the structure of the benthic community. Studies of the upper reaches of the river basin show that the agricultural, built-up, and mineral disturbance of the catchment influences the chemical and physical nature of the sediment available to form benthic communities. Several field and experimental studies show that excess fine sediment may reduce interstitial space, inhibit hyporheic exchange, and hyporheic refugia, thereby adversely affecting sensitive rheophilic taxa. The addition of organic matter may change food resources and the oxygen demand of the sediments. Bioavailable fractions of metals present in sediments should also be addressed. The suggested evaluations support direct Jhelum evidence of substratum and flow pathways, broad hydrochemical controls, and insufficient direct sediment-metal-to-benthos evidence. A suggested standardized monitoring program includes grain-size fractions, sediment organic matter, embeddedness, nutrient chemistry, metal fractionation, hydrology, and macroinvertebrates and DNA-based taxonomy.
Keywords: *River Jhelum; sediment chemistry; substratum; benthic macroinvertebrates; fine sediment; freshwater ecology; biomonitoring.*

INTRODUCTION

River sediments are not passive. Sediment-water interfaces feature interactions between mineral and organic matter and nutrients and contaminants, as well as microbes, processes, and hydraulics that control oxygen input and output, resource availability, and habitat design. For benthic macroinvertebrates, sediments offer attachment, refuge, feeding, oviposition, and defense against disturbance. Consequently, changes in disposition of sediments, enrichment of sediments, or increases in the loading of sediment contaminants can have strong impacts on community structure, even when standard measures of water column conditions are satisfactory [20-32] Sediment is therefore an important component of ecological analysis due to its dual role in chemistry and physics.

The River Jhelum drains a region of the Himalayas that has a wide range of climate and geomorphology and includes an extensive range of snowmelt-influenced headwaters, tributaries, reaches that have been influenced by a range of human activities, and low gradient depositional systems. Recent basin studies have documented large changes in water quality, pressure on land use, and aquatic systems over both large and small spatial scales and across all seasons [1-19]. Sabha et al. analyzed 18 Jhelum Basin watersheds. Across a two-year period, they found that metrics of the EPT (Ephemeroptera, Plecoptera, and Trichoptera) Community declined in the metrics of richness, diversity, and density. Streamflow discharge and water temperature measured during the summer months positively affected both EPT Community metrics and EPT Community metrics. In contrast, biological variation in the winter months was explained best by the presence of fine sand and the pH of stream water [1]. Lopez et al. also studied the Jhelum longitudinal gradient [4], and their research confirmed the importance of mesohabitat and substrata. Similar research on the Sindh tributary conducted by Zahid et al. and earlier studies, also indicated that changes in benthic assemblages were correlated with changes in the structure of sediments [3,7,8].

A major research gap exists. The majority of the studies conducted at Jhelum research sites have examined water quality, hydrology, land use, bio-diversity, and sediments separatly. However, Jhelum studies have not directly integrated sediment chemistry, sediment bioavailability, substratum structure, and macroinvertebrate responses. Total sediment metal concentrations do not reflect biological exposure, and the ecological impact of fine sediment depends on the concentration of organic matter, the velocity of the current, and the season and habitat complexity [20-29,42-50]. Therefore, this review examines sediment chemistry interacting with substratum and how this interplay impacts the taxonomic composition, diversity, abundance, functional organization, and condition of benthic communities in the Jhelum system. Additionally, this review examines different studies and provides direct evidence from the Jhelum system and other studies of the Himalayan region to support this evidence. By examining the studies, this review will prioritize the strength of the evidence and determine the gaps that exist and the measurements needed to develop an effective monitoring framework for sediment-benthos in the region.

REVIEW METHODOLOGY

Rather than conducting primary field or lab research, this review used a structured secondary-data approach. Published literature on the River Jhelum, Kashmir Himalayan tributaries, sediment chemistry, substratum, fine sediment, heavy metals, nutrient enrichment, benthic macroinvertebrates, biomonitoring, and hydrological regulation was reviewed. Search combinations included “Jhelum sediment chemistry”, “Jhelum benthic macroinvertebrates”, “Kashmir substrate benthos”, “fine sediment macroinvertebrates”, “sediment metals benthic invertebrates”, and related terms. The most current evidence (2020-2025) was selected, however older studies retained where Jhelum-specific hydrochemistry or relevant regional studies were provided. The final corpus contains exactly 100 scholarly sources. Matching and duplicate articles were checked using publisher sites, and/or DOI-resolving or equivalent scholarly metadata.

Studies were classified into three broad categories based on the type of evidence they provided: (i) direct Jhelum/Jhelum basin evidence; (ii) Kashmir or Western Himalayan comparative evidence; or (iii) broader mechanistic/biomonitoring evidence. The different sampling gears, levels of taxonomic resolution, differing definitions of particle size, methods of sediment measurement, varying hydrological conditions and different biological endpoints prevented the pooling of numerical values. Thus a formal meta-analysis was not justified. Instead, a semi-quantitative evidence assessment based on directness, consistency and replication was employed. "Strong" means several mutually consistent direct or closely comparable studies; "moderate" means repeated support with some contextual dependence; "limited" means few studies or indirect support; "inconsistent" means contrasting response directions; and "insufficient Jhelum-specific evidence" means a plausible mechanism, which has been described outside the basin, has not been examined in the Jhelum. No new field observations, concentrations, effect sizes, p-values or model coefficients were constructed.

Evidence Synthesis Results

The evidence map indicated that macroinvertebrate evidence dominates physical habitat evidence. Direct Jhelum and Kashmir studies repeatedly showed macroinvertebrate variation as a result of variations in fine substrate, habitat type, flow, temperature, solids and longitudinal position (1-8). In contrast, basin studies of hydrochemistry, trophic state and land use primarily described the chemical setting and did not demonstrate coupled sediment-chemistry effects on macroinvertebrates (9-19). This distinction is crucial to interpretation: it supports the conclusion that bed structure and hydrology act as ecological filters, but only a conclusion of moderate assurance can be drawn that broad chemical gradients impact benthic structure, and it is not appropriate to attribute biological change to any sediment contaminant.

Relative to other phenomena, fine-sediment effects were the most uniformly represented in comparative literature. Field studies, multi-year studies, and experimental studies have found that a build-up of deposited fines can decrease interstitial space, alter the use of drift and refuge, react with reduced velocity, and also affect both the taxonomic and functional measures [20-29]. Biomonitoring studies have also found that changes in sediment abundance and velocity, the presence of organic matter in the sediment, and disturbance of the upland region can explain different parts of the assemblage [30-41]. The metal literature makes a different point: when total sediment concentration is measured, ecological understanding is enhanced by the presence of extractable fractions, chemistry of pore waters, bioaccumulation or ecotoxicity [42-50]. Nonlinear responses can exist in nutrient and organic matter studies, where enrichment can act as a supply of nutrients or a stressor dependent on the background and the state of oxygen [51-59].

Hydrological regulation and trait-based studies further support the need for integration [60-80]. When sediment, hydraulic habitat and connectivity are all changed by dams, biological responses cannot be explained solely by flow. Flow response traits and biomolecular approaches provide increased mechanistic sensitivity, but still require concurrent environmental measurements [68-79; 87; 95]. Overall, the evidence is strongest for the substrate and flow paths, moderate for hydrochemical and organic/nutrient paths, and insufficient Jhelum-specific evidence for a causal relationship between metals and benthos. This evidence informed the construction of the analytical tables and the conceptual model.

Sediment Chemistry of the Jhelum System

Current data pertaining to the Jhelum basin suggest a chemically diverse river system influenced by factors including lithology, snowmelt, human activities and land use. Published hydro-chemical data report both natural and man-made controls on weathering, while some catchment studies suggest that different land use classes, including agriculture, construction, bare and other classes of land cover, change water quality at multiple scales [9-15]. Recent studies on the status of aquatic ecosystems and chlorophyll have added new insights on the potential of the basin to experience nutrient enrichment, while others have focused on the relatively longer time period [16]. While these studies have not measured sediment-to-benthos exposure, they have provided important insights regarding the context in which sedimentary processes and biological assemblages may occur.

Organic matter and nutrients can impact the benthic community in several ways. Organic matter can positively impact microbial stream process, but organic enrichment can lead to low oxygen concentrations in sediments. Comparative studies of other river systems have shown that the presence of nutrients is dependent on background concentrations, and that nutrient enrichment can lead to changes in both the community and the food web [51-59]. Therefore, higher sediment organic matter or phosphorus does not necessarily lead to reduced benthostic diversity. For the Jhelum system, the more reasonable hypothesis will likely be that the effects of organic and nutrient enrichment will occur in combination with low-flow benthic systems, fine sediments, and temperature to affect food availability and oxygen concentration.

Potentially toxic elements require extra care. Comparative studies on urban and agricultural catchments report metal sediment accumulation in rivers, and advances in literature show metal sediment pattern contamination differences for various functional land uses and sediment characteristics [42-50]. Importantly, studies on the macroinvertebrates exposure show a closer relationship to the bioavailable fractions compared to total sediment exposure, and these fractions include the total extractable and the biological [43,44]. For metal-related community shifts, sensitive taxa may decline or other taxa may become dominant, but these shifts are pH, organic matter, grain size and metal speciation dependent. The DOI-bearing literature reviewed herein provides little direct evidence to support the hypothesis that benthic assemblages of the Jhelum are presently structured by Cd, Pb, Cr, Zn and other sediment metals. Therefore, metal contamination is an important but unresolvable pathway of the Jhelum and requires paired sediment fractionation and biological measurements instead of total concentrations.

Substratum Characteristics and Benthic Habitat

The most robust sediment-related determinant of benthic structure of the Jhelum is substratum. Direct basin evidence identifies fine substrate as a seasonal correlate of macroinvertebrate assemblage variability [1], while habitat focused surveys show that community variability occurs for longitudes and within mesohabitats. In the Kashmir rivers, substrate along with solids, flow and fragmentation are related to changes in alpha and beta diversity. These results are ecologically sound as coarse, heterogeneous beds create interstitial spaces and hydraulic refugia, whereas sand and silt infill reduces physical complexity.

Experimental and multi-year studies provide more detail. Fine sediment can lessen macroinvertebrate abundance, diminish rheophilic and sediment-sensitive taxa, alter feeding groups, and negatively impact several sediment-related biomonitoring metrics [20-29]. With regards to sediment, treatment type, size, and velocity can all impact the biology of an organism [22]. Deposition can also substantially reduce the hyporheic zone and can possibly create effects that last beyond a single disturbance [27,29]. Additionally, long-term monitoring shows that sediment and land use change can impact how sediment and biota dynamically respond over time [23].

For the Jhelum, the issue may not be fine sediment, as it may be a natural process and expected in depositional reaches. If deposition exceeds the geomorphic setting of the Jhelum, and the reach becomes more embedded, more likely to block flow and has low interstitial exchange and is combined with anthropogenic activities and low flows, then there may be some negative effects on the biota. Thus, monitoring should differentiate various sediment fractions, measure the substrate, and evaluate the sediment embeddedness jointly with measures of flow and several other factors. From the current evidence, there is a strong case to be made for the benthic filtering hypothesis, where sedimentation can impact a system and simplify habitats, and the thresholds associated with the Jhelum are still undefined.

Benthic Community Responses

Benthic macroinvertebrates provide insight into physical habitat and chemical water quality, which can vary seasonally. Because of this, they are useful for assessing the health of rivers on a range of spatial and temporal scales [30-41]. Longitudinal and seasonal trends have been studied in the Jhelum Basin. Some species establish preferences to habitat along environmental gradients, while others become more sensitive to environmental disturbance [1-6]. Changes to hydrological conditions, temperature, fine sediment, and stress on the catchment have likely caused the observed reduction in overall macroinvertebrate richness and diversity, and in the EPT metrics, of the Jhelum Watersheds. This reduction is indicative of a cumulative effect, not caused by a single contaminant [1]. In the 2025 assessment of the Jhelum tributaries, it was confirmed that macrobenthic assemblages are appropriate indicators of the condition of a river [2].

Sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) require well-oxygenated habitats and can decline from fine particle influx, or organic pollution, which may be interpreted as an increase in sedimentation. Other taxa, such as some Chironomidae and Oligochaeta, and even some molluscs, can be found in sediment- or nutrient-enriched environments, but this should not lead to the generalization of tolerance among these phyla [30-41]. From the existing macroinvertebrate studies in Korea, several aspects of streambed substrate, and particularly the interplay of organic pollution, flow velocity, and gradient, have been noted to influence the composition of macroinvertebrate assemblages [32,58]. Similar studies from India and Africa show the influence of disturbance on the physicochemical environment [36,39-41].

Functional traits have the potential to enhance diagnoses. Traits associated with attachment, burrowing, respiration, body form, feeding mode and dispersal have the potential to shed light on mechanisms that taxonomic richness might miss [68-79]. One example is sediment stress. Sediment stress may provide an advantage to taxa comprised of burrowers or deposit feeders, while selected Taxa may include coarse sediment feeders. Metabarcoding of DNA may improve taxonomic resolution and reveal stress responses. This method has been shown to be particularly useful in cases in which morphology and family-level identification have been obscured by species-level responses. However, the measurement of habitat is still necessary. Molecular techniques, grain size, hydraulics, chemistry and sediment measurement should be used to answer a question in such cases.

For the Jhelum, community responses may be interpreted as multicausal filtering. A reduction in EPT richness may not indicate sediment metal toxicity. An increase in Chironomidae may not be a clear indicator of organic pollution. The most productive interpretation may be that substratum, flow and gradients of sediment chemistry, combined with the broad physicochemical conditions of the Jhelum, may define the benthic fauna of the Jhelum. Refined measurements of the relative contributions of components of sediment chemistry may be insufficient.

Integrated Analytical Assessment

The evidence shows a pressure-pathway-response model rather than a single-variable model. Increases in sedimentation, agricultural activities, land use, waste water discharges, land transformations and the construction of infrastructure may affect the sediment load and the organics and nutrient load of receiving waters, as well as the variability of the contaminant load and flow competence. These pressures impact two connected filters: sediment chemistry and physical substratum. The chemical filter is responsible for redox and nutrient balance and contaminant equilibrium. The physical filter is responsible for the sediment frame and the refuge hydraulic and sediment-water exchange. Benthic fauna will respond to the combined filters and their ecological tolerances and traits.

Evidence strength is uneven. Fine sediment, substratum, habitat and flow have the strongest direct evidence in the Jhelum/Kashmir literature [1,3,4,6-8], and their mechanisms are independently supported by experiments and long-term studies [20-29]. Broad hydrochemical and land use controls have moderate support, as direct studies on the basin show the existence of chemical gradients which are spatially and temporally variable [9-19]. These gradients can be related to community structure by teleo-Biomonitoring studies [30-41,51-59]. Enrichment by organics and nutrients is important, but is probably context related. In low or moderate enrichment, basal resources would increase, but under high enrichment, along with slow flow and fine sediment, would cause oxygen deprivation. The effects of sediments and metals are the weakest local inferences. International studies show accumulation and bioavailability pathways [42-50], but comparable paired sediment-fractionation and benthic studies are absent for the Jhelum.

Hydrological regulation can either reduce or enhance these pathways by modifying sediment transport and the persistence and recolonization of habitat. Dam and flow regulation studies show changes in the composition of macroinvertebrates, beta diversity, and ecological quality, but the magnitude is dependent on the operating regime and geomorphic context [60-67]. This is particularly relevant for the regulated tributaries of the Jhelum, where flow modification can change the transport and the retention of fine sediment [3,7,8].

Variables representing the sediment should never be analyzed independently of the flow. The first-order predictor set that may be significant in future assessments of the Jhelum River is as follows: particle-size distribution, embeddedness, heterogeneity of the substrate, fine sediment deposited and suspended, discharge, velocity, sediment TOC/organic matter, sediment or pore water oxygen/redox, nutrients, and pH. The fractionation of metals may also be relevant. Biological endpoints could include EPT metrics, Chironomidae/Oligochaeta composition, diversity, and functional feeding groups and trait profiles. The integration of the mentioned measurements offers the ability to analyze the shift in biology, and determine if the shift is likely from enrichment, simplification, toxicity or hydrological changes as opposed to a multitude of other factors acting concurrently

Table 1. Major sediment and substratum variables relevant to benthic communities in the River Jhelum

Variable	Mechanistic relevance	Expected benthic response	Evidence strength	Key refs.
Fine sand/silt deposition	Fills interstices; modifies hyporheic exchange and refuge	Loss of sensitive/rheophilic taxa; functional shifts	Strong direct/ comparative	[1,20-29]
Cobble-gravel heterogeneity	Creates stable attachment surfaces and hydraulic refugia	Greater niche diversity and sensitive taxa where water quality is suitable	Strong	[3,4,6,32]

Variable	Mechanistic relevance	Expected benthic response	Evidence strength	Key refs.
Flow/velocity and embeddedness	Controls transport, bed mobility and sediment retention	Context-dependent richness, beta diversity and recolonization	Strong	[1,3,7,8,60-67]
pH and redox/oxygen	Modulates physiology, decomposition and metal speciation	Taxon filtering; possible oxygen stress in depositional zones	Moderate	[1,9-19,42-59]
Organic matter and nutrients	Food subsidy versus microbial oxygen demand	Non-linear shifts in richness and functional composition	Moderate/context-dependent	[51-59]
Potentially toxic metals	Exposure depends on speciation, grain size and organic matter	Possible toxicity/bioaccumulation and sensitive-taxa loss	Insufficient Jhelum-specific	[42-50]

Table 2. Representative secondary studies linking sediment/habitat conditions and benthic communities

Study	River/region	Sediment/habitat factor	Biological endpoint	Main inference	DOI
Sabha et al. 2020	Jhelum basin	Fine substrate, pH, discharge, temperature	Richness, density, EPT, assemblage	Fine substrate and pH were important non-summer correlates; flow/temperature important in summer	10.1002/eco.2236
Sabha et al. 2023	Jhelum River	Longitudinal habitats/substrata	Habitat preference, biomonitoring	Mesohabitat context materially structures assemblages	10.1007/s13762-022-04523-y
Sofi et al. 2022	Sindh River, Kashmir	Regulation, solids, substrate, flow	Alpha/beta diversity	Regulation and habitat variables correspond with biotic alteration	10.1016/j.ecoleng.2022.106560
Khanday et al. 2021	Jhelum basin	Lithology, anthropogenic water-quality controls	Hydrochemistry	Defines basin-scale physicochemical context for benthic exposure	10.1016/j.catena.2020.104853

Study	River/region	Sediment/habitat factor	Biological endpoint	Main inference	DOI
Mathers et al. 2022	European streams	Fine sediment deposition	Structure, function, biodiversity	Effects depend on landscape setting and time	10.1016/j.scitotenv.2022.154612
Bylak & Kukula 2022	Mountain streams	Fine sediment	Density and functional groups	Clogging reduces rheophilic taxa and alters feeding structure	10.1016/j.scitotenv.2022.155079
Blocher et al. 2020	Mesocosms	Grain size x velocity	Community dynamics	Fine sediment effects interact with reduced flow	10.1016/j.scitotenv.2020.137070
Schwantes et al. 2021	Ouro River, Brazil	Total/bioavailable metals	Bioaccumulation, richness/abundance	Exposure differs among sediment fractions and taxa	10.1016/j.ecoleng.2021.106194
Sahli et al. 2021	Freshwater sediments	Sediment contamination	Risk/ecotoxicity	Chemical and biological approaches are complementary	10.1080/02757540.2020.1853106
Min & Kong 2020	Korean rivers	Substrate, velocity, BOD, gradient	Assemblage distribution	Microhabitat and organic pollution help separate community types	10.1080/02705060.2020.1815599

Figure 1. Conceptual framework linking catchment pressures, sediment/substratum pathways and benthic community structure in the River Jhelum

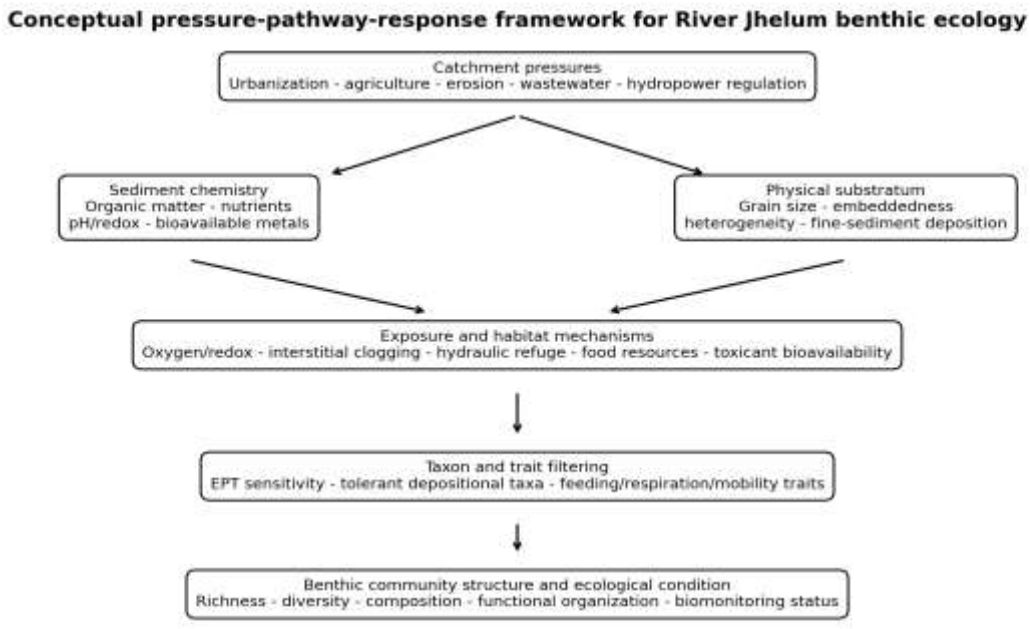

Table 3. Analytical evidence assessment

Driver	Sediment/substratum change	Mechanism	Likely benthic response	Evidence rating
Catchment erosion/agriculture	Higher fine-sediment delivery	Interstitial clogging, habitat homogenization	Lower sediment-sensitive/rheophilic taxa	Strong for mechanism; direct Jhelum support
Hydropower/flow regulation	Altered transport and retention	Changed hydraulics, refuge and connectivity	Assemblage turnover; altered alpha/beta diversity	Strong in Kashmir comparative reaches
Wastewater/nutrient input	Organic and nutrient enrichment	Resource subsidy vs oxygen demand	Context-dependent tolerant/sensitive shifts	Moderate
Urban/industrial contamination	Sediment metal accumulation	Bioavailable exposure and toxicity	Potential bioaccumulation/community filtering	Insufficient Jhelum-specific
Habitat simplification	Reduced coarse-bed heterogeneity	Loss of niches and attachment/refuge space	Reduced sensitive-taxa diversity	Strong

Research Gaps and Future Directions

The main gap in the research focuses on creating co-located sediment-benthos designs across the basin to capture the physical substrate and sediment chemistry along with macroinvertebrates across the same spatial and seasonal scales. Currently, the available studies of the Jhelum River focus on the development of baseline datasets for biology, hydrology, and water chemistry. However, sediment grain size, sediment bed embeddedness, sediment organic matter, and pore water chemistry and the bioavailability of metals have not been incorporated into the studies. Subsequent sampling initiatives should adopt a standardized upstream-downstream and reference-impact framework to encompass headwater, urban, and farm sectors and regulated tributaries across different hydrological seasons.

Laboratory analysis should distinguish total from operationally bioavailable metal fractions and should include pore-water chemistry and tissue bioaccumulation, where possible. Physical habitat assessment should classify silt/clay, fine sand, coarse sand, gravel, pebble, cobble, and boulder and avoid reporting fine sediment as a percent. Use of trait-based indices, functional feeding groups and DNA metabarcoding may complement family or genus identification [68-79,87,95]. Comparative studies also demonstrate the utility of Himalayan and regional assemblage benchmarks, citizen-science screening, validated river typologies, habitat-suitability models and multivariate community analysis [81-86]. Sediment multi-stress research demonstrates that chemistry should be evaluated along with other co-occurring stressors [88]. Fine-sediment studies conducted recently refine our understanding of seasonal exposure and inorganic versus organic sediment exposure [89-91]. Other studies use species-distribution modeling and a combination of sediment-water interaction and catchment deposition studies [92-94]. Pressure caused by river regulation and the global dam construction are framed by studies conducted on river regulation and on the existent dams [96-98,100]. Taxonomic revisions are also major biomonitoring quality-control issues [99]. Statistical analysis should focus on multivariate ordination and mixed-effects models and causal diagrams constructed with explicit hydrological covariates, rather than broad correlation screening. Long-term studies should focus on evaluating the sediment legacy effects, flood resetting, and possible climatic impacts. These suggested changes would shift the current pressure-pathway model toward a more understandable management-based model of Jhelum benthic ecology.

Table 4. Priority research gaps and recommended approaches for the River Jhelum

Research gap	Current limitation	Recommended method	Expected contribution
Paired sediment-benthos evidence	Chemistry and biology often measured separately	Co-located seasonal sediment, habitat and macroinvertebrate sampling	Direct attribution of ecological gradients
Metal bioavailability	Total concentration can overstate or understate exposure	Sequential/extractable fractions, pore water and tissue analysis	Mechanistic contaminant-risk inference
Fine-sediment characterization	Single percentage obscures particle effects	Separate silt/clay, fine/coarse sand; embeddedness measures	Improved sediment thresholds and diagnostics
Taxonomic resolution	Family-level metrics can mask cryptic responses	Genus/species identification plus DNA metabarcoding	Greater sensitivity and trait resolution
Long-term dynamics	Snapshot surveys miss legacy and flood effects	Permanent stations and multi-season repeated measures	Detection of recovery, climate and regulation effects

CONCLUSION

Current data show that both sediment and substratum affect benthic community organization in the River Jhelum, and the strength of inference also varies among pathways. The most established local relationship relates to the physical bed, and the repeated association of the fine substrate, habitat type, discharge, and temperature, as well as conditions of regulated flow, with the variation of benthic assemblages across the Jhelum basin and the Kashmir Himalayan tributaries [1-8]. A credible chemical context is provided by the catchment land use and hydrochemistry [9-19], and the wider experimental literature explains how excess fine sediment, nutrient/organic enrichment and altered flow can filter sensitive taxa and functional traits [20-41,51-79].

What is still unclear is the direct role of sediment chemicals, and potentially toxic metals, in the benthic change of the Jhelum. There is comparative evidence that sediment-bound metals can be ecologically important, but total concentration is an inadequate proxy for exposure [42-50]. Therefore it would be unknown to attribute observed change in Jhelum communities to metal toxicity without pore-water, bioaccumulation or fractionation data. The next phase of biomonitoring in the Jhelum should include measuring sedimentary grains and embeddedness together with sedimentary organic matter, nutrients, pH/redox, fractioned metals, hydrology and high resolution benthic taxonomy. Such a combination would allow managers to distinguish natural longitudinal change from anthropogenic change of sedimentation, enrichment, pollution and change of flow regime, and would give a justified case to set ecological limits and priorities for change.

REFERENCES

1. Sabha I, Khanday SA, Islam ST, Bhat SU. Longitudinal and temporal assemblage patterns of benthic macroinvertebrates in snow melt stream waters of the Jhelum River Basin of Kashmir Himalaya (India). Ecohydrology. 2020; 13:e2236.
2. https://doi.org/10.1002/eco.2236

2. Mir ZA, Bakhtiyar Y, Parveen M, Khan NA, Akhtar M, Nissar S. Macrobenthic invertebrate structure, diversity, and water quality indicators in Jhelum tributaries of Kashmir Himalaya. Environmental Monitoring and Assessment. 2025; 197:915. https://doi.org/10.1007/s10661-025-14346-2

3. Sofi MS, Hamid A, Bhat SU, Rashid I, Kuniyal JC. Biotic alteration of benthic macroinvertebrate communities based on multispatial-scale environmental variables in a regulated river system of Kashmir Himalaya. Ecological Engineering. 2022; 177:106560. https://doi.org/10.1016/j.ecoleng.2022.106560

4. Sabha I, Islam ST, Hamid A, Bhat SU. Habitat preferences and biomonitoring of aquatic macroinvertebrates along the longitudinal gradient of Jhelum River, Kashmir Himalaya. International Journal of Environmental Science and Technology. 2023; 20:10123-10140. https://doi.org/10.1007/s13762-022-04523-y

5. Hamid A, Bhat SU, Jehangir A. Assessment of ecological characteristics of macroinvertebrate communities and their relationship with environmental factors in a stream ecosystem. Chemistry and Ecology. 2021; 37:746-766. https://doi.org/10.1080/02757540.2021.1987419

6. Lone SA, Hamid A, Bhat SU, Bhat FA. Benthic macroinvertebrate dynamics and responses to environmental factors in spring habitats of Kashmir Himalaya. Chemistry and Ecology. 2025; 41:152-172. https://doi.org/10.1080/02757540.2024.2416644

7. Sofi MS, Bhat SU, Muslim M. Navigating a broken river: Understanding the ecological consequences of fragmentation on benthic life. Ecohydrology. 2024; 17:e2575. https://doi.org/10.1002/eco.2575

8. Sofi MS, Bhat SU, Rashid I, Kuniyal JC. The natural flow regime: A master variable for maintaining river ecosystem health. Ecohydrology. 2020; 13:e2247. https://doi.org/10.1002/eco.2247

9. Khanday SA, Bhat SU, Islam ST, Sabha I. Identifying lithogenic and anthropogenic factors responsible for spatio-seasonal patterns and quality evaluation of snow melt waters of the River Jhelum Basin in Kashmir Himalaya. CATENA. 2021; 196:104853. https://doi.org/10.1016/j.catena.2020.104853

10. Mir RA, Jeelani G, Dar FA. Spatio-temporal patterns and factors controlling the hydrogeochemistry of the River Jhelum basin, Kashmir Himalaya. Environmental Monitoring and Assessment. 2016; 188:438. https://doi.org/10.1007/s10661-016-5429-6

11. Rather MI, Rashid I, Shahi N, et al.. Massive land system changes impact water quality of the Jhelum River in Kashmir Himalaya. Environmental Monitoring and Assessment. 2016; 188:185. https://doi.org/10.1007/s10661-016-5190-x

12. Bhat FA, Yousuf AR, Aftab A, et al.. Occurrence of macro-zoobenthos against the varied altitudinal gradient and ecology in a trout stream (Lidder) of Kashmir Himalaya, India. Proceedings of the National Academy of Sciences, India Section B. 2014; 84:287-297. https://doi.org/10.1007/s40011-013-0217-3

13. Ganaie HA, et al.. Quality assessment of drinking water sources in upper Jhelum basin. International Journal of River Basin Management. 2023; 21:513-524. https://doi.org/10.1080/15715124.2022.2036747

14. Ara S, et al.. Drinking quality assessment of some groundwater sources along the stretch of Jhelum River in Kashmir Himalaya. Environmental Earth Sciences. 2017; 76:630. https://doi.org/10.1007/s12665-017-6960-7

15. Bhat SU, Khanday SA, Islam ST, Sabha I. Understanding the spatiotemporal pollution dynamics of highly fragile montane watersheds of Kashmir Himalaya, India. Environmental Pollution. 2021; 286:117335. https://doi.org/10.1016/j.envpol.2021.117335

16. Islam ST, Bhat SU, Sabha I, Sofi MS, Dar SA. Comprehensive assessment of trophic status and chlorophyll-a dynamics in the Jhelum River Basin: Implications for river ecosystem management. International Journal of Environmental Research. 2025; 19. https://doi.org/10.1007/s41742-024-00705-3

17. Sofi MS, Hamid A, Bhat SU, Rashid I, Kuniyal JC. Impact evaluation of the run-of-river hydropower projects on the water quality dynamics of the Sindh River in the Northwestern Himalayas. Environmental Monitoring and Assessment. 2022; 194:626. https://doi.org/10.1007/s10661-022-10303-5

18. Sofi MS, Hamid A, Bhat SU, Rashid I, Kuniyal JC. Understanding the role of natural and anthropogenic forcings in structuring the periphytic algal assemblages in a regulated river ecosystem. Scientific Reports. 2023; 13:1882. https://doi.org/10.1038/s41598-023-27773-3

19. Sofi MS, Rautela KS, Bhat SU, Rashid I, Kuniyal JC. Application of geomorphometric approach for the estimation of hydro-sedimentological flows and cation weathering rate: Towards understanding the sustainable land use policy for the Sindh Basin, Kashmir Himalaya. Water, Air, & Soil Pollution. 2021; 232. https://doi.org/10.1007/s11270-021-05217-w

20. Mathers KL, Doretto A, Fenoglio S, Hill MJ, Wood PJ. Temporal effects of fine sediment deposition on benthic macroinvertebrate community structure, function and biodiversity likely reflects landscape setting. Science of the Total Environment. 2022; 829:154612. https://doi.org/10.1016/j.scitotenv.2022.154612

21. Bylak A, Kukula K. Impact of fine-grained sediment on mountain stream macroinvertebrate communities: Forestry activities and beaver-induced sediment management. Science of the Total Environment. 2022; 832:155079. https://doi.org/10.1016/j.scitotenv.2022.155079

22. Blocher JR, Ward MR, Matthaei CD, Piggott JJ. Multiple stressors and stream macroinvertebrate community dynamics: Interactions between fine sediment grain size and flow velocity. Science of the Total Environment. 2020; 717:137070. https://doi.org/10.1016/j.scitotenv.2020.137070

23. Davis NG, Hodson R, Matthaei CD. Long-term variability in deposited fine sediment and macroinvertebrate communities across different land-use intensities in a regional set of New Zealand rivers. New Zealand Journal of Marine and Freshwater Research. 2022; 56:191-212. https://doi.org/10.1080/00288330.2021.1884097

24. Duan N, Song J, Mao H, Sun H, Huang P. Environmental context mediates the interaction between fine sediment and hyporheic macroinvertebrate. Ecohydrology. 2022; 15:e2392. https://doi.org/10.1002/eco.2392
25. Ntloko P, Palmer CG, Akamagwuna FC, et al.. Exploring macroinvertebrates ecological preferences and trait-based indicators of suspended fine sediment effects in the Tsitsa River and its tributaries, Eastern Cape, South Africa. Water. 2021; 13:798. https://doi.org/10.3390/w13060798
26. Huchzermeyer N, Rowntree K. Developing a taxa-related physical habitat score based on response of macroinvertebrate community structure to fine bed sediment composition in the Tsitsa River, Eastern Cape, South Africa. River Research and Applications. 2021; 37. https://doi.org/10.1002/rra.3857
27. Milner VS, Maddock IP, Jones I, Bunting GC. Do legacy effects of deposited fine sediment influence ecological response of drifting invertebrates to a fine sediment pulse?. Aquatic Sciences. 2021; 83:70. https://doi.org/10.1007/s00027-021-00825-4
28. Beermann AJ, Werner MT, Elbrecht V, Zizka VMA, Leese F. DNA metabarcoding improves the detection of multiple stressor responses of stream invertebrates to increased salinity, fine sediment deposition and reduced flow velocity. Science of the Total Environment. 2021; 750:141969. https://doi.org/10.1016/j.scitotenv.2020.141969
29. Milner VS, Jones JI, Maddock IP, Bunting GC. The hyporheic zone as an invertebrate refuge during a fine sediment disturbance event. Ecohydrology. 2022; 15:e2450. https://doi.org/10.1002/eco.2450
30. Tampo L, Kabore I, Alhassan EH, Oueda A, Bawa LM, Djaneye-Boundjou G. Benthic macroinvertebrates as ecological indicators: Their sensitivity to the water quality and human disturbances in a tropical river. Frontiers in Water. 2021; 3:662765. https://doi.org/10.3389/frwa.2021.662765
31. Medupin C. Spatial and temporal variation of benthic macroinvertebrate communities along an urban river in Greater Manchester, UK. Environmental Monitoring and Assessment. 2020; 192:84. https://doi.org/10.1007/s10661-019-8019-6
32. Min JK, Kong DS. Distribution patterns of benthic macroinvertebrate communities based on multispatial-scale environmental variables in the river systems of Republic of Korea. Journal of Freshwater Ecology. 2020; 35:323-347. https://doi.org/10.1080/02705060.2020.1815599
33. Chattopadhyay S, Oglecki P, Keller A, et al.. Effect of a summer flood on benthic macroinvertebrates in a medium-sized, temperate, lowland river. Water. 2021; 13:885. https://doi.org/10.3390/w13070885
34. Salmaso F, Crosa G, Espa P, Quadroni S. Climate change and water exploitation as co-impact sources on river benthic macroinvertebrates. Water. 2021; 13:2778. https://doi.org/10.3390/w13192778
35. Dou P, Wang X, Lan Y, Cui B, Bai J, Xie T. Benthic macroinvertebrate diversity as affected by the construction of inland waterways along montane stretches of two rivers in China. Water. 2022; 14:1080. https://doi.org/10.3390/w14071080
36. Khatri N, Raval K, Jha AK. Integrated water quality monitoring of Mahi River using benthic macroinvertebrates and comparison of its biodiversity among various stretches. Applied Water Science. 2021; 11:143. https://doi.org/10.1007/s13201-021-01451-z
37. Zhang Q, Yang T, Wan X, Wang Y, Wang W. Community characteristics of benthic macroinvertebrates and identification of environmental driving factors in rivers in semi-arid areas - A case study of Wei River Basin, China. Ecological Indicators. 2021; 121:107153. https://doi.org/10.1016/j.ecolind.2020.107153
38. Kownacki A, Szarek-Gwiazda E. The impact of pollution on diversity and density of benthic macroinvertebrates in mountain and upland rivers. Water. 2022; 14:1349. https://doi.org/10.3390/w14091349
39. Khatri N, Raval K, Jha AK, Tharmavaram M, Rawtani D. Impact of seasonal changes in the abundance of benthic macroinvertebrates & physico-chemical conditions of a major river in Western India. Environmental Claims Journal. 2023; 35:157-183. https://doi.org/10.1080/10406026.2022.2047430
40. Addo-Bediako A. Spatial distribution patterns of benthic macroinvertebrate functional feeding groups in two rivers of the Olifants River System, South Africa. Journal of Freshwater Ecology. 2021; 36:97-109. https://doi.org/10.1080/02705060.2021.1901789
41. Raphahlelo ME, Addo-Bediako A, Luus-Powell WJ. Distribution and diversity of benthic macroinvertebrates in the Mohlapitsi River, South Africa. Journal of Freshwater Ecology. 2022; 37:145-160. https://doi.org/10.1080/02705060.2021.2023054
42. Wang F, Dong W, Zhao Z, et al.. Heavy metal pollution in urban river sediment of different urban functional areas and its influence on microbial community structure. Science of the Total Environment. 2021; 778:146383. https://doi.org/10.1016/j.scitotenv.2021.146383
43. Schwantes D, Goncalves Junior AC, Manfrin J, et al.. Distribution of heavy metals in sediments and their bioaccumulation on benthic macroinvertebrates in a tropical Brazilian watershed. Ecological Engineering. 2021; 163:106194. https://doi.org/10.1016/j.ecoleng.2021.106194
44. Sahli L, Belhiouani H, Burga Perez KF, et al.. Assessment of freshwater sediment quality: potential ecological risk and ecotoxicity tests as complementary approaches. Chemistry and Ecology. 2021; 37:219-233. https://doi.org/10.1080/02757540.2020.1853106
45. Lian G, Lee X. Concentrations, Distribution, and Pollution Assessment of Metals in River Sediments in China. International Journal of Environmental Research and Public Health. 2021; 18:6908. https://doi.org/10.3390/ijerph18136908
46. Xiao H, et al.. Heavy metal pollution, ecological risk, spatial distribution, and source identification in sediments of the Lijiang River, China. Environmental Pollution. 2021; 269:116189. https://doi.org/10.1016/j.envpol.2020.116189
47. Addo-Bediako A, Nukeri S, Kekana M. Heavy metal and metalloid contamination in the sediments of the Spekboom River, South Africa. Applied Water Science. 2021; 11:133. https://doi.org/10.1007/s13201-021-01464-8
48. Debnath A, Singh PK, Sharma YC. Metallic contamination of global river sediments and latest developments for their remediation. Journal of Environmental Management. 2021; 298:113378. https://doi.org/10.1016/j.jenvman.2021.113378
49. Mmako TV, Addo-Bediako A, Luus-Powell WJ, Kekana M. Assessment of river health using benthic macroinvertebrates in the Dwars River, Olifants Water Management Area, Limpopo province, South Africa. African Journal of Aquatic Science. 2021; 46:441-451. https://doi.org/10.2989/16085914.2021.1922348

50. Alric B, Geffard O, Chaumot A. Metal bioavailable contamination engages richness decline, species turnover but unchanged functional diversity of stream macroinvertebrates at the scale of a French region. Environmental Pollution. 2022; 308:119565. https://doi.org/10.1016/j.envpol.2022.119565
51. Pearce NJT, Lavoie I, Thomas KE, Chambers PA, Yates AG. Nutrient enrichment effects are conditional on upstream nutrient concentrations: Implications for bioassessment in multi-use catchments. Ecological Indicators. 2021; 124:107440. https://doi.org/10.1016/j.ecolind.2021.107440
52. Zhang Y, Leung JYS, Zhang Y, Cai Y, Zhang Z, Li K. Agricultural activities compromise ecosystem health and functioning of rivers: Insights from multivariate and multimetric analyses of macroinvertebrate assemblages. Environmental Pollution. 2021; 275:116655. https://doi.org/10.1016/j.envpol.2021.116655
53. Canning AD, Joy MK, Death RG. Nutrient criteria to achieve New Zealand's riverine macroinvertebrate targets. PeerJ. 2021; 9:e11556. https://doi.org/10.7717/peerj.11556
54. Koperski P. Linear and nonlinear effects of nutrient enrichments on diversity of macrobenthos in lowland watercourses. Aquatic Ecology. 2021; 55:1011-1031. https://doi.org/10.1007/s10452-021-09878-x
55. Demars BOL, Kemp JL, Marteau B, Friberg N, Thornton B. Stream Macroinvertebrates and Carbon Cycling in Tangled Food Webs. Ecosystems. 2021; 24:1944-1961. https://doi.org/10.1007/s10021-021-00626-8
56. Canning AD, Death RG. The influence of nutrient enrichment on riverine food web function and stability. Ecology and Evolution. 2021; 11. https://doi.org/10.1002/ece3.7107
57. Ferreira V, Silva J, Cornut J, et al.. Organic-matter decomposition as a bioassessment tool of stream functioning: A comparison of eight decomposition-based indicators exposed to different environmental changes. Environmental Pollution. 2021; 290:118111. https://doi.org/10.1016/j.envpol.2021.118111
58. Min JK, Kong DS. Development of a predictive model for benthic macroinvertebrates by using environmental variables for the biological assessment of Korean streams. Journal of Freshwater Ecology. 2021; 36:189-216. https://doi.org/10.1080/02705060.2021.1958078
59. Juvigny-Khenafou NPD, Piggott JJ, Atkinson D, et al.. Impacts of multiple anthropogenic stressors on stream macroinvertebrate community composition and functional diversity. Ecology and Evolution. 2021; 11:133-152. https://doi.org/10.1002/ece3.6979
60. Mahan DC, Betts JT, Nord E, Van Dyke F, Outcalt JM. Response of benthic macroinvertebrates to dam removal in the restoration of the Boardman River, Michigan, USA. PLOS ONE. 2021; 16:e0245030. https://doi.org/10.1371/journal.pone.0245030
61. Zhang H, Zhu C, Mo K, et al.. Dam cascade alters taxonomic composition of benthic macroinvertebrate community in upper Yangtze River. River Research and Applications. 2021; 37:1070-1079. https://doi.org/10.1002/rra.3787
62. Wang J, Ding C, Tao J, et al.. Damming affects riverine macroinvertebrate metacommunity dynamics: Insights from taxonomic and functional beta diversity. Science of the Total Environment. 2021; 763:142945. https://doi.org/10.1016/j.scitotenv.2020.142945
63. Ko NT, Suter P, Conallin J, Rutten M, Bogaard T. Aquatic macroinvertebrate community changes downstream of hydropower generating dams in Myanmar - potential negative impacts from increased power generation. Frontiers in Water. 2020; 2:573543. https://doi.org/10.3389/frwa.2020.573543
64. Vasco AN, Dantas JO, et al.. Impacts of dam construction on the macroinvertebrate community in the Poxim-Acu, in a tropical region. Ambiente & Agua. 2021; 16:e2704. https://doi.org/10.4136/ambi-agua.2704
65. Rodríguez-Pérez H, Pannard A, Gorzerino C, Pellan L, Massé S, et al.. Ecological consequences of consecutive river damming for three groups of bioindicators. Ecological Indicators. 2021; 131:108103. https://doi.org/10.1016/j.ecolind.2021.108103
66. Rosero-López D, Knighton J, Lloret P, Encalada AC. Invertebrate response to impacts of water diversion and flow regulation in high-altitude tropical streams. River Research and Applications. 2020; 36:223-233. https://doi.org/10.1002/rra.3578
67. Quadroni S, Salmaso F, Gentili G, Crosa G, Espa P. Response of benthic macroinvertebrates to different hydropower off-stream diversion schemes. Ecohydrology. 2021; 14:e2267. https://doi.org/10.1002/eco.2267
68. Edegbene AO, Arimoro FO, Odume ON. How does urban pollution influence macroinvertebrate traits in forested riverine systems?. Water. 2020; 12:3111. https://doi.org/10.3390/w12113111
69. Larras F, Usseglio-Polatera P. Heterogeneity in macroinvertebrate sampling strategy introduces variability in community characterization and stream trait-based biomonitoring: Influence of sampling effort and habitat selection criteria. Ecological Indicators. 2020; 119:106758. https://doi.org/10.1016/j.ecolind.2020.106758
70. de Brouwer JHF, Verdonschot PFM, Eekhout JPC, Verdonschot RCM. Macroinvertebrate taxonomic and trait-based responses to large-wood reintroduction in lowland streams. Freshwater Science. 2020; 39:693-703. https://doi.org/10.1086/710710
71. Odume ON. Searching for urban pollution signature and sensitive macroinvertebrate traits and ecological preferences in a river in the Eastern Cape of South Africa. Ecological Indicators. 2020; 108:105759. https://doi.org/10.1016/j.ecolind.2019.105759
72. De Castro-Català N, Dolédec S, Kalogianni E, Skoulikidis NT, Paunovic M, Vasiljević B, Sabater S, Tornés E, Muñoz I. Unravelling the effects of multiple stressors on diatom and macroinvertebrate communities in European river basins using structural and functional approaches. Science of the Total Environment. 2020; 742:140543. https://doi.org/10.1016/j.scitotenv.2020.140543
73. Kefford BJ, Botwe PK, Brooks AJ, Kunz S, Marchant R, Maxwell S, Metzeling L, Schäfer RB, Thompson RM. An integrated database of stream macroinvertebrate traits for Australia: concept and application. Ecological Indicators. 2020; 114:106280. https://doi.org/10.1016/j.ecolind.2020.106280
74. Arenas-Sánchez A, Dolédec S, Vighi M, et al.. Effects of anthropogenic pollution and hydrological variation on macroinvertebrates in Mediterranean rivers: A case-study in the upper Tagus river basin (Spain). Science of the Total Environment. 2021; 766:144044. https://doi.org/10.1016/j.scitotenv.2020.144044

75. Paz LE, Rodriguez M, Gullo B, Rodrigues Capítulo A. Impacts of urban and industrial pollution on functional traits of benthic macroinvertebrates: Are some traits advantageous for survival?. Science of the Total Environment. 2022; 807:150650. https://doi.org/10.1016/j.scitotenv.2021.150650
76. Sun J, Xu G, Chi J, Zheng Q, Zhang T. Macroinvertebrates beta diversity and responses of functional traits to water environmental factors in the Qingyijiang River, China. River Research and Applications. 2024; 40:264-276. https://doi.org/10.1002/rra.4227
77. Jiang W, Pan B, Jiang X, Shi P, Zhu P, Zhang L, Chen J, Wu N. A comparative study on the indicative function of species and traits structure of stream macroinvertebrates to human disturbances. Ecological Indicators. 2021; 129:107939. https://doi.org/10.1016/j.ecolind.2021.107939
78. Peng FJ, ter Braak CJF, Rico A, Van den Brink PJ. Double constrained ordination for assessing biological trait responses to multiple stressors: A case study with benthic macroinvertebrate communities. Science of the Total Environment. 2021; 754:142171. https://doi.org/10.1016/j.scitotenv.2020.142171
79. Elo M, Jyrkänkallio-Mikkola J, Ovaskainen O, Soininen J, Tolonen KT, Heino J. Does trait-based joint species distribution modelling reveal the signature of competition in stream macroinvertebrate communities?. Journal of Animal Ecology. 2021; 90:1276-1287. https://doi.org/10.1111/1365-2656.13453
80. Wegscheider B, Monk W, Lento J, Haralampides K, et al.. Developing environmental flow targets for benthic macroinvertebrates in large rivers using hydraulic habitat associations and taxa thresholds. Ecological Indicators. 2023; 146:109821. https://doi.org/10.1016/j.ecolind.2022.109821
81. Khatri K, Gurung S, Jha BR, Khadka UR. Benthic macroinvertebrate assemblages of glacial-fed Bheri and rain-fed Babai rivers, western Nepal. Biodiversity Data Journal. 2022; 10:e79275. https://doi.org/10.3897/BDJ.10.e79275
82. Makumbe P, Kanda A, Chinjani T. Relationship between benthic macroinvertebrate assemblages and water quality parameters in Sanyati Basin, Lake Kariba, Zimbabwe. The Scientific World Journal. 2022; 2022:5800286. https://doi.org/10.1155/2022/5800286
83. Onion AM, Smith AJ, Duffy BT. New York State's WAVE Method - Evaluation of a Method for Water Quality Monitoring by Citizen Scientists using Benthic Macroinvertebrates. Environmental Management. 2023; 71:432-438. https://doi.org/10.1007/s00267-022-01753-1
84. Jupke JF, Birk S, Álvarez-Cabria M, Aroviita J, et al.. Evaluating the biological validity of European river typology systems with least disturbed benthic macroinvertebrate communities. Science of the Total Environment. 2022; 842:156689. https://doi.org/10.1016/j.scitotenv.2022.156689
85. Shen Z, Yang Y, Ai L, Yu C, Su M. A hybrid CART-GAMs model to evaluate benthic macroinvertebrate habitat suitability in the Pearl River Estuary, China. Ecological Indicators. 2022; 143:109368. https://doi.org/10.1016/j.ecolind.2022.109368
86. Yao KS, He YJ, Van den Brink PJ, Dai YN, Yang Y, Cui YD. Multivariate approaches to assess the drivers of benthic macroinvertebrate communities and biotic indices in a highly urbanized fluvial-estuarine system. Ecological Indicators. 2022; 139:108956. https://doi.org/10.1016/j.ecolind.2022.108956
87. Ji F, Han D, Yan L, Yan S, Zha J, Shen J. Assessment of benthic invertebrate diversity and river ecological status along an urbanized gradient using environmental DNA metabarcoding and a traditional survey method. Science of the Total Environment. 2022; 806:150587. https://doi.org/10.1016/j.scitotenv.2021.150587
88. Wieringa N, van der Lee GH, de Baat ML, Kraak MHS, Verdonschot PFM. Contribution of sediment contamination to multi-stress in lowland waters. Science of the Total Environment. 2022; 844:157045. https://doi.org/10.1016/j.scitotenv.2022.157045
89. Mathers KL, Armitage PD, Hill M, McKenzie M, Pardo I, Wood PJ. Seasonal variability of lotic macroinvertebrate communities at the habitat scale demonstrates value of discriminating fine sediment fractions in ecological assessments. Ecology and Evolution. 2023; 13:e10564. https://doi.org/10.1002/ece3.10564
90. McKenzie M, Brooks A, Callisto M, et al.. Freshwater invertebrate responses to fine sediment stress: A multi-continent perspective. Global Change Biology. 2024; 30:e17084. https://doi.org/10.1111/gcb.17084
91. McKenzie M, Collins AL, Davis NG, et al.. Stream invertebrate responses to fine sediment depend on the organic and inorganic components. Freshwater Biology. 2025; 70:e70022. https://doi.org/10.1111/fwb.70022
92. Lee H, Kong D. Interaction between Water Quality and Substrate on Benthic Macroinvertebrates Index (BMI). Journal of Korean Society on Water Environment. 2023; 39:261-268. https://doi.org/10.15681/KSWE.2023.39.4.261
93. Kopp DA, Stoddard JL, Hill RA, Doyle JM, Kaufmann PR, Herlihy AT, Paulsen SG. Joint species distribution models reveal taxon-specific sensitivities to potential anthropogenic alteration. Freshwater Science. 2023; 42:268-284. https://doi.org/10.1086/726283
94. Grangeon T, Gracianne C, Favreau Y, Vandromme R, et al.. Catchment-scale variability and driving factors of fine sediment deposition: insights from a coupled experimental and machine-learning-based modeling study. Journal of Soils and Sediments. 2023; 23:3620-3637. https://doi.org/10.1007/s11368-023-03496-w
95. Vourka A, Karaouzas I, Parmakelis A. River benthic macroinvertebrates and environmental DNA metabarcoding: a scoping review of eDNA sampling, extraction, amplification and sequencing methods. Biodiversity and Conservation. 2023; 32:4221-4238. https://doi.org/10.1007/s10531-023-02710-y
96. Calapez AR, Serra SRQ, Rivaes R, Aguiar FC, Feio MJ. Influence of river regulation and instream habitat on invertebrate assemblage' structure and function. Science of the Total Environment. 2021; 794:148696. https://doi.org/10.1016/j.scitotenv.2021.148696
97. Couto TBA, Rezende RS, de Aquino PPU, Costa-Pereira R, de Campos GL, Occhi TV, Vitule JRS, Espírito-Santo HMV, Soares YFF, Olden JD. Effects of small hydropower dams on macroinvertebrate and fish assemblages in southern Brazil. Freshwater Biology. 2023; 68:956-971. https://doi.org/10.1111/fwb.14078
98. Zhang AT, Gu VX. Global Dam Tracker: A database of more than 35,000 dams with location, catchment, and attribute information. Scientific Data. 2023; 10:111. https://doi.org/10.1038/s41597-023-02008-2

99. Guareschi S, Wood PJ. Taxonomic changes and non-native species: An overview of constraints and new challenges for macroinvertebrate-based indices calculation in river ecosystems. Science of the Total Environment. 2019; 660:40-46.
https://doi.org/10.1016/j.scitotenv.2019.01.008
100. Zhao W, Guo W, Zhao L, Li Q, Cao X, Tang X. Influence of Different Types of Small Hydropower Stations on Macroinvertebrate Communities in the Changjiang River Basin, China. Water. 2019; 11:1892. https://doi.org/10.3390/w11091892